DESIGN AND DEVELOPMENT OF SOLAR PV ARRAY FED SYNCHRONOUS RELUCTANCE MOTOR DRIVE FOR WATER PUMPING SYSTEM WITH GRID SYNCHRONIZATION

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by

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CERTIFICATE

This is to certify that the thesis entitled, **"Design and Development of Solar PV Array fed Synchronous Reluctance Motor Drive for Water Pumping System with Grid Synchronization"** being submitted by **Ms. Hina Parveen** for the award of the degree of Doctor of Philosophy is a record of bonafide research work carried out by her in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Ms. Hina Parveen has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

This research work deals with the analysis, design, development and control of synchronous reluctance motor (SyRM) drive for solar PV based water pumping systems. Compared to conventional three-phase induction motor, which exhibits a three-phase stator winding and either a wound rotor or a squirrel cage on the rotor, a synchronous reluctance motor has flux-barriers and flux-carriers, the presence of which produces torque, exhibit no rotor winding losses, thereby making them relatively more energy-efficient. In this work, a SyRM is designed using analytical and finite element analysis-based solution for improved performance and control for solar PV based water pumping systems. Designed SyRM is fabricated and simulated results are verified on the fabricated prototype. A reduced sensor-based simple, efficient and cost-effective SyRM drive is investigated. The estimation of rotor speed and position, is made stator flux linkage-based field oriented control.

The system possesses a maximum power point tracking (MPPT) of the PV array by introducing a DC-DC converter between the PV array and VSI, feeding the motor. The work is extended towards an elimination of DC-DC converter and a single-stage PV array SyRM drive is also investigated for water pumping. Standalone solar PV based systems have serious constraints of power intermittency, which results in unreliability of overall system. Moreover, the installed water pump is underutilized in bad atmosphere conditions and is completely shut down at night. This problem is resolved through the introduction of auxiliary power source in the form of battery storage. In addition to it, an attempt is made for integrating unidirectional and bidirectional converters to the utility grid. The auxiliary power source, i.e., the battery integrated into the system, helps fulfill the power requirement to the load (pump, domestic loads) when the PV power is insufficient to obtain rated water discharge.

Moreover, both the unidirectional and bidirectional power flow controls are implemented for a grid-interfaced PV array based SyRM driven water pumping system. In addition, the single-stage, grid-connected configurations are also developed and tested successfully. The bidirectional power flow control based topologies offer additional advantage of feeding power to the grid from the installed PV array, in conditions when water pumping is not required, which acts as a secondary source of earning, by the seller. This practice leads to the full utilization of installed resources. The power quality standards, such as power factor and total harmonic distortion (THD) of grid currents as per IEEE-519 standards are met by these configurations.

All these configurations are simulated in MATLAB/Simulink platform and the laboratory prototypes of them are developed to validate the topology, control algorithm and the developed simulated model. The applicability of commercial potential of these systems are justified by their in-depth analysis based on efficiency, cost, simplicity and performance.

अमूर्त

यह शोध कार्य सोलर फोटोवोल्टिक आधारित जल पंपिंग प्रणालियों के लिए सिंक्रोनस रिलक्टेंस मोटर (SyRM) ड्राइव के विश्लेषण, डिजाइन, विकास और नियंत्रण से संबंधित है। पारंपरिक तीन-चरण प्रेरण मोटर की तुलना में, जो तीन-चरण स्टेटर वाइंडिंग और या तो एक घाव रोटर या रोटर पर एक गिलहरी पिंजरे को प्रदर्शित करता है, एक तुल्यकालिक अनिच्छा मोटर में फ्लक्स-अवरोधक और फ्लक्स-वाहक होते हैं, जिनकी उपस्थिति टोक़ उत्पन्न करती है, रोटर वाइंडिंग में कोई हानि नहीं होती है, जिससे वे अपेक्षाकृत अधिक ऊर्जा-कुशल बन जाते हैं। इस कार्य में, सोलर फोटोवोल्टिक आधारित जल पंपिंग प्रणालियों के बेहतर प्रदर्शन और नियंत्रण के लिए विश्लेषणात्मक और परिमित तत्व विश्लेषण-आधारित समाधान का उपयोग करके एक SyRM डिज़ाइन किया गया है। डिज़ाइन किया गया SyRM गढ़ा गया है और सिम्युलेटेड परिणाम गढ़े गए प्रोटोटाइप पर सत्यापित किए गए हैं। एक कम सेंसर-आधारित सरल, कुशल और लागत प्रभावी SyRM ड्राइव की जांच की जाती है। रोटर की गति और स्थिति का अनुमान, स्टेटर फ्लक्स लिंकेज-आधारित क्षेत्र उन्मुख नियंत्रण से बनाया गया है।

सिस्टम सोलर फोटोवोल्टिक सरणी और वीएसआई के बीच एक DC-DC कनवर्टर शुरू करके मोटर को खिलाकर पीवी सरणी की अधिकतम पावर पॉइंट ट्रैकिंग (MPPT) रखता है। DC-DC कनवर्टर को खत्म करने की दिशा में काम बढ़ाया गया है और पानी पंपिंग के लिए सिंगल-स्टेज सोलर फोटोवोल्टिक सरणी SyRM ड्राइव की भी जांच की जा रही है। स्टैंडअलोन सोलर फोटोवोल्टिक आधारित प्रणालियों में बिजली की रुक-रुक कर होने वाली गंभीर बाधाएँ होती हैं, जिसके परिणामस्वरूप समग्र प्रणाली अविश्वसनीय हो जाती है। इसके अलावा, खराब वातावरण की स्थिति में स्थापित जल पंप का कम उपयोग किया जाता है और रात में पूरी तरह से बंद कर दिया जाता है। बैटरी भंडारण के रूप में सहायक ऊर्जा स्रोत की शुरूआत के माध्यम से इस समस्या का समाधान किया जाता है। इसके अतिरिक्त, यूनीडायरेक्शनल और द्विदिशात्मक बिजली कन्वर्टर्स को उपयोगिता ग्रिड में एकीकृत करने का प्रयास

किया गया है। सहायक बिजली स्रोत, यानी, सिस्टम में एकीकृत बैटरी, लोड (पंप, घरेलू भार) के लिए बिजली की आवश्यकता को पूरा करने में मदद करती है जब पीवी बिजली रेटेड जल निर्वहन प्राप्त करने के लिए अपर्याप्त होती है।

इसके अलावा, ग्रिड-इंटरफ़ेस्ड सोलर फोटोवोल्टिक सरणी आधारित SyRM संचालित जल पंपिंग प्रणाली के लिए यूनिडायरेक्शनल और द्विदिशात्मक बिजली प्रवाह नियंत्रण दोनों लागू किए जाते हैं। इसके अलावा, सिंगल-स्टेज, ग्रिड-कनेक्टेड कॉन्फ़िगरेशन भी सफलतापूर्वक विकसित और परीक्षण किए गए हैं। द्वि-दिशात्मक विद्‌युत प्रवाह नियंत्रण आधारित टोपोलॉजी स्थापित सोलर फोटोवोल्टिक सरणी से ग्रिड को बिजली खिलाने का अतिरिक्त लाभ प्रदान करती है, उन स्थितियों में जब पानी पंपिंग की आवश्यकता नहीं होती है, जो विक्रेता द्वारा कमाई के द्वितीयक स्रोत के रूप में कार्य करता है। इस अभ्यास से स्थापित संसाधनों का पूर्ण उपयोग होता है। आई.ई.ई.ई-519 मानकों के अनुसार बिजली गुणवत्ता मानकों, जैसे पावर फैक्टर और ग्रिड धाराओं के कुल हार्मोनिक विरूपण (THD) को इन कॉन्फ़िगरेशन से पूरा किया जाता है।

इन सभी कॉन्फ़िगरेशन को MATLAB/Simulink प्लेटफ़ॉर्म में सिमुलेशन किया गया है और टोपोलॉजी, नियंत्रण एल्गोरिदम और विकसित सिमुलेशन मॉडल को मान्य करने के लिए उनके प्रयोगशाला प्रोटोटाइप विकसित किए गए हैं। इन प्रणालियों की व्यावसायिक क्षमता की प्रयोज्यता को दक्षता, लागत, सरलता और प्रदर्शन के आधार पर उनके गहन विश्लेषण द्वारा उचित ठहराया जाता है।s

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
Ah	Ampere Hour
ALA	Axially Laminated Anisotropic
BDDC	Bidirectional DC-DC Converter
BES	Battery Energy Storage
BEMF	Back EMF
BIS	Bureau of Indian Standards
BLDC	Brushless DC
CCM	Continuous Conduction Mode
CEC	Clean Energy Council
CPU	Central Processing Unit
DAC	Digital to Analog Converter
DBR	Diode Bridge Rectifier
DC	Direct Current
DSP	Digital Signal Processor
DSOGI	Dual Second Order Generalized Integrator
DTC	Direct Torque Control
EMF	Electromotive Force
EMI	Electromagnetic Interference
FEA	Finite Element Analysis
FEM	Finite Element Methods
FFT	Fast Fourier transformation
FLL	Frequency Locked Loop
FOC	Field Oriented Control
IC	Integrated Circuits
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Integrated Gate Bipolar Transistor
IM	Induction Motor
InC	Incremental Conductance
LPF	Low Pass Filter
MHRD	Ministry of Human Resource Development
MNRE	Ministry of New & Renewable Energy
MOGI	Mixed Order Generalized Integrator
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MTPA	Maximum Torque Per Ampere
NASA	National Aeronautics and Space Administration
P & O	Perturb and observe
PCC	Point of Common Coupling
PFC	Power Factor Correction
PI	Proportional- Integrator
PLL	Phase Locked Loop

PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
PQ	Power Quality
PV	Photovoltaic
PWM	Pulse width Modulation
RE	Renewable Energy
RMS	Root Mean Square
SOC	State of Charge
S-SOGI	Single Second Order Generalized Integrator
SOGI	Second Order Generalized Integrator
SPV	Solar Photovoltaic
SRM	Switched Reluctance Motor
STS	Solid State Switch
SWP	Solar Water Pumping
SyRM	Synchronous Reluctance Motor
TF	Transfer Function
THD	Total Harmonic Distortion
TLA	Transversally Laminated Anisotropic
TOGI	Third Order Generalized Integrator
UPF	Unity Power Factor
UVT	Unit Vector Template
VSC	Voltage Source Converter
VSI	Voltage Source Inverter

LIST OF SYMBOLS

ρ_{Cu}	Resistivity of copper (Ωm)
B	Magnetic flux density (T)
H	Magnetic field intensity (A/m)
D_{si}, D_{so}	Stator inner and outer diameters (mm)
l_g	Airgap length (mm)
A_g	Area of airgap (mm^2)
D_{ri}, D_{ro}	Rotor inner and outer diameters (mm)
L_{stk}	Stack height (mm)
L_{end}	End winding length (mm)
Q_s	Number of stator poles
P	Number of poles
k_{w1}	Fundamental winding factor
N_{ph}	Number of turns in series per phase
N_c	Number of coils per phase
N_{par}	Number of parallel paths
A_{su}	Area of the slot (mm^2)
a_z	Conductor cross section area (mm^2)
d_{en}	Diameter of the enameled copper wire (mm)
d_{bare}	Diameter of the bare copper wire (mm)
B_g	Average air gap flux density (T)
A_c	Linear current density (A/m)
C_o	Output coefficient (J/m^3)
I_{phase}, I_{line}	Rated phase and line currents of the motor (A)
V_{phase}, V_{line}	Rated phase and line voltages of the motor (V)
f_s	Operating frequency (Hz)
J	Current density (A/mm^2)
Q_{in}	Input apparent power (kVA)
P_{in}	Input real power (kW)
Pf	Power factor
T_{out}	Average output torque (Nm)
P_{out}	Average power output (kW)
E_{ph}	Induced emf/phase (V)
N_s	Rated speed (rpm)
η_{nom}	Efficiency
τ_u	Stator slot pitch (mm)
A_{st}	Area of the stator tooth (mm)
k_{is}	Iron stacking factor
B_{gmax}	Maximum air gap flux density (T)
ϕ_{slot}	Slot flux (Wb)
B_{slot}	Slot flux density (T)
w_{st}	Width of stator tooth (mm)
w_{sty}	Width of stator yoke (mm)
b_{sl1}	Slot width (mm)
n_b	Number of flux barrier

n_c	Number of flux carrier
K_{inq}	Insulation ratio
w_{br}	Barrier width (mm)
w_{cr}	Carrier width (mm)
w_{Tr}	Width of tangential rib (mm)
R_{ph}	Phase resistance (Ω)
k_s	Saturation factor
$L_{mag(d}$, $L_{mag(q)}$	Dq magnetizing inductances (H)
L_{ls}	Leakage inductance (H)
m	Number of phases
D	Air gap diameter (mm)
ς_{slot}	Slot leakage permeance (Wb/A)
ς_{tooth}	Tooth tip permeance (Wb/A)
ς_h	Differential permeance (Wb/A)
ς_{ew}	End winding permeance (Wb/A)
θ	Current angle
I_d	d-axis component of the phase current (A)
I_q	q-axis component of the phase current (A)
$V_{s\text{-}core}$	Stator core volume (mm^3)
$A_{s\text{-}core}$	Area of the stator core (mm^2)
D_{sc}	Stator core diameter (mm)
$W_{s\text{-}core}$	Mass of the stator core (kg)
$V_{s\text{-}tooth}$	Stator teeth volume (mm^3)
$W_{s\text{-}teeth}$	Total mass of all stator teeth (kg)
$A_{barrier}$	Barrier area (mm^2)
D_{shaft}	Shaft Diameter (mm)
W_{rotor}	Rotor mass (kg)
P_{rotor}	Rotor core losses (W)
P_{add}	Additional losses (W)
ξ	Saliency ratio
L_d, L_q	dq axis inductances (H)
V_{pv}	Solar PV array voltage (V)
I_{pv}	Solar PV array current (A)
P_{pv}	Solar PV array power (W)
C_{pv}	PV array capacitance (F)
V_{oc}	Open circuit voltage (V)
I_{sc}	Short circuit current (A)
V_{mpp}	Solar PV array voltage at MPP (V)
I_{mpp}	Solar PV array current at MPP (A)
P_{mpp}	Solar PV array power at MPP (W)
C_{dc}	DC link capacitor (μF)
L	Boost Inductor (mH)
S_1-S_6	Switching pulses for three phase VSI
S_{l1}-S_{l4}	Switching pulses for single phase VSC
C_{dc}	DC link capacitor (μF)
i_a, i_b, i_c	Three phase current of SyRM (A)

V_{dc}	DC link voltage (V)
V_{dcr}	Reference DC link voltage (V)
L_b	Boost converter inductor (mH)
D_b	Duty ratio of boost convert
D_B	Duty ratio of battery energy storage
L_B	Bidirectional DC-DC converter inductor (mH)
V_B	Battery energy storage voltage (V)
i_B	Battery current (A)
i_{Br}	Reference battery current (A)
L_f	Interfacing Inductor (mH)
R_f, C_f	Ripple filter (Ω, μF)
V_L	Local load voltage (V)
I_L	Local load current (A)
i_g	Sensed grid current (A)
v_g	Sensed grid voltage (V)
u_p, u_q	Unit template
i_{ga}, i_{gb}, i_{gc}	Sensed three phase grid currents (A)
v_{ga}, v_{gb}, v_{gc}	Sensed three phase grid voltages (V)
i_{gar}, i_{gbr}, i_{gcr}	Reference three phase grid current (A)
I_{La}, I_{Lb}, I_{Lc}	Sensed three phase load current (A)
f_g, f_L	Grid and load frequency (Hz)
θ_g, θ_L	Phase angle of grid and load
m	Modulation index
α	Overloading factor
V_{rms}, I_{rms}	Rms voltage (V)
ω_{ref}, ω_{est}	Reference and estimated speed (rpm)
θ_{est}	Estimated rotor position (rad)
T_e	Electromagnetic torque (Nm)
T_{eref}	Reference electromagnetic torque (Nm)
i_{sd}, i_{sq}, i_{sdr}, i_{sqr}	Actual and reference dq axis current (A)
ψ_{sd}, ψ_{sq}	dq axes flux linkages (Wb)
P	Number of pole pairs
ρ_s	Angle between stator flux with direct axis of rotor
Δ	Angle between stator flux linkage vector and direct axis of rotor.
t	Dynamics time period.
S_{B1}, S_{B2}	Switching pulse of bidirectional DC-DC converter
K_{vf}, K_{if}	Voltage and current safety factor
α	Overloading factor
R_s	Stator resistance (Ω)
S_g	Switching pulse of PFC boost converter
S_w	Switching pulse of DC-DC boost converter