

**ANALYSIS OF A SYNCHRONOUS RELUCTANCE
MOTOR DRIVE CONNECTED TO A WEAK GRID**

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DEPARTMENT OF ELECTRICAL ENGINEERING

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ANALYSIS OF A SYNCHRONOUS RELUCTANCE MOTOR DRIVE CONNECTED TO A WEAK GRID

A thesis submitted in partial fulfillment for the requirements of the degree of

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under the guidance of

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श्रीगुरु प्रणाम मन्त्र
(SRI GURU PRANAM)

ॐ

अज्ञानतिमिरान्धस्य ज्ञानाञ्जनशालाकया
चक्षुरुन्मीलितं येन तस्मै श्रीगुरवे नमः

(*Om Ajnana Timirandhasya Jnananjana Shalaakaaya
Chakshurunmilitam Yena Tasmai Sri Gurave Namaha*)

(I bow to my teacher who has opened my eyes blinded by the darkness of ignorance,
with enlightening rays of knowledge)

To my teacher, parents and friends.

Certificate of Approval

This is to certify that the thesis titled, "**Analysis of a Synchronous Reluctance Motor Connected to a Weak Grid**" being submitted by **Mr. Pradyumna Ranjan Ghosh** 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. Pradyumna Ranjan Ghosh has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

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Abstract

The present scenario of power demand ensures that electricity must be available for all types of applications, starting from pumps to its use in several industrial and commercial application like in electric traction, hospitals etc. Many application sectors may be located in rural areas like pumps in vast agricultural fields and wide network of electric railways in remote areas. It is essential to maintain constant power availability for these applications to perform in a better way. But usually the grids located in remote areas are weak which have varying voltage profile posing serious problems towards proper operation of electrical loads. So in order to maintain constant operation of electrical loads in such weak grids, an analysis need to be done directed towards undisturbed functioning of these electrical apparatus in the presence of lower voltages which may dip for a short time or may remain for a day or even for a longer duration.

Synchronous reluctance motor (SYNRM) due to its promising features over other motors in pump applications, is considered in this thesis for exploration. The analysis has also been extended to synchronous reluctance motors driving constant torque loads like positive displacement pumps and constant power loads like electric railway applications. It can be possible that a motor coupled to a load may not be able to deliver the required output when voltage dip of different magnitudes strike the motor terminals while it is connected to a weak grid. In this context, a novel analysis estimating the voltage dip margin of the SYNRM is presented in this thesis. The estimation of voltage dip margin is discussed in detail for pump, constant torque and constant power type loads. The effect on voltage dip margin as well as other quantities of SYNRM like current, torque pulsations, power output, power factor etc. has been analyzed with respect to variations in inductance and current drawn. Inductance variation can be introduced due to manufacturing defects as well as through different inductance measurement techniques. The focus of all analysis is to retain the original speed and torque despite the occurrence of voltage dips of different magnitudes. The solution required to maintain the motor speed and torque in the event of voltage dips is to adjust the direct axis current (i_d) appropriately. The analysis of the performance of the SYNRM when the voltage dip is greater than the tolerable voltage dip

margin is discussed thoroughly, where the major aim is to observe the magnitude of change in speed, power output, current and other quantities. All of the above motor quantities are assessed in detail by utilizing their mathematical expressions and are validated through simulations and experiments.

सार

बिजली की मांग का वर्तमान परिदृश्य यह सुनिश्चित करता है कि बिजली सभी प्रकार के अनुप्रयोगों के लिए उपलब्ध होनी चाहिए, पंपों से इसके उपयोग के लिए कई औद्योगिक और वाणिज्यिक अनुप्रयोगों में जैसे बिजली के कर्षण, अस्पतालों आदि में। कई आवेदन क्षेत्र ग्रामीण क्षेत्रों में पंप जैसे पंपों में स्थित हो सकते हैं। विशाल कृषि क्षेत्र और दूरदराज के क्षेत्रों में इलेक्ट्रिक रेलवे का व्यापक नेटवर्क। इन अनुप्रयोगों के लिए बेहतर तरीके से प्रदर्शन करने के लिए निरंतर बिजली की उपलब्धता बनाए रखना आवश्यक है। लेकिन आमतौर पर दूरदराज के इलाकों में स्थित ग्रिड कमजोर होते हैं जिनमें वोल्टेज प्रोफाइल अलग-अलग होती है जिससे बिजली के लोड के उचित संचालन के लिए गंभीर समस्याएं पैदा होती हैं। तो इस तरह के कमजोर ग्रिड में बिजली के भार के निरंतर संचालन को बनाए रखने के लिए, कम वोल्टेज की उपस्थिति में इन विद्युत उपकरण के स्वास्थ्यकर कामकाज की दिशा में एक विश्लेषण करने की आवश्यकता होती है जो थोड़े समय के लिए कम हो सकते हैं या एक दिन भी रह सकते हैं या फिर लंबी अवधि के लिए।

पंप अनुप्रयोगों में अन्य मोटर्स पर इसकी आशाजनक विशेषताओं के कारण सिंक्रोनस रिलाकतंस मोटर (SYNRM), इस शोध में अन्वेषण के लिए माना जाता है। विश्लेषण को समकालिक अनिच्छा मोटर्स के लिए विस्तारित किया गया है, जो सकारात्मक विस्थापन पंपों की तरह लगातार टॉर्क लोड और इलेक्ट्रिक रेलवे अनुप्रयोगों की तरह निरंतर बिजली लोड करता है। यह संभव हो सकता है कि एक लोड के लिए युग्मित मोटर आवश्यक आउटपुट देने में सक्षम नहीं हो सकता है जब विभिन्न परिमाण के वोल्टेज डिप मोटर के टर्मिनलों पर प्रहार करते हैं जबकि यह एक कमजोर ग्रिड से जुड़ा होता है। इस संदर्भ में, SYNRM के वोल्टेज डिप मार्जिन का आकलन करने वाला एक उपन्यास विश्लेषण इस थीसिस में प्रस्तुत किया गया है। वोल्टेज डिप मार्जिन के आकलन पर पंप, निरंतर टोक और निरंतर बिजली के प्रकार के भार के बारे में विस्तार से चर्चा की गई है। वोल्टेज डिप मार्जिन पर प्रभाव के साथ-साथ SYNRM की अन्य मात्रा जैसे करंट, टॉर्क स्पंदना, पावर आउटपुट, पावर फैक्टर आदि का विश्लेषण इंडक्शन और करंट ड्रा में बदलाव के संबंध में किया गया है। विनिर्माण दोषों के साथ-साथ विभिन्न अधिष्ठापन माप तकनीकों के माध्यम से अनिच्छा भिन्नता पेश की जा सकती है। सभी विश्लेषणों का ध्यान विभिन्न गति के वोल्टेज डिप्स की घटना के बावजूद मूल गति और टोक को बनाए रखना है। वोल्टेज डिप्स की स्थिति में मोटर की गति और टोक को बनाए रखने के लिए आवश्यक समाधान प्रत्यक्ष अक्ष वर्तमान (i_d) को उचित रूप से समायोजित करना है। SYNRM के प्रदर्शन का विश्लेषण जब वोल्टेज डिप को बर्दाश्त करने योग्य वोल्टेज डिप मार्जिन से अधिक होता है, तो अच्छी तरह से चर्चा की जाती है, जहां प्रमुख उद्देश्य गति, बिजली उत्पादन, वर्तमान और अन्य मात्रा में परिवर्तन के परिमाण का निरीक्षण करना है। उपरोक्त सभी मोटर मात्राओं का उनके गणितीय अभिव्यक्तियों के उपयोग द्वारा विस्तार से मूल्यांकन किया जाता है और सिमुलेशन और प्रयोगों के माध्यम से मान्य किया जाता है।

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Nomenclature

δ	Current angle between stator direct axis current and overall stator current
δ_ψ	Flux angle between direct axis stator flux and overall stator flux
ω_e	Electrical angular speed of motor
ω_m	Mechanical angular rotor speed
ω_n	Normalized electrical angular speed of the motor
ψ_{dn}	Normalized direct axis stator flux linkage
ψ_n	Normalized stator flux linkage
ψ_{qn}	Normalized quadrature axis stator flux linkage
ψ_{sa}	Phase A magnetic flux linkage
ψ_{sb}	Phase B magnetic flux linkage
ψ_{sc}	Phase C magnetic flux linkage
ψ_{sd}	Direct axis stator flux linkage
ψ_{sq}	Quadrature axis stator flux linkage
θ_e	Electrical rotor angular position
θ_r	Mechanical rotor angular position
$\vec{\psi}_{abc}$	Three phase stator flux linkage vector

\vec{i}_{abc}	Thee phase instantaneous stator current vector
\vec{v}_{abc}	Thee phase instantaneous stator voltage vector
ξ	Machine Saliency
i_{dn}	Normalized direct axis stator current
i_n	Normalized stator current
i_{qn}	Normalized quadrature axis stator current
i_{sa}	Phase A instantaneous stator current
i_{sb}	Phase B instantaneous stator current
i_{sc}	Phase C instantaneous stator current
i_{sd}	Direct axis stator current
i_{sq}	Quadrature axis stator current
i_s	Overall current of the motor
J	Moment of inertia of the motor
L_d	Direct axis inductance
L_q	Quadrature axis inductance
L_{dn}	Normalized direct axis stator inductance
L_{ls}	Stator winding leakage inductance
L_{qn}	Normalized quadrature axis stator inductance
L_{sa}	Self inductance of phase A winding
L_{sb}	Self inductance of phase B winding
L_{sc}	Self inductance of phase C winding

M	Magnitude of three phase space vector
M_A	Phase A space vector
M_B	Phase B space vector
M_C	Phase C space vector
M_k	Vector sum and magnitude of phase x and phase y vectors
M_{sab} and M_{sba}	Mutual inductances between A and B phases
M_{sac} and M_{sca}	Mutual inductances between A and C phases
M_{sbc} and M_{scb}	Mutual inductances between B and C phases
M_x	Phase y space vector
M_y	Phase y space vector
$MPFC$	Maximum power factor control
$MTPA$	Maximum torque per ampere control
$MTPF$	Maximum torque per flux control
P	Number of poles of motor
P_{out}	Motor power output
r	stator resistance
r_{abc}	Thee phase resistance
r_n	Normalized stator resistance of the motor
r_{sa}	Phase A stator resistance
r_{sb}	Phase B stator resistance
r_{sc}	Phase C stator resistance

T_e	Electromagnetic torque
T_n	Normalized electromagnetic torque of the motor
v_{dn}	Normalized direct axis stator voltage
v_n	Normalized stator voltage
v_{qn}	Normalized quadrature axis stator voltage
v_{sa}	Phase A instantaneous stator voltage
v_{sb}	Phase B instantaneous stator voltage
v_{sc}	Phase C instantaneous stator voltage
v_{sd}	Direct axis stator voltage
v_{sq}	Quadrature axis stator voltage
p	Number of pole pairs