CONTROL OF SYNCHRONOUS RELUCTANCE MOTOR DRIVE FOR SOLAR PV ARRAY FED WATER PUMPING

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by

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CERTIFICATE

This is to certify that the thesis entitled, **"Control of Synchronous Reluctance Motor Drive for Solar PV Array Fed Water Pumping"** being submitted by **Mr. Anshul Varshney** 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. Anshul Varshney 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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Date: Anshul Varshney

ABSTRACT

This research work presents numerous topologies of a synchronous reluctance motor (SyRM) drive based solar PV array fed water pumping system. A SyRM is chosen because of its simple control, robustness and higher efficiency than other AC motors. The SyRM is characterized by the absence of rotor currents, which makes ideally the winding losses in the rotor zero. Therefore, the efficiency of the SyRM, is superior to than some other motors. It makes the drive control intelligible in comparison to an induction motor and permanent magnet motors. Thus, the use of SyRM for driving the pump and elimination of speed/position sensor, provide a unique solution for solar powered water pumping system.

In this work, an attempt has been made to develop solar photovoltaic array fed water pumping system with added features of grid interface. In standalone systems, single stage and two stage systems are implemented. Merits and demerits of both the systems are pointed out. For standalone system, reference speed is altered until maximum power point is reached as power drawn is proportional to the cube of the speed. In two stage system, a boost converter is utilized for harvesting maximum available power from a PV array through an incremental conductance based maximum power point tracking algorithm. Here, it feeds power to a voltage source inverter (VSI) through a DC link capacitor. DC link voltage is maintained to the reference value by adjusting the speed of the motor. However, in single stage system, only one power converter, i.e., VSI is required for MPPT as well as motor control. In case of grid connected single phase unidirectional topology, power factor correction (PFC) boost converter is used in continuous conduction mode (CCM). The pump is run at rated speed in case of availability of the grid at unity power factor while taking maximum available power from the solar PV array. As variable frequency drives draw nonlinear current, PFC boost converter reduces the total harmonics distortion (THD) of the current drawn to less than allowable limit of 5%. In case of grid failure, pump continues to run at available maximum power from the solar PV array. Grid connected three phase bidirectional power flow configuration using front end converter (FEC) is also designed and tested in the laboratory. Apart from the features of the unidirectional topology, here excess power from the solar PV array is fed to the grid. This is important from the electricity bill reduction point of view. Moreover single phase, bidirectional configuration is conceptualized and simulated. The prime objective of proposed system, is to provide water supply for domestic and irrigation purposes, therefore, to avoid

complexity and for increased reliability, the speed/position sensor is eliminated. A speed/position observer is utilized for the estimation of angular position of SyRM. A PV feed-forward term is used to estimate the reference speed, which aids in enhancing the transient behavior of proposed system. Moreover, the control is inherently resistant to the ageing related variation in pump's constant. In this work, the magnetic saturation and cross coupling effects are taken into consideration while estimating the position. The magnetic saturation effects on the position estimation in SyRM, because the position is estimated with the help of direct and quadrature axis flux linkages. The direct and quadrature axis flux linkages directly depend on direct and quadrature axis inductances. If magnetic saturation or cross coupling effect is not taken into consideration, the center of the circle plotted between direct and quadrature axis flux linkages, is shifted from the origin because of magnetic saturation and cross coupling effect. Due to this effect, a delay is introduced between actual position and estimated position. All the proposed topologies are modelled and simulated using MATLAB/Simulink platform in order to demonstrate their behaviour during starting, steady state and dynamic conditions. The validity of simulation results are verified through test results obtained from experimental setup developed 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.

सार

इस शोध कार्य में एक सिंक्रोनस रिलक्टेंस मोटर (एसवाईआरएम) ड्राइव आधारित सौर पीवी ऐरे फेड वाटर पम्पिंग सिस्टम की कई टोपोलॉजी प्रस्तुत की गई हैं। एक एसवाईआरएम को अन्य एसी मोटरों की तुलना में इसके सरल नियंत्रण, मजबूती और उच्च दक्षता के कारण चुना जाता है। एसवाईआरएम को रोटर धाराओं की अनुपस्थिति की विशेषता है, जिसके कारण रोटर वाइंडिंग में होने वाली हानि लगभग समाप्त हो जाती है, इसीलिए एसवाईआरएम की दक्षता कुछ अन्य मोटरों कि तुलना मे बेहतर है। यह इंडक्शन मोटर और परमानेंट मैगनेट मोटर्स की तुलना में ड्राइव नियंत्रण को सुगम बनाता है। इस प्रकार, पंप चलाने के लिए एसवाईआरएम का उपयोग और गति / स्थिति सेंसर को समाप्त करना, सौर ऊर्जा संचालित जल पंपिंग प्रणाली के लिए एक अनूठा समाधान प्रदान करता है।

इस कार्य में ग्रिड इंटरफेस सिस्टम की अतिरिक्त विशेषताओं के साथ एक ऐसा सौर फोटोवोल्टिक ऐरे फेड वाटर पम्पिंग सिस्टम विकसित करने का प्रयास किया गया है, जिसमे ग्रिड इंटरफेस सिस्टम की अतिरिक्त विशेषताएँ हैं । स्टैंडअलोन सिस्टम में, सिंगल स्टेज और टू स्टेज सिस्टम लागू किए जाते हैं। दोनों प्रणालियों के गुण और दोष बताए गए हैं। स्टैंडअलोन सिस्टम के लिए, संदर्भ गति को तब तक बदल दिया जाता है जब तक कि अधिकतम पावर पॉइंट तक नहीं पहुंच जाता क्योंकि शक्ति गति के घन के आनुपातिक होती है। दो चरण प्रणाली में, एक इंक्रीमेंटल कन्डक्टन्स आधारित अधिकतम पावर प्वाइंट ट्रैकिंग एल्गोरिदम के माध्यम से एक पीवी ऐरे से अधिकतम शक्ति एक्सट्रेक्ट करने के लिए एक बूस्ट कनवर्टर का उपयोग किया जाता है। यहां, यह डीसी लिंक कैपेसिटर के माध्यम से वोल्टेज स्रोत इन्वर्टर (वीएसआई) को पॉवर सप्लाई करता है। डीसी लिंक वोल्टेज मोटर की गति को समायोजित करके संदर्भ वैल्यू पर बनाए रखा जाता है। हालांकि, सिंगल स्टेज सिस्टम में, एमपीपीटी के साथ-साथ मोटर नियंत्रण के लिए केवल एक पावर कन्वर्टर यानी वीएसआई की आवश्यकता होती है। ग्रिड कनेक्टेड सिंगल फेज यूनिडायरेक्शनल टोपोलॉजी के मामले में, पावर फैक्टर करेक्शन (पीएफसी) बूस्ट कन्वर्टर का इस्तेमाल कंटीन्यूअस कंडक्शन मोड (सीसीएम) में किया जाता है। सोलर पीवी एरे से अधिकतम उपलब्ध बिजली लेते हुए यूनिटी पावर फैक्टर पर ग्रिड की उपलब्धता के मामले में पंप को रेटेड गति से चलाया जाता है। चूंकि वेरिएबल फ्रीक्वेंसी ड्राइव नॉनलाइनियर करंट खींचते हैं, पीएफसी बूस्ट कन्वर्टर वर्तमान के टोटल हार्मोनिक्स डिस्टॉर्शन (टी एच् डी) को 5% की स्वीकार्य सीमा से कम कर देता है। ग्रिड की विफलता के मामले में, सौर पीवी ऐरे से उपलब्ध अधिकतम शक्ति पर पंप चालू रहता है। फ्रंट एंड कन्वर्टर (एफईसी) का उपयोग करके ग्रिड से जुड़े थ्री फेज बाइडायरेक्शनल पॉवर फ्लो कण्ट्रोल आधारित सिस्टम को भी प्रयोगशाला में डिजाइन और परीक्षण किया गया है। यूनिडायरेक्शनल

टोपोलॉजी की विशेषताओं के अलावा, यहां सोलर पीवी ऐरे से अतिरिक्त पॉवर ग्रिड को फीड की जाती है। यह बिजली बिल में कमी की दृष्टि से महत्वपूर्ण है। इसके अलावा सिंगल फेज बाइडायरेक्शनल कॉन्फ़िगरेशन को कन्सेप्चूअलाइज़ और सिमुलेट किया गया है। प्रस्तावित प्रणाली का मुख्य उद्देश्य, घरेलू और सिंचाई उद्देश्यों के लिए पानी की आपूर्ति प्रदान करना है, इसलिए जटिलता से बचने के लिए और बढ़ी हुई विश्वसनीयता के लिए, गति/स्थिति सेंसर को समाप्त कर दिया जाता है। एसवाईआरएम की कोणीय स्थिति के आकलन के लिए एक गति/स्थिति पर्यवेक्षक का उपयोग किया जाता है। संदर्भ गति का अनुमान लगाने के लिए पीवी फीड-फॉरवर्ड टर्म का उपयोग किया जाता है, जो प्रस्तावित प्रणाली के क्षणिक व्यवहार को बढ़ाने में सहायता करता है। इसके अलावा, कण्ट्रोल पंप स्थिरांक में बदलाब का प्रतिरोधी है। इस कार्य में स्थिति का आकलन करते समय मैग्नेटिक सैचरेशन और क्रॉस कपलिंग प्रभावों को ध्यान में रखा जाता है। एसवाईआरएम में स्थिति के आकलन पर मैग्नेटिक सैचरेशन प्रभाव डालता है, क्योंकि स्थिति का अनुमान डायरेक्ट और क्वाड्रचर अक्षों के फ्लक्स लिंकेज की सहायता से लगाया जाता है। डायरेक्ट और क्वाड्रैचर एक्सिस फ्लक्स लिंकेज सीधे डायरेक्ट और क्वाड्रैचर एक्सिस इंडक्शन पर निर्भर करते हैं। यदि मैग्नेटिक सैचरेशन या क्रॉस कपलिंग प्रभाव को ध्यान में नहीं रखा जाता है, तो मैग्नेटिक सैचरेशन और क्रॉस कपलिंग प्रभाव के कारण डायरेक्ट और क्वाड्रैचर एक्सिस फ्लक्स लिंकेज के बीच प्लॉट किए गए सर्कल के केंद्र को मूल से स्थानांतरित कर दिया जाता है। इस प्रभाव के कारण, वास्तविक स्थिति और अनुमानित स्थिति के बीच एक डिले आ जाता है। सभी प्रस्तावित टोपोलॉजी को मेटलैब/सिमुलिंक प्लेटफॉर्म का उपयोग करके मॉडलिंग और सिम्युलेट किया जाता है ताकि स्टार्टिंग, स्टेडी स्टेट और डायनामिक कंडीशन के दौरान उनके व्यवहार को प्रदर्शित किया जा सके। सिमुलेशन परिणामों की वैधता प्रयोगशाला में विकसित प्रयोगात्मक सेटअप से प्राप्त परीक्षण परिणामों के माध्यम से सत्यापित की जाती है। प्रस्तावित प्रणालियों की प्रयोज्यता और व्यावसायिक क्षमता दक्षता, लागत, सरलता और प्रदर्शन के आधार पर उनके गहन विश्लेषण द्वारा जस्टिफाई की गयी है।

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VSI	Voltage Source Inverter
SECS	Solar Energy Conversion System
DCM	Disconteneous Conduction Mode
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
VFD	Variable Frequency Drive
MAF	Moving Average Filter
IC	Integrated Circuit
UPF	Unity Power Factor
LPF	Low Pass Filter

LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
ANN	Artificial Neural Network
ASD	Adjustable Speed Drives
BLDC	Brushless DC
CCM	Contineous Conduction Mode
DAC	Digital to Analog Converter
DC	Direct Current
DTC	Direct Torque Control
EMI	Electro-magnetic Interference
IM	Induction Motor
PMSM	Permanent Magnet Synchronous Motor
SRM	Switched Reluctance Motor
SyRM	Synchronous Reluctance Motor
FEC	Front End Converter
DSP	Digital Signal Processor
IEC	International Electrotechnical Commision
IEEE	Institute of Electrical and Electronics Engineers
INC	Incremental Conductance
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
PFC	Power Factor Correction
PI	Proportional Integral
PLL	Phase Locked Loop
PV	Solar Photovoltaic
THD	Total Harmonic Distortion
VSC	Voltage Source Converter

LIST OF SYMBOLS

a	Over loading factor
C_{dc}	DC-link capacitor
C_f	Capacitor of the R-C ripple filter
C_{pv}	Capacitor across the PV array
D	Duty cycle of boost converter
P_{mpp}	MPP power
V_{mpp}	MPP power
I_{mpp}	MPP power
P_{PV}	PV array power
V_{PV}	PV array voltage
I_{PV}	PV array current
m	Modulation index
f_{sw}	Switching frequency of PV boost converter
θ_r	SyRM rotor angle
ρ_s	Angle of stator flux linkage space vector to the real-axis of the stator reference frame
δ_s	Angle of stator flux vector to the d- axis of the rotor reference frame
ω_{est}	Estimated speed of SyRM
ω_{ref}	Reference speed of SyRM
ω_s and ω_d	Speeds of stator flux vector of stator and the rotor
$\psi_{s\alpha}$ and $\psi_{s\beta}$	Fluxes in orthogonal reference frame
v_α, v_β, i_α and i_β	Voltages and current in orthogonal reference frame
S_A, S_B, S_C	Switching signals
v_a, v_b and v_c	Stator voltages
i_a, i_b and i_c	Stator currents
i_d^*, i_q^* and i_d, i_q	d-q axis reference and actual fluxes
ψ_d^*, ψ_q^* and ψ_d, ψ_q	d-q axis reference and actual currents
p	Pole pair
L_d,L_q	Direct and Quardature axis inductances
T_e	Electromagnetic torque
T_L	Pump load torque
R_a	Stator winding resistance of SyRM
I_g	Utility grid current
V_g	Utility grid current
K_{pump}	Pump constant

L_f	Interfacing inductor
N_S, N_P	Numbers of PV modules connected in series and parallel
R_f	Resistance of the R-C ripple filter
S	Solar irradiance
$V_{VS}C, I_{VSC}, VA_{VSC}$	Voltage (V), current (A) and VA (kVA) rating of the VSC
$V_{VSI}, I_{VSI}, VA_{VSI}$	Voltage (V), current (A) and VA (kVA) rating of the VSI