SENSORLESS CONTROL OF SOLAR PV FED INDUCTION MOTOR DRIVE FOR WATER PUMPING

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by

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CERTIFICATE

It is certified that the thesis entitled "**Sensorless Control of Solar PV Fed Induction Motor Drive For Water Pumping**," being submitted by **Mr. Saurabh Shukla** 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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ABSTRACT

Water pumps in irrigation sector as well as domestic and industrial sectors have been benefitted by the introduction of renewable source based power production. An induction motor is quite popular for PV fed water pumping because of its robustness, ruggedness ease of operation and its capability to work in hazardous environment. Scalar control has long been in use for speed control as it requires no sensor. However, its unstable operation and unfavorable sustained oscillation in lower speed range is the matter of concern. Therefore, in this work, mechanical sensorless control of an induction motor drive is investigated with fast speed control and better stability. Moreover, some issues related to its low efficiency is solved by optimizing the motor flux and minimizing the total loss in partial loading condition. The system is made simplified and cost-effective by reducing the number of voltage and current sensors and all parameters are estimated through DC link voltage and DC link current. The system possesses a maximum power point tracking (MPPT) of the PV array by introducing a DC-DC boost converter between the PV array and a VSI, feeding the motor. The work is extended towards an elimination of DC-DC converter and a single stage PV array fed induction motor drive is also investigated for water pumping.

The recurrence in PV power generation leads to an unreliable water pumping in a PV based pumping system. This problem is aggravated when there is a bad climatic condition. In all these conditions, the system is underutilized as the pump is not operated at its full capacity and sometime leads to complete shutdown. This problem is resolved by an external power backup in the form of a battery storage with a bidirectional buck-boost converter, in a PV-pumping system. In addition to it, an attempt is made for integrating unidirectional and bidirectional converters to the utility grid. The bidirectional power flow control based topology offers an additional merit of feeding power to the utility grid by the installed PV array, in case the water pumping is not required. The

prime attention is to achieve an uninterrupted and full volume of water delivery irrespective of the operating conditions, whether day or night. These proposed techniques with PV array provide a practical solution for electricity generation and an economic liberty for the consumer through sale of electricity.

All these proposed configurations are modeled and simulated in MATLAB/Simulink environment by using Simpower system toolbox to study the performance during various environmental conditions realized by change in insolation and the operability of the system is justified 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

नवीकरणीय स्रोत आधारित बिजली उत्पादन की शुरुआत से सिंचाई क्षेत्र के साथ-साथ घरेलू और औद्योगिक क्षेत्रों में पानी के पंपों को फायदा हुआ है। सौर ऊर्जा आधारित पंपिंग के लिए एक इंडक्शन मोटर काफी लोकप्रिय है क्योंकि इसकी मजबूती, संचालन में उत्कृष्टता और खतरनाक वातावरण में काम करने की क्षमता अद्वितीय है। गति नियंत्रण के लिए स्केलर नियंत्रण लंबे समय से उपयोग में है क्योंकि इसमें सेंसर की आवश्यकता नहीं होती है। हालांकि, कम गति सीमा में इसका अस्थिर संचालन और प्रतिकूल निरंतर दोलन चिंता का विषय है। इसलिए, इस कार्य में तेज़ मोटर नियंत्रण और बेहतर स्थिरता के साथ एक इंडक्शन मोटर ड्राइव के यांत्रिक सेंसरलेस नियंत्रण की जांच की जाती है। इसके अलावा, इसकी कम दक्षता से जुड़े कुछ मुद्दों को मोटर फ्लक्स के अनुकूलन और आंशिक लोडिंग स्थिति में कुल नुकसान को कम करके हल किया जाता है। वोल्टेज और करंट सेंसर की संख्या को कम करके सिस्टम को सरल और लागत प्रभावी बनाया जाता है और डीसी लिंक वोल्टेज और डीसी लिंक करंट के माध्यम से सभी मापदंडों का अनुमान लगाया जाता है। सिस्टम में सौर ऊर्जा पैनल और वी एस आई के बीच डीसी- डीसी बूस्टर कनवर्टर को नियोजित करके सौर ऊर्जा पैनल का अधिकतम पावर प्वाइंट ट्रैकिंग होता है। शोध कार्य को डीसी-डीसी कनवर्टर के उन्मूलन की दिशा में आगे बढ़ाया गया है और एक एकल चरण सौर ऊर्जा पैनल द्वारा संचालित इंडक्शन मोटर ड्राइव को पानी के पंपिंग के लिए भी परीक्षण किया गया है।

सौर ऊर्जा उत्पादन में रुकावट एक सौर ऊर्जा आधारित पंपिंग सिस्टम में एक अविश्वास को स्पंदित करता है। खराब जलवायु की स्थिति होने पर यह समस्या बढ़ जाती है। इन सभी स्थितियों में पंप अपनी पूर्ण क्षमता पर संचालित नहीं होता है और कभी-कभी पूरी तरह से बंद हो जाता है। इस समस्या को एक सौर ऊर्जा आधारित पंपिंग प्रणाली में एक द्विदिश बक-बूस्ट कनवर्टर के साथ बैटरी के रूप में बिजली बैकअप द्वारा हल किया जाता है। इसके अतिरिक्त, ग्रिड में एकल दिशात्मक और द्विदिश कन्वर्टर्स को एकीकृत करने का प्रयास किया जाता है। द्विदिशीय विद्युत प्रवाह नियंत्रण आधारित टोपोलॉजी स्थापित सौर ऊर्जा पैनल द्वारा ग्रिड को बिजली प्रदान करने का एक अतिरिक्त गुण प्रदान करता है, अगर पानी पंप करने की आवश्यकता नहीं है। मुख्य ध्यान दिवस की परवाह किए बिना, चाहे दिन हो या रात, जल वितरण की एक निर्बाध और पूर्ण मात्रा प्राप्त करना है। सौर ऊर्जा पैनल के साथ ये प्रस्तावित तकनीक

बिजली उत्पादन के लिए एक व्यावहारिक समाधान और बिजली की बिक्री के माध्यम से उपभोक्ता के लिए आर्थिक स्वतंत्रता प्रदान करती है।

इन सभी प्रस्तावित विन्यासों को मैटलैब / सिमुलिंक परिवेश में मॉडल और सिम्युलेट किया गया है, जो विकिरण में परिवर्तन द्वारा महसूस की गई विभिन्न पर्यावरणीय स्थितियों के दौरान प्रदर्शन का अध्ययन करने के लिए सिमपावर सिस्टम टूलबॉक्स का उपयोग करता है और सिस्टम का सञ्चालन आरम्भ, गतिशील और स्थिर राज्य स्थितियों के दौरान उचित सिद्ध करता है। प्रयोगशाला में एक विकसित प्रोटोटाइप का उपयोग करके हार्डवेयर कार्यान्वयन से प्राप्त परीक्षण परिणामों के माध्यम से सिम्युलेटेड परिणाम सत्यापित किए जाते हैं। दक्षता, लागत, सादगी और प्रदर्शन के आधार पर गहन विश्लेषण में प्रस्तावित प्रणालियों की प्रयोज्यता और व्यावसायिक क्षमता उनके द्वारा उचित है।

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LIST OF ABBREVIATIONS

PV	Photovoltaic
PMSM	Permanent Magnet Synchronous Motor
DC	Direct Current
BLDC	Brushless DC
MPPT	Maximum Power Point Tracking
VSI	Voltage Source Inverter
PQ	Power Quality
THD	Total Harmonics Distortion
IEEE	Institute of Electrical and Electronics Engineers
PD	Positive Displacement
SVM	Space Vector Modulation
VSC	Voltage Source Converter
PFC	Power Factor Correction
NASA	National Aeronautics and Space Administration
MNRE	Ministry of New and Renewable Energy
BIS	Bureau of Indian Standards
IEC	International Electrotechnical Commission
CEC	Clean Energy Council
IM	Induction Motor
PMSM	Permanent Magnet Synchronous Motor
SRM	Switched Reluctance Motor
SyRM	Synchronous Reluctance Motor
P&O	Perturb and Observe
InC	Incremental Conductance
SEPIC	Single Ended Primary Inductor Converter
CSC	Canonical Switching Cell
MRAS	Model Reference Adaptive System
EMF	Electromotive Force
PI	Proportional Integral
ANN	Artificial Neural Network
FOC	Field-Oriented Control
AC	Alternating Current

BES	Battery Energy Support
IMD	Induction Motor Drive
IGBT	Insulated Gate Bipolar Transistor
DSP	Digital Signal Processor
DSO	Digital Signal Oscilloscope
CPU	Central Processing Unit
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
SPS	Sim Power System
DTC	Direct Torque Control
SOC	State of Charge
UVT	Unit Vector Template
STC	Standard Temperature and Pressure
LPF	Low Pass Filter
PLL	Phase-Locked Loop
DRAM	Dynamic Random Access Memory
SOGI	Second Order Generalized Integral
ISOGI	Improved Second Order Generalized Integral

LIST OF SYMBOLS

V_{mpp}, V_{mp}	Solar PV voltage (V) of one module and one array at MPP
I_{mpp}, I_{mp}	Solar PV current (A) of one module and one array at MPP
V_{oca}, V_{oc}	Open-circuit voltage (V) of one module and one array
I_{sca}, I_{sc}	Short-circuit current (A) of one module and one array
V_{pv}, I_{pv}	Solar PV array voltage (V) and current (A)
N_{ser}, N_{par}	Number of series and parallel modules
P_{mp}	Solar PV power of one array at MPP
D	Duty ratio
f_s	Switching frequency of boost inductor
T_{sw}	Time period of VSI
L_1	Boost inductor
ΔI_1	Ripple allowed in converter current
V_L, I_L	Boost inductor voltage (V), inductor current (A)
V_D, V_{sw}	Diode voltage, switch voltage in boost converter
C_{dc}	DC link capacitor
V_{dc}, V_{dc1}	DC link voltage, maximum ripple allowed in DC link voltage
I_{dc}	DC link current
a	Overloading factor
i_a	Motor phase current
V_p, $V_{L\text{-}L}$	Phase voltage, line voltage of induction motor
m	Modulation index
V_{VSI}, I_{VSI}	Voltage rating of VSI, current rating of VSI
K_V and K_I	Voltage safety factor, current safety factor
K_1	Pump constant
P_m	Rated power of induction motor
ω_{sl}, ω_e and ω_m	Slip speed, synchronous speed and motor speed in rad/s
ω_{ref}	Reference speed
ω_1, ω_2	Speed components for reference speed calculation
S_{a}, S_{b} and S_{c}	Switching function of VSI
v_{a}, v_{b} and v_{c}	Phase voltages (V) of induction motor
v_α, v_β	Voltages in α-β domain
i_α, i_β	Motor currents in α-β domain

$\psi_\alpha, \psi_\beta, \psi_s$	Fluxes in α-β domain, resultant flux
$\psi_{\alpha r}, \psi_{\beta r}, \psi_r$	Rotor fluxes in stationary reference frame, resultant flux
$L_\mathrm{r}, L_\mathrm{s}, L_\mathrm{m}$	Rotor inductance, stator inductance and mutual inductance
$L_\mathrm{lr}, L_\mathrm{ls}$	Rotor leakage inductance, stator leakage inductance
R_r, R_s	Rotor resistance, stator resistance
V_{ref}	Reference voltage (V)
ψ^*_{ds}, ψ_{ds}	Reference d-axis flux (Wb), actual d-axis flux (Wb)
i^*_{ds}, i_{ds}	Reference d-axis current (A), actual d-axis current (A)
i^*_{qs}, i_{qs}	Reference q-axis current (A), actual q-axis current (A)
T^*_e, T_e	Reference developed torque (Nm), estimated developed torque (Nm)
P	Number of poles
T	Signal sampling period
i_a^*, i_b^*, i_c^*	Reference motor phase currents (A)
θ_e	Flux angle
T_p	Pump torque (Nm)
I_{dcp}, I_{mr}	Decoupling component of current (A), magnetizing current component (A)
T_r	Rotor time constant
P_t	Total power loss in induction motor (W)
R_g	Magnetizing resistance (Ω)
η	Efficiency (%)
$I^H(t_c), I^L(t_c)$	Instantaneous components of reconstructed current
i_{ar}, i_{br}, i_{cr}	Reconstructed motor phase currents
D_{bat}	Duty ratio of bidirectional buck-boost converter
V_{bat}	Battery voltage
f_{sbb}	Switching frequency of buck-boost converter
L_{bb}	Boost inductor of bidirectional buck-boost converter
ΔI_bat	Ripple allowed in the battery current
S_{bu}, S_{bl}	Bidirectional buck-boost converter switches
ω_L	Fundamental frequency (rad/s)
V_d	Average input voltage of PFC boost converter
D_2	Duty ratio of PFC boost converter
f_{sw2}	Switching frequency of PFC boost converter
L_2	PFC boost inductor
Δi_{gL}	Ripple allowed in PFC boost inductor current

R_f, C_f	Resistance (Ω) and capacitance (μF) of RC filter
T_{sw2}	Switching time of PFC boost converter
L_s	Boost inductor for Vienna converter
$f_{sw\text{-}g}$	Switching frequency of Vienna rectifier
V_{in}	Average voltage of Vienna rectifier
C_1, C_2	DC link capacitances of Vienna rectifier
v_{ab}, v_{bc}, v_{ca}	Three-phase grid line voltages
$v_{ab1}^{+}, v_{bc1}^{+}, v_{ca1}^{+}$	Positive sequence voltages of three-phase grid
$u_{ab1}^{+}, u_{bc1}^{+}, u_{ca1}^{+}$	Unit template of positive sequence voltages of three-phase grid
V_{c1}, V_{c2}	C_1 and C_2 capacitor voltages
i_{g1}^{*}, i_{g2}^{*}, i_{g3}^{*}	Reference three-phase grid currents
i_{g1}, i_{g2}, i_{g3}	Three-phase grid currents
P_1, P_2, P_3	Switching logics of Vienna rectifier
v_g, i_g	Grid voltage (V), grid current (A) of single-phase utility grid
L_i	Interfacing inductor
f_{ss}	switching frequency of VSC
e_d, e_q	Back-EMF in *d*-*q* domain
ω_c	Cut-off frequency
K_{sv}, K_{dc}	Gains of ISOGI