DESIGN AND CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVES FOR STANDALONE AND GRID INTERFACED SOLAR WATER PUMPING SYSTEMS

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by

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CERTIFICATE

It is certified that the thesis entitled "**Design and Control of Permanent Motor Synchronous Motor Drives for Standalone and Grid Interfaced Solar Water Pumping System**," being submitted by **Mr. Mohd. Kashif** 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.

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Dated:

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ABSTRACT

Due to worldwide acceptance of net zero carbon emission policy and the subsequent necessity to minimize carbon footprints of energy infrastructure, there is an accelerated growth of solar photovoltaic (PV) array fed systems for several crucial applications like solar water pumping. The domains like irrigation, residential/commercial buildings, forest conservation, livestock, aquaculture and others are the potential beneficiary of solar water pumping systems. Besides, the declining cost of PV technology and the availability of low-cost digital signal processors have increased the number of installations of PV array fed water pumping systems. Meanwhile, permanent magnet synchronous motor (PMSM) has emerged as a potential candidate for driving solar water pumping systems due to its advantages like higher efficiency, higher torque density and unity power factor operation over induction motors. In this research work, various configurations of PMSM drive suitable for solar water pumping system.

In developed configurations of PMSM, the reverse-saliency is realized through introduction of flux barriers along q-axis in rotor to minimize permanent magnet demagnetization risk. While the developed topologies of PMSM operated solar water pumping system are broadly classified into standalone and grid interfaced systems. The PV array and battery energy storage (BES) are the two energy sources for standalone system. For such systems, a bidirectional power flow controller is developed for controlling battery power based on weather conditions. This enables delivery of constant water discharge for intermittent irradiation, thereby increasing utilization of the system. Whereas, the grid is available as another energy source in addition to PV array and BES for grid-interfaced system. Such a configuration facilitates on-demand water pumping irrespective of availability of irradiation. For this system, the fundamental component of grid voltage is extracted by using presented frequency locked loop (FLL). This enables the smooth operation of system even under abnormal grid conditions as the power quality at grid terminals is maintained in accordance to the IEEE-519 standard. Besides, a synchronization unit is added to the grid interfaced system for seamless synchronization of water pumping system with grid. For this purpose, the presented FLL based synchronizing controls are developed. Such a unit facilitates interconnection and interoperability between water pumping system and grid so that these two units work effectively, which thereby satisfies the IEEE 1547-2018 updated standard.

Besides, mechanical position sensor is eliminated from PMSM drive by using presented rotor flux observer, which estimates speed and rotor position. The estimated speed and rotor position are then used for implementing field-oriented control of PMSM drive. The elimination of position sensor reduces cost and increases reliability of the solar water pumping system. Even

a provision to supply power to local-loads of the system such as pressure boosters, cooling fans, lighting load, fan-load and others is included into the system. Such a load is necessary and unavoidable as it represents the auxiliary components of solar water pumping system, which are necessary for smooth operation of the system.

The performance of the presented configurations of solar water pumping system and the associated control techniques is analyzed by performing simulation on MATLAB/Simulink platform. Several simulation results are acquired and reported for each topology during starting, steady-state and dynamics under practical operating scenarios. Besides, an experimental validation of all the presented topologies is carried out on the laboratory prototype of the system, and the associated test results are reported.

संक्षेप

शून्य कार्बन उत्सर्जन नीति की विश्वव्यापी स्वीकृति और ऊर्जा अवसंरचना के कार्बन फुटप्रिंट्स को कम करने की आवश्यकता के कारण, सौर जल पंपिंग जैसे कई महत्वपूर्ण अनुप्रयोगों के लिए सौर फोटोवोल्टिक (पीवी) सरणी फेड सिस्टम की त्वरित वृद्धि हुई है। सिंचाई, आवासीय/वाणिज्यिक भवनों, वन संरक्षण, पशुधन, जलीय कृषि और अन्य जैसे डोमेन सौर जल पम्पिंग प्रणालियों के संभावित लाभार्थी हैं। इसके अलावा, पीवी तकनीक की घटती लागत और कम लागत वाले डिजिटल सिग्नल प्रोसेसर की उपलब्धता ने पीवी ऐरे फेड वॉटर पंपिंग सिस्टम की स्थापनाओं की संख्या में वृद्धि की है। इस बीच, स्थायी चुंबक तुल्यकालिक मोटर (PMSM) उच्च दक्षता, उच्च टोक़ घनत्व और प्रेरण मोटर्स पर एकता शक्ति कारक संचालन जैसे लाभों के कारण सौर जल पंपिंग सिस्टम को चलाने के लिए एक संभावित उम्मीदवार के रूप में उभरा है। इस शोध कार्य में पीएमएसएम ड्राइव के विभिन्न विन्यास सौर जल पम्पिंग प्रणाली के लिए उपयुक्त हैं।

पीएमएसएम के विकसित विन्यास में, स्थायी चुंबक विचुंबकीकरण जोखिम को कम करने के लिए रोटर में क्यू-अक्ष के साथ फ्लक्स बैरियर की शुरूआत के माध्यम से रिवर्स-सलियेन्सी को महसूस किया जाता है। जबकि पीएमएसएम संचालित सौर जल पम्पिंग प्रणाली की विकसित टोपोलॉजी को मोटे तौर पर स्टैंडअलोन और ग्रिड इंटरफेस्ड सिस्टम में वर्गीकृत किया गया है। पीवी सरणी और बैटरी ऊर्जा भंडारण (बीईएस) स्टैंडअलोन सिस्टम के लिए दो ऊर्जा स्रोत हैं। ऐसी प्रणालियों के लिए, मौसम की स्थिति के आधार पर बैटरी पावर को नियंत्रित करने के लिए एक द्विदिश शक्ति प्रवाह नियंत्रक विकसित किया जाता है। यह आंतरायिक विकिरण के लिए निरंतर जल निर्वहन को सक्षम बनाता है, जिससे सिस्टम का उपयोग बढ़ता है। जबकि, ग्रिड-इंटरफेस सिस्टम के लिए पीवी सरणी और बीईएस के अतिरिक्त ग्रिड एक अन्य ऊर्जा स्रोत के रूप में उपलब्ध है। इस तरह का विन्यास विकिरण की उपलब्धता के बावजूद ऑन-डिमांड पानी पंपिंग की सुविधा देता है। इस प्रणाली के लिए, प्रस्तुत फ्रीक्वेंसी लॉक लूप (FLL) का उपयोग करके ग्रिड वोल्टेज के मूलभूत घटक को निकाला जाता है। यह असामान्य ग्रिड परिस्थितियों में भी सिस्टम के सुचारू संचालन को सक्षम बनाता है क्योंकि ग्रिड टर्मिनलों पर बिजली की गुणवत्ता IEEE-519 मानक के अनुसार बनाए रखी जाती है। इसके अलावा, ग्रिड के साथ जल पम्पिंग प्रणाली के निर्बाध तुल्यकालन के लिए ग्रिड इंटरफेस प्रणाली में एक तुल्यकालन इकाई जोड़ी जाती है। इस प्रयोजन के लिए, प्रस्तुत FLL आधारित तुल्यकालन नियंत्रण विकसित किए गए हैं। ऐसी इकाई जल पम्पिंग प्रणाली और ग्रिड के बीच अंतर्संबंध और अंतर्संचालनीयता की सुविधा प्रदान करती है ताकि ये दोनों इकाइयाँ प्रभावी ढंग से काम करें, जिससे IEEE 1547-2018 अद्यतन मानक को पूरा किया जा सके।

इसके अलावा, प्रस्तुत रोटर फ्लक्स ऑब्जर्वर का उपयोग करके पीएमएसएम ड्राइव से मैकेनिकल पोजीशन सेंसर को हटा दिया जाता है, जो गति और रोटर की स्थिति का अनुमान लगाता है। अनुमानित गति और रोटर की स्थिति का उपयोग तब PMSM ड्राइव के क्षेत्र-उन्मुख नियंत्रण को लागू करने के लिए किया जाता है। स्थिति संवेदक के उन्मूलन से लागत कम हो जाती है और सौर जल पम्पिंग प्रणाली की विश्वसनीयता बढ़ जाती है। यहां तक कि सिस्टम के लोकल-लोड जैसे प्रेशर बूस्टर, कूलिंग फैन, लाइटिंग लोड, फैन-लोड और अन्य को बिजली की आपूर्ति करने का प्रावधान भी सिस्टम में शामिल है। ऐसा भार आवश्यक और अपरिहार्य है क्योंकि यह सौर जल पम्पिंग सिस्टम के सहायक घटकों का प्रतिनिधित्व करता है, जो सिस्टम के सुचारू संचालन के लिए आवश्यक हैं।

MATLAB / Simulink प्लेटफॉर्म पर सिमुलेशन प्रदर्शन करके सौर जल पंपिंग सिस्टम और संबंधित नियंत्रण तकनीकों की प्रस्तुत कॉन्फ़िगरेशन का प्रदर्शन विश्लेषण किया जाता है। व्यावहारिक ऑपरेटिंग परिदृश्यों के तहत प्रारंभिक, स्थिर-अवस्था और गतिशीलता के दौरान प्रत्येक टोपोलॉजी के लिए कई सिमुलेशन परिणाम प्राप्त और रिपोर्ट किए जाते हैं। इसके अलावा, सभी प्रस्तुत टोपोलॉजी का प्रायोगिक सत्यापन सिस्टम के प्रयोगशाला प्रोटोटाइप पर किया जाता है, और संबंधित परीक्षण के परिणाम रिपोर्ट किए जाते हैं।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
ANF	Adaptive Notch Filter
AMNF	Adaptive Multi-Notch Filter
APF	All Pass Filter
ASTM	American Society for Testing and Materials
BDC	Bidirectional Converter
BIS	Bureau of Indian Standards
BJT	Bipolar Junction Transistor
BLDCM	Brushless DC Motor
BES	Battery Energy Storage
CCM	Continuous Conduction Mode
CEC	Clean Energy Council
CER	Clean Energy Regulator
CPU	Central Processing Unit
CS-PMSM	Conventional Spoke PMSM
DAC	Digital to Analog Converter
DC	Direct Current
DSC	Delayed Signal Cancellation
DSO	Digital Signal Oscilloscope
DSP	Digital Signal Processor
DTC	Direct Toque Control
EMC	Electro-Magnetic Compatibility
EMF	Electro-Motive Force
EMI	Electro-Magnetic Interference
EMN	Electromagnetic Noise
FEA	Finite Element Analysis
FEC	Front End Converter

FEM	Finite Element Method
FL	Fuzzy Logic
FLL	Frequency Locked Loop
FOC	Field Oriented Control
GCC	Grey Correlation Coefficient
GCG	Grey Correlation Grade
IB	Internal Barriers
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IANF	Improved Adaptive Notch Filter
IGBT	Insulated Gate Bipolar Junction Transistor
INC	Incremental Conductance
ISES	International Solar Energy Society
IM	Induction Motor
INC	Incremental Conductance
IS	Indian Standard
ISOGI	Improved SOGI
KF	Kalman Filter
LPF	Low Pass Filter
MAF	Moving Average Filter
MMF	Magnetomotive Forces
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NdFeB	Neodymium-Iron-Boron
PB	Peripheral Barriers
PFC	Power Factor Correction
PI	Proportional Integral
PLL	Phase Locked Loop
PMBDCM	Permanent Magnet Brushed DC Motor
PMD	Permanent Magnet Demagnetization

PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
PQ	Power Quality
P&O	Perturb and Observe
PV	Photo-Voltaic
PWM	Pulse Width Modulation
RE	Renewable Energy
RMS	Root Mean Square
RS-PMSM	Reverse Saliency PMSM
RS-PMSM-WMB	Reverse Saliency PMSM With Multilayer Barriers
RS-PMSM-WPB	Reverse Saliency PMSM With Peripheral Barriers
SHE	Selective Harmonic Elimination
SMO	Sliding Mode Observer
SOGI	Second Order Generalized Integrator
SMPS	Switched Mode Power Supply
SRF	Synchronous Reference Frame
SRM	Switched Reluctance Motor
STC	Standard Test Condition
SWPS	Solar Water Pumping System
SyRM	Synchronous Reluctance Motor
TF	Transfer Function
THD	Total Harmonic Distortion
UPF	Unity Power Factor
UVT	Unit Vector Template
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
WPS	Water Pumping System

LIST OF SYMBOLS

AH_{BES}	Ampere-hour capacity of BES
AH_{BESn}	Nominal ampere-hour capacity of BES
EC_{BES}	Energy capacity of BES
EC_{BESn}	Nominal energy capacity of BES
C_f, r_f	Capacitor, and resistor across RC-ripple filter
C_{DC}	Capacitor across DC bus
C_{PV}	PV array capacitor
D	Duty ratio of boost converter
DOD	BES Depth of Discharge
e_α, e_β	αβ-axis back EMF components
e_ω	Speed error
e_{vdc}	DC link voltage error
f_{sb}	Switching frequency of boost converter IGBT
G	Solar irradiation
I_d, I_q	dq-axes currents of PMSM
I_{dr}, I_{qr}	Reference dq-axes currents of PMSM
i_α, i_β	αβ-axes PMSM currents
i_{ga}, i_{gb}, i_{gc}	Grid currents
i_{gr}	Reference grid currents
i_{ma}, i_{mb}, i_{mc}	PMSM currents
i_{mar}, i_{mbr}, i_{mcr}	Reference PMSM currents
I_{dm}, I_{qm}	dq-components of the PMSM currents
I_{dmr}, I_{qmr}	Reference dq-components of the PMSM currents
I_{PVr}, V_{PVr}, P_{PVr}	Reference value of PV array current, voltage, and power
I_{PV}, V_{PV}, P_{PV}	PV array current, voltage, and power at MPPT
I_{sc}, V_{oc}	PV array short circuit current and open circuit voltage
I_{BES}, V_{BES}, P_{BES}	BES current, voltage, and power
I_{BESn}, V_{BESn}, P_{BESn}	Nominal BES current, voltage, and power

i_L, v_L	Load current, and load voltage
i_{Lin}, i_{Lq}	In-phase and quadrature component of load current
i_{Lf}	Filtered load current
i_{Lfr}	Reference value of filtered load current
v_{Lr}	Reference load-voltage
I_{BESr}	Reference BES current
I_{DC}	DC link current
L	Inductance of boost converter
L_f	Inductance of interfacing inductor
N_r	Rated speed of PMSM
N_p	Number of poles in PMSM
P_L	Active power requirement of load
P_{pmsmr}	Rated power of PMSM
P_{pmsm}	Output power of PMSM
Q_L	Reactive power requirement of load
S_L	Apparent power requirement of load
T_{b1}, T_{b2}	Switching pulses for bidirectional converter
T_{m1}-T_{m6}	Switching pulses for motor-side three-phase VSI
T_{g1}-T_{g6}	Switching pulses for grid-side three-phase VSC
T_{g1}-T_{g4}	Switching pulses for grid-side single-phase VSC
T_{em}, T_{mech}	Electromagnetic and mechanical PMSM torque
T_{est}	Estimated PMSM torque
T_{ref}	Reference PMSM torque
T_L	Load torque
T_{syn}	Status of synchronizing switch
u_{gp}	Unit template corresponding to grid voltage
v_α, v_β	αβ-axes PMSM voltages
V_{DC}	DC link voltage
V_{DCr}	Reference DC link voltage
V_{Lp}	Peak value of load voltage

v_{ag}, v_{bg}, v_{cg}	Estimated grid voltages per phase
v_{abg}, v_{bcg}, v_{cag}	Estimated line-to-line grid voltages
V_{rmsg}	RMS grid voltage
v_{ma}, v_{mb}, v_{mc}	PMSM phase-voltages
v_{mab}, v_{mbc}, v_{mca}	PMSM line-voltages
w_T	Total weighting-component
w_{loss}	DC-loss weighting factor
w_L	Load weighting-factor
λ_α, λ_β, λ_r	αβ-axes and resultant PMSM flux
ϕ_{pm}	Permanent magnet flux linkage
θ_{me}	Estimated rotor angle
θ_g	Phase-angle of grid voltage
θ_L	Phase-angle of load-voltage
ω_e	Estimated PMSM speed in elect.
ω_g	Grid frequency
ω_{me}	Estimated PMSM speed in mech.
ω_{mrt}	Rated PMSM speed
ω_{mer}	Reference PMSM speed in elect.