STANDALONE AND GRID INTERFACED SRM DRIVES FOR SOLAR WATER PUMPING

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by

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CERTIFICATE

It is certified that the thesis entitled "**Standalone and Grid Interfaced SRM Drives for Solar Water Pumping**," being submitted by **Mr. Anjanee Kumar Mishra** 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.

Dated:

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Anjanee Kumar Mishra

ABSTRACT

The utilization of solar photovoltaic (PV) energy in water pumping is conservative particularly in isolated regions where the transmission of power is either impractical or exorbitant. In this research work, various topologies for solar PV array powered water pumping are developed using a 4-phase switched reluctance motor (SRM) drive. A high-efficiency SRM substantially reduces the size of PV array and hence its installation cost. Moreover, its great reliability, high torque to weight ratio, easy construction and invariant performance under harsh environment offers a compact and user-friendly solar-powered water pumping system. Besides these, unlike an induction motor (IM), the speed of a SRM drive is not limited by power frequency. This leads to a reduced size of the motor.

A reduced sensor-based simple, efficient and cost-effective SRM drive is investigated with fast control of its speed. The motor phase current sensors are completely eliminated in the proposed drive. In addition, the speed control loop is not required, as the speed of SRM-pump is adjusted by the DC link voltage of the mid-point converter. The mid-point converter is switched at the fundamental frequency, which offers a high conversion efficiency by reducing the switching losses in mid-point converter. The system possesses a maximum power point tracking (MPPT) of PV array by introducing a DC-DC converter between the PV array and a mid-point converter, feeding the motor. The various single input dual output (SIDO) DC-DC converters are proposed for MPPT and analyzed based on their performance, simplicity, design, cost, efficiency, and ability to provide two balanced voltage outputs. The work is extended towards the elimination of DC-DC converter and a single-stage PV array powered SRM drive is also investigated for water pumping. This system is capable of operating the solar PV array at its optimum power using the same mid-point converter, which is used for motor control.

A promising case of an interruption in the water pumping due to the intermittency of PV array power generation is resolved by using a battery storage system (BSS), single-phase utility grid or both battery storage system (BSS) and single-phase utility grid as an external power backup. All these combinations are capable to provide the continuous water supply irrespective to the environmental conditions. A battery supported, grid interacted or both the battery and grid integrated PV array and their control are demonstrated to get a reliable and fully utilized water pumping with SRM such that the pumping is not affected by the intermittency of PV array power generation. The power is drawn from the battery storage system (BSS) or utility grid in case the PV array is unable to meet the required power demand. Both the unidirectional and bidirectional power flow controls are implemented for a grid interfaced PV array powered SRM driven water pump. In addition, the single-stage topologies for all these configurations are also developed and tested successfully. The bidirectional power flow control based topologies offer additional merit of feeding power to the utility grid by the installed PV array, in case the water pumping is not required. This practice leads to full utilization of installed resources. Moreover, it emerges as a source of earning by the sale of electricity to the utility. The maximum power point (MPP) operation of PV array, and power quality (PQ) standards such as power factor and total harmonic distortion (THD) of grid current as per the IEEE-519 standard, are met by this system.

All the proposed configurations are modeled and simulated using MATLAB/Simulink platform in order to demonstrate their performance during starting, dynamic and steady-state conditions. Simulated results are verified through test results obtained from hardware implementation using a developed prototype in the laboratory. The applicability and commercial potential of proposed systems are justified by their in-depth analysis based on efficiency, cost, simplicity, and performance.

सारांश

पानी के पंपिंग में सौर फोटोवोल्टिक (पीवी) ऊर्जा का उपयोग विशेष रूप से पृथक क्षेत्रों में रूढ़िवादी है जहां बिजली का संचरण या तो अव्यावहारिक या अत्यधिक है। इस शोध कार्य में, 4-चरण स्विचड अनिच्छा मोटर (एसआरएम) ड्राइव का उपयोग करके सौर पीवी सरणी संचालित पानी पंपिंग के लिए विभिन्न टोपोलॉजी विकसित की जाती हैं। एक उच्च दक्षता वाला एसआरएम पीवी सरणी के आकार को काफी कम कर देता है और इसलिए इसकी स्थापना लागत। इसके अलावा, इसकी महान विश्वसनीयता, वजन अनुपात के लिए उच्च टोक़, कठोर पर्यावरण के तहत आसान निर्माण और अपरिवर्तनीय प्रदर्शन, एक कॉम्पैक्ट और उपयोगकर्ता के अनुकूल सौर-संचालित जल पम्पिंग प्रणाली प्रदान करता है। इन के अलावा, एक इंडक्शन मोटर के विपरीत, एसआरएम ड्राइव की गति बिजली आवृत्ति द्वारा सीमित नहीं है। इससे मोटर का आकार कम हो जाता है।

एक कम सेंसर-आधारित सरल, कुशल और लागत प्रभावी एसआरएम ड्राइव की जांच इसकी गति के तेज नियंत्रण के साथ की जाती है। प्रस्तावित चरण में मोटर चरण वर्तमान सेंसर पूरी तरह से समाप्त हो गए हैं। इसके अलावा, गति नियंत्रण लूप की आवश्यकता नहीं है, क्योंकि एसआरएम-पंप की गति को मध्य-बिंदु कनवर्टर के डीसी लिंक वोल्टेज द्वारा समायोजित किया जाता है। मध्य-बिंदु कनवर्टर को मौलिक आवृत्ति पर स्विच किया जाता है, जो मध्य-बिंदु कनवर्टर में स्विचिंग घाटे को कम करके उच्च रूपांतरण दक्षता प्रदान करता है। सिस्टम में पी.वी. सरणी और एक मिड-पॉइंट कनवर्टर के बीच डीसी-डीसी कनवर्टर पेश करके मोटर खिलाते हुए पीवी सरणी की अधिकतम पावर प्वाइंट ट्रैकिंग (एमपीपीटी) होती है। विभिन्न एकल इनपुट दोहरे आउटपुट डीसी डीसी कन्वर्टर्स एमपीपीटी के लिए प्रस्तावित हैं और उनके प्रदर्शन, सादगी, डिजाइन, लागत, दक्षता और दो संतुलित वोल्टेज आउटपुट प्रदान करने की क्षमता के आधार पर विश्लेषण किया गया है। काम को डीसी-डीसी कनवर्टर के उन्मूलन की ओर बढ़ाया जाता है और एक एकल-चरण पीवी सरणी संचालित एसआरएम ड्राइव को पंपिंग के लिए भी जांच की जाती है। यह प्रणाली एक ही मध्य-बिंदु कनवर्टर का उपयोग करके अपनी इष्टतम शक्ति पर सौर पीवी सरणी को संचालित करने में सक्षम है, जिसका उपयोग मोटर नियंत्रण के लिए किया जाता है।

पीवी सरणी बिजली उत्पादन की रुक-रुक कर पानी के पंपिंग में रुकावट का एक आशाजनक मामला एक बैटरी भंडारण प्रणाली, एकल-चरण उपयोगिता ग्रिड या बैटरी भंडारण प्रणाली और एकल-चरण ग्रिड ग्रिड का उपयोग करके हल किया जाता है एक बाहरी शक्ति बैकअप के रूप में। ये सभी संयोजन पर्यावरणीय परिस्थितियों के बावजूद निरंतर जल आपूर्ति प्रदान करने में सक्षम हैं। एक बैटरी समर्थित, ग्रिड इंटरैक्टेड या दोनों बैटरी और ग्रिड एकीकृत पीवी सरणी और उनके नियंत्रण को एसआरएम के साथ एक विश्वसनीय और पूरी तरह से उपयोग किए जाने वाले पानी को पंप करने के लिए प्रदर्शित किया जाता है, जैसे कि पंप पीवी सरणी बिजली उत्पादन की आंतरायिकता से प्रभावित नहीं होता है। पीवी पावर आवश्यक बिजली की मांग को पूरा करने में असमर्थ होने के कारण पावर बैटरी स्टोरेज सिस्टम (बीएसएस) या यूटिलिटी ग्रिड से तैयार की जाती है। यूनिडायरेक्शनल और बिडायरेक्शनल पावर फ्लो कंट्रोल दोनों ग्रिड इंटरेस्ड पीवी एरे पावर्ड एसआरएम संचालित वॉटर पंप के लिए लागू किए जाते हैं। इसके अलावा, इन सभी विन्यासों के लिए एकल-चरण टोपोलॉजी भी सफलतापूर्वक विकसित और परीक्षण की जाती है। द्विदिशीय विद्युत प्रवाह नियंत्रण आधारित टोपोलॉजी स्थापित पीवी सरणी द्वारा उपयोगिता ग्रिड को बिजली खिलाने की अतिरिक्त योग्यता प्रदान करती है, अगर पानी की पंपिंग की आवश्यकता नहीं है। इस अभ्यास से स्थापित संसाधनों का पूर्ण उपयोग होता है। इसके अलावा, यह उपयोगिता को बिजली की बिक्री से कमाई के स्रोत के रूप में उभरता है। पीवी सिस्टम की अधिकतम पावर प्वाइंट (एमपीपी) ऑपरेशन, और आईईईई-519 मानक के अनुसार पावर करंट और ग्रिड के करंट के कुल हार्मोनिक डिस्टॉर्शन जैसे पावर क्वालिटी मानक इस सिस्टम से मिलते हैं।

प्रारंभ, गतिशील और स्थिर-स्थिति के दौरान अपने प्रदर्शन को प्रदर्शित करने के लिए सिमुलिंक प्लेटफ़ॉर्म का उपयोग करके सभी प्रस्तावित कॉन्फ़िगरेशन मॉडल और सिम्युलेटेड हैं। प्रयोगशाला में एक विकसित प्रोटोटाइप का उपयोग करके हार्डवेयर कार्यान्वयन से प्राप्त परीक्षण परिणामों के माध्यम से नकली परिणाम सत्यापित किए जाते हैं। प्रस्तावित प्रणालियों की प्रयोज्यता और व्यावसायिक क्षमता उनके दक्षता, लागत, सादगी और प्रदर्शन के आधार पर गहन विश्लेषण द्वारा उचित है।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
ANN	Artificial Neural Network
BIS	Bureau of Indian Standards
BLDC	Brushless DC
CBPWM	Carrier Based Pulse Width Modulation
CCM	Continuous Conduction Mode
CEC	Clean Energy Council
CER	Clean Energy Regulator
CLP	Connector LED Panel
CPU	Central Processing Unit
CSC	Canonical Switching Cell
CSI	Current Source Inverter
DAC	Digital to Analog Converter
DC	Direct Current
DCM	Discontinuous Current Mode
DSP	Digital Signal Processor
DTC	Direct Torque Control
EMF	Electromotive Force
EMI	Electro-magnetic Interference
FL	Fuzzy Logic
HMC	Hysteresis Mode Control
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
IM	Induction motor
InC	Incremental Conductance

LED	Light Emitting Diode
LPF	Low Pass Filter
MNRE	Ministry of New & Renewable Energy
MPPT	Maximum Power Point Tracking
NASA	National Aeronautics and Space Administration
Op-Amp	Operational Amplifier
P&O	Perturbation and Observation
PD	Positive Displacement
PFC	Power Factor Corrected
PI	Proportional-Integral
PLL	Phase Locked Loop
PMSM	Permanent Magnet Synchronous Motor
PQ	Power Quality
PV	Photovoltaic
PWM	Pulse Width Modulation
RMS	Root Mean Square
SEPIC	SEPIC Single Ended Primary Inductor Converter
Si	Silicon
SOGI	Second Order Generalized Integrator
SRM	Switched Reluctance Motor
STC	Standard Test Condition
SyRM	Synchronous Reluctance Motor
TCDIC	Transformer Coupled Dual Input Converter
THD	Total Harmonic Distortion
TLBC	Three Level Boost Converter
TIBC	Two Inductor Boost Converter
TIBuck	Two Input Buck
TOGI	Third Order Generalized Integrator
VSC	Voltage Source Converter
VSI	Voltage Source Inverter

LIST OF SYMBOLS

a	Overloading factor
C_{dc1}, C_{dc2}	Split DC link capacitors of mid-point converter (μF)
C_m, C_{m1}	Intermediate capacitors of DC-DC converters (μF)
C_{f}	Capacitor of the R-C ripple filter (μF)
C_{pv}	Capacitor across the PV array (μF)
D, D_1	Duty ratios
D_{m1}, D_{m2}, D_{m3}, D_{m4}	Freewheeling diodes of mid-point converter
f_{sw}, f_{sw1}, f_{sw2}	Switching frequencies (Hz)
f	Excitation frequency of the individual phase of SRM (Hz)
G	PV array irradiance level (W/m^2)
H_1, H_2, H_3, H_4	Hall-Effect Position signals
I_{dc}	Current at the DC link of mid-point converter (A)
i_L, i_{Lp}, i_{L1}, i_{L2}, i_{Lg}	Currents flowing through the inductors (A)
I_m, V_m	Solar PV module current (A) and voltage (V) at MPP
I_{mpp}, V_{mpp}, P_{mpp}	Solar PV array current (A), voltage (V) and power (W) at MPP
i_{pv}, v_{pv}, p_{pv}	Solar PV array current (A), voltage (V) and power (W)
i_g	Utility grid current (A)
i_g^*	Reference utility grid current (A)
i_{ph1}, i_{ph2}, i_{ph3}, i_{ph4}	Winding currents of SRM (A)
I_{sp}	Amplitude of fundamental component of utility grid current (A)
J	Moment of inertia of the SRM (kg.cm^2)
k_1	Pump constant [W/(rad/sec)^3]
K_ω	speed constant of SRM
L, L_{P}, L_1, L_2, L_3, L_{g}	Inductors (mH)
L_{f}	Interfacing inductor (mH)
L_{u}, $\mathrm{L_a}$	Unaligned and Aligned inductance of SRM (mH)
m_a	Modulation index
m	Number of phases of SRM

N	Instantaneous speed of SRM-pump (rpm)
N_{ss}, N_{pp}	Numbers of PV modules connected in series and parallel
N_s , N_r	Number of stator and rotor poles
N_c	Number of commutation of SRM winding during a cycle
T_e	Electro-magnetic torque (Nm)
S_1, S_2, S_{g1}, S_{g2}	Switches of DC-DC converter
T_{ph1} T_{ph2} T_{ph3} T_{ph4}	Phase torque of SRM
T_1, T_2, T_3, T_4	Commutation signals of mid-point converter switches
T_p	Pump load torque (Nm)
T_s	Sampling rate
T_{sw2}	Switching time of the PFC boost converter (s)
v_{ph1}, v_{ph2}, v_{ph3}, v_{ph4}	Voltages cross SRM windings (V)
v_{Cm}, v_{C1}	Voltage across intermediate capacitor (V)
v_{dc1}, v_{dc2}	Voltage across split DC link capacitors (V)
v_{dc}	Net DC link voltage (V)
V_{dc}	Output DC voltage of the bridge rectifier (V)
v_g	Utility grid voltage (V)
$V_{split\_conv.}$, $I_{split\_conv.}$, $VA_{split\_conv.}$	Voltage (V), current (A) and VA (kVA) rating of the mid-point converter
ΔD	Perturbation in the duty ratio
Δi_L, Δi_{L1}, Δi_{L2} Δi_{Lp}	Permitted ripples in the currents through the inductors (A)
ΔI_{VSC}	Permitted ripple in the current through the interfacing inductor (A)
Δv_{Cm}, Δv_{Cm1}	Permitted ripple in the voltage across intermediate capacitor (V)
Δv_{dc1}, Δv_{dc1}	Permitted ripple in the split DC link voltages of mid-point converter (V)
η	Overall system efficiency (%)
θ_{on}, θ_{off}	Turn on and off angles (º)
α	Dwell angle of SRM (º)
β_s, β_r	Stator and rotor pole pitches (º)
ω	Speed or frequency (rated) of SRM (rad/sec.)
ω_L	Line frequency of the utility grid (rad/sec.)

$\Phi_{ph1}, \Phi_{ph2}, \Phi_{ph3}, \Phi_{ph4}$	Magnetic flux across SRM windings (Wb/m^2)
w_c	Energy received by the SRM through one phase excitation (J)
ρ and g	Density of water (1000 kg/m^3) and gravity (9.8 m/s^2)
η_p	Pump efficiency (%)