

**DESIGN AND DEVELOPMENT OF INDUCTION MOTOR
DRIVE FOR GRID INTERACTIVE AND STANDALONE
BASED SOLAR PV ARRAY FED WATER PUMPING**

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DRIVE FOR GRID INTERACTIVE AND STANDALONE
BASED SOLAR PV ARRAY FED WATER PUMPING**

by
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Electrical Engineering Department

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CERTIFICATE

It is certified that the thesis entitled “**Design and Development of Induction Motor Drive for Grid Interactive and Standalone Based Solar PV Array Fed Water Pumping,**” being submitted by Mrs. Rashmi Rai 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 her under our supervision and guidance. The matter embodied in this thesis, has not been submitted for the award of any other degree or diploma.

Dated:

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ABSTRACT

This thesis deals with different topologies for water pumping system powered by solar PV array, utilizing an induction motor drive. It includes mechanical sensorless control of an induction motor drive to enable quick speed adjustments and a wide speed range. To enhance performance, this system utilizes maximum power point tracking (MPPT) for solar PV array. This is accomplished by placing a DC-DC boost converter between PV array and a voltage source inverter (VSI) that powers the motor. Additionally, this research explores a feasibility of a single-stage PV array-based system, eliminating a need for a DC-DC converter, and its application in long cable-fed submersible induction motor drive for water pumping. To mitigate potential disruptions in water pumping caused by the intermittent nature of solar PV array power generation, this study suggests employing a single-phase utility grid as an external power backup. A grid-interacted solar PV array, along with its control mechanisms, ensures consistent and reliable water pumping irrespective of solar PV array power intermittency. The power flow for unidirectional and bidirectional control strategies are employed for grid-connected PV array-powered induction motor-driven water pump. Bidirectional power flow control provides added benefit of feeding excess power to grid when water pumping is not required, thus maximizing resource utilization. The system adheres to maximum power point (MPP) operation of PV array and complies power quality (PQ) standard, such as power factor and total harmonics distortion (THD) of grid current, in accordance with the IEEE standard.

In remote locations, standalone solar PV pumping systems are installed because of absence of the grid. Main reason behind it is geographical remoteness as well as unavailability of continuous power since these places are not properly connected to the grid. However, despite having obvious benefits when it comes to lowering carbon emissions, solar PV array is not very reliable when it comes to continuous power for water pumping. Hence, a battery energy storage (BES) is utilised at DC link with bidirectional converter to resolve the intermittency issues. The advancement of solar photovoltaic array operated drives not only provides an economical solution but also reduces the strain on the grid. The functionality of the grid-integrated SPV system in different operating modes is discussed in a synchronization and desynchronisation logic with islanding identification technique to transition between standalone and grid-interactive modes and vice versa.

In grid-interactive mode, the system delivers power quality (PQ) solution such as elimination of harmonics, correction of PF and load compensation and grid currents balancing. In off-grid mode, control objectives focus on regulating voltage and frequency at point of common coupling (PCC). Primary goal of system is to ensure continuous power to emergency loads,

even during a grid failure. Control algorithms for grid-side converter, are developed, with an extended phase-locked loop (EPLL) presented for improving power quality during integration with a weak grid. Unbalanced voltage dips are responded by the system by remaining connected at PCC while supplying residential and nonlinear loads and the main utility grid. To stabilize PCC voltage as per the IEEE standard 1547.4, reactive power is supplied by the system. To withstand fault conditions, a ride through technique is developed for the system, which avoids triggering of overcurrent protection by introducing a control for current limiting. Simulated and test results demonstrate balanced grid currents with sinusoidal profiles along with improved harmonic spectra even when the conditions are not favorable. Moreover, grid-side power factor is recorded nearly unity.

The grid-integrated system featuring multiple solar PV arrays and battery energy storage (BES) feeding multiple water pumping systems is designed and its performance is studied in detail. Main and ancillary grid-side converters are connected at DC links to individual solar PV arrays, each employing its own MPPT technique. Grid side converters (GSC) parallel connection at PCC, increases power rating of the system and expanding the system to supply surplus solar power to grid. The reliability of the system in standalone mode is also enhanced. When operating conditions are normal, then for main GSC, current control is used in grid-interactive mode and to maintain frequency and voltage at PCC, voltage control is employed during grid-disconnection. Performance of proposed configuration is studied during starting, dynamics and steady-state conditions. When analyzed in depth on basis of its simplicity, efficiency, performance and cost, the potential for commercial adoption and applicability of proposed systems are justified.

सारांश

यह शोध प्रबंध सौर पीवी सरणी द्वारा संचालित जल पंपिंग प्रणाली के लिए विभिन्न टोपोलॉजी से संबंधित है, जो एक इंडक्शन मोटर ड्राइव का उपयोग करता है। इसमें त्वरित गति समायोजन और एक विस्तृत गति सीमा को सक्षम करने के लिए एक इंडक्शन मोटर ड्राइव का यांत्रिक सेंसर रहित नियंत्रण शामिल है। प्रदर्शन को बढ़ाने के लिए, यह प्रणाली सौर पीवी सरणी के लिए अधिकतम पावर पॉइंट ट्रैकिंग (एमपीपीटी) का उपयोग करती है। यह पीवी सरणी और मोटर को शक्ति देने वाले वोल्टेज स्रोत इन्वर्टर (वीएसआई) के बीच एक डीसी-डीसी बूस्ट कनवर्टर रखकर पूरा किया जाता है। इसके अतिरिक्त, यह शोध एक एकल-चरण पीवी सरणी-आधारित प्रणाली की व्यवहार्यता की खोज करता है, जो डीसी-डीसी कनवर्टर की आवश्यकता को समाप्त करता है, और जल पंपिंग के लिए लंबी केबल-फेड सबमर्सिबल इंडक्शन मोटर ड्राइव में इसके अनुप्रयोग को दर्शाता है। सौर पीवी सरणी बिजली उत्पादन की आंतरायिक प्रकृति के कारण जल पंपिंग में संभावित व्यवधानों को कम करने के लिए, यह अध्ययन एक बाहरी बिजली बैकअप के रूप में एकल-चरण उपयोगिता ग्रिड को नियोजित करने का सुझाव देता है। ग्रिड-इंटरैक्टिव सोलर पीवी ऐरे, अपने नियंत्रण तंत्र के साथ, सोलर पीवी ऐरे पावर इंटरमिटेंसी के बावजूद लगातार और विश्वसनीय जल पंपिंग सुनिश्चित करता है। ग्रिड से जुड़े पीवी ऐरे-पावर्ड इंडक्शन मोटर-चालित जल पंप के लिए यूनिटायरेक्शनल और बाइडायरेक्शनल कंट्रोल स्ट्रैटेजी के लिए पावर फ्लो का इस्तेमाल किया जाता है। द्विदिशीय पावर फ्लो कंट्रोल, जब पानी पंपिंग की आवश्यकता नहीं होती है, तो ग्रिड को अतिरिक्त बिजली खिलाने का अतिरिक्त लाभ प्रदान करता है, जिससे संसाधन उपयोग को अधिकतम किया जा सकता है। सिस्टम पीवी ऐरे के अधिकतम पावर पॉइंट (एमपीपी) ऑपरेशन का पालन करता है और IEEE मानक के अनुसार पावर क्वालिटी (PQ) मानक, जैसे कि पावर फैक्टर और ग्रिड करंट का कुल हार्मोनिक्स डिस्टॉर्शन (THD) का अनुपालन करता है।

दूरदराज के स्थानों में, ग्रिड की अनुपस्थिति के कारण स्टैंडअलोन सोलर पीवी पंपिंग सिस्टम स्थापित किए जाते हैं। इसके पीछे मुख्य कारण भौगोलिक दूरदराज के साथ-साथ निरंतर बिजली की अनुपलब्धता है क्योंकि ये स्थान ग्रिड से ठीक से जुड़े नहीं हैं। हालांकि, कार्बन उत्सर्जन को कम करने के मामले में स्पष्ट लाभ होने के बावजूद, पानी पंपिंग के लिए निरंतर बिजली की बात आने पर सोलर पीवी सरणी बहुत विश्वसनीय नहीं है। इसलिए, बैटरी ऊर्जा भंडारण (बीईएस) का उपयोग डीसी लिंक पर द्विदिश कनवर्टर के साथ किया जाता है ताकि रुकावट के मुद्दों को हल किया जा सके। सौर फोटोवोल्टिक सरणी संचालित ड्राइव की उन्नति न केवल एक किफायती समाधान प्रदान करती है बल्कि ग्रिड पर तनाव को भी कम करती है। अलग-अलग ऑपरेटिंग मोड में ग्रिड-एकीकृत एसपीवी सिस्टम की कार्यक्षमता को स्टैंडअलोन और ग्रिड-इंटरैक्टिव मोड और इसके विपरीत के बीच संक्रमण के लिए आइलैंडिंग पहचान तकनीक के साथ सिंक्रोनाइज़ेशन और डिस्क्रोनाइज़ेशन लॉजिक में चर्चा की गई है।

ग्रिड-इंटरैक्टिव मोड में, सिस्टम हार्मोनिक्स को खत्म करने, PF और लोड क्षतिपूर्ति को सही करने और ग्रिड करंट को संतुलित करने जैसे पावर क्वालिटी (PQ) समाधान प्रदान करता है। ऑफ-ग्रिड मोड में, नियंत्रण उद्देश्य कॉमन कपलिंग (PCC) के बिंदु पर वोल्टेज और आवृत्ति को विनियमित करने पर ध्यान केंद्रित करते हैं। सिस्टम का

प्राथमिक लक्ष्य आपातकालीन लोड को निरंतर बिजली सुनिश्चित करना है, यहां तक कि ग्रिड विफलता के दौरान भी। ग्रिड-साइड कनवर्टर के लिए नियंत्रण एल्गोरिदम विकसित किए गए हैं, जिसमें एक कमजोर ग्रिड के साथ एकीकरण के दौरान बिजली की गुणवत्ता में सुधार के लिए एक विस्तारित चरण-लॉक लूप (EPLL) प्रस्तुत किया गया है। असंतुलित वोल्टेज डिप्रेस का जवाब सिस्टम द्वारा आवासीय और नॉनलाइनियर लोड और मुख्य उपयोगिता ग्रिड की आपूर्ति करते हुए PCC से जुड़े रहकर दिया जाता है। IEEE मानक 1547.4 के अनुसार PCC वोल्टेज को स्थिर करने के लिए, सिस्टम द्वारा प्रतिक्रियाशील शक्ति की आपूर्ति की जाती है। दोष स्थितियों का सामना करने के लिए, सिस्टम के लिए एक राइड थ्रू तकनीक विकसित की गई है, जो करंट लिमिटिंग के लिए एक नियंत्रण शुरू करके ओवरकरंट सुरक्षा को ट्रिगर करने से बचाती है। सिम्युलेटेड और परीक्षण के परिणाम साइनसॉइडल प्रोफाइल के साथ संतुलित ग्रिड धाराओं को प्रदर्शित करते हैं, साथ ही बेहतर हार्मोनिक स्पेक्ट्रा के साथ, जब स्थितियां अनुकूल नहीं होती हैं। इसके अलावा, ग्रिड-साइड पावर फैक्टर लगभग एकता दर्ज किया जाता है।

कई सौर पीवी सरणियों और बैटरी ऊर्जा भंडारण (बीईएस) की विशेषता वाली ग्रिड-एकीकृत प्रणाली को कई जल पंपिंग प्रणालियों को खिलाने के लिए डिज़ाइन किया गया है और इसके प्रदर्शन का विस्तार से अध्ययन किया गया है। मुख्य और सहायक ग्रिड-साइड कन्वर्टर्स डीसी लिंक पर व्यक्तिगत सौर पीवी सरणियों से जुड़े हुए हैं, जिनमें से प्रत्येक अपनी एमपीपीटी तकनीक का उपयोग करता है। ग्रिड साइड कन्वर्टर्स (जीएससी) पीसीसी में समानांतर कनेक्शन, सिस्टम की पावर रेटिंग को बढ़ाता है और ग्रिड को अधिशेष सौर ऊर्जा की आपूर्ति करने के लिए सिस्टम का विस्तार करता है। स्टैंडअलोन मोड में सिस्टम की विश्वसनीयता भी बढ़ जाती है। जब परिचालन की स्थिति सामान्य होती है, तब मुख्य जीएससी के लिए ग्रिड-इंटरैक्टिव मोड में करंट कंट्रोल का इस्तेमाल किया जाता है और पीसीसी पर फ्रीक्वेंसी और वोल्टेज को बनाए रखने के लिए ग्रिड-डिस्कनेक्शन के दौरान वोल्टेज कंट्रोल का इस्तेमाल किया जाता है।

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Table 3.1 Power Management and Control for Islanded Mode

LIST OF ABBREVIATIONS

PV	Photovoltaic
VSI	Voltage Source Inverter
BLDC	Brushless DC
PMSM	Permanent Magnet Synchronous Motor
PQ	Power Quality
MPPT	Maximum Power Point Tracking
MRAS	Model Reference Adaptive System
EMF	Electromotive Force
DGS	Distributed Generation System
GSC	Grid Side Converter
VSC	Voltage Source Converter
IGBT	Insulated Gate Bipolar Transistor
BES	Battery Energy Storage
BESS	Battery Energy Storage System
PCC	Point of Common Coupling
FOC	Field Oriented Control
MPP	Maximum Power Point
PI	Proportional Integral
SMC	Sliding Mode Control
SOGI	Second Order Generalized Integrator
SOGI-QSG	Second Order Generalized Integrator with Quadrature Signal Generator
SPV	Solar Photovoltaic
SPVA	Solar Photovoltaic Array
SRF	Synchronous Reference Frame
LVRT	Low Voltage Ride Through
BDDC	Bi-directional DC-DC Converter
IMD	Induction Motor Drive
LFM	Load Follower Mode
IM	Induction Motor
FLL	Frequency-locked loop
SOIFO- FLL	Second Order Integrator Frequency-Locked Loop
THD	Total Harmonic Distribution
EPLL	Enhanced Phase-Locked Loop

PLL	Phase Locked Loop
FC	Fundamental Component
P&O	Perturb and observe
ILST	improved theory based linear sinusoidal tracer
InC	Incremental-Conductance
STS	Solid State Switch

LIST OF SYMBOLS

V_{mpp}	Solar PV voltage (V) of one module at MPP
I_{mpp}	Solar PV current (A) of one module at MPP
V_{ocm}	Open-circuit voltage (V) of one module
I_{scm}	Short-circuit current (A) of one module
V_{pv}, I_{pv}	Solar PV array voltage (V) and current (A)
n_s, n_p	Number of series and parallel modules
P_{mpp}	Solar PV power of one module at MPP
P_{mppA}	Solar PV power of one array at MPP
V_{mppA}	Solar PV voltage (V) of one module at MPP
I_{mppA}	Solar PV current (A) of one module at MPP
C_{dc}	DC link Capacitance
P_{pv}	Maximum available solar power
V_{dc}	DC link voltage
V_{dc}^*	Reference DC link voltage
ΔI_{inv}	switching ripple current in inverter
f_{sw}, f_s, F_r	Switching frequency, fundamental frequency, Resonant frequency
D_B	Duty ratio of bidirectional DC-DC converter
L_B	Inductor of bidirectional DC-DC converter
I_B, V_B	Battery current, battery voltage
K_1	Pump constant
$P_{I.M.}$	Rated power of induction motor
P_L	Rated power of local load
P_g	Rated power of grid
P_B	Rater power of battery
ω_{sl}, ω_e and ω_m	Slip speed, synchronous speed and motor speed in rad/s
ω_{ref}	Reference speed
a	Overloading factor
I_{sa}	Motor phase current
V_a, V_b, V_c	Phase voltages (V) of induction motor
$V_{s\alpha}, V_{s\beta}$	Stator voltages in α - β domain
$I_{s\alpha}, I_{s\beta}$	Stator currents in α - β domain
$\psi_{s\alpha}, \psi_{s\beta}, \psi_s$	Stator fluxes in α - β domain, resultant flux
$\psi_{r\alpha}, \psi_{r\beta}, \psi_r$	Rotor fluxes in stationary reference frame, resultant flux

L_r, L_s, M	Rotor inductance, stator inductance and mutual inductance
L_{lr}, L_{ls}	Rotor leakage inductance, stator leakage inductance
R_r, R_s	Rotor resistance, stator resistance
R_c, L_c, C_c	Long Cable Parameters
R_f, L_f, C_f	Inverter Output Parameters
I_{sd}, I_{sdref}	Reference d -axis current (A), actual d -axis current (A)
I_{sq}, I_{sqref}	Reference q -axis current (A), actual q -axis current (A)
T_{ref}, T_e	Reference developed torque (Nm), estimated developed torque (Nm)
τ_r	Rotor time constant
V_{sd} and V_{sq}	d -axis and q -axis voltages
T_s	Signal sampling period
V_a^*, V_b^*, V_c^*	Reference motor phase voltages (V)
S_a, S_b and S_c	Switching signals
θ_e	Flux angle
T_p	Pump torque (Nm)
P	Number of poles
D_b	duty ratio (d_b) of the boost converter
L_b	inductance value of the boost converter
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
L_i	Interfacing Inductor
Δi_{gL}	Ripple allowed in PFC boost inductor current
R_f, C_f	Resistance (Ω) and capacitance (μF) of RC filter
V_L, I_L	Local Load voltage, local load current
V_d	PCC voltage amplitude
u_{pa}, u_{pb}, u_{pc}	In-phase unit templates
u_{qa}, u_{qb}, u_{qc}	quadrature unit templates
$v_{pga}, v_{pgb}, v_{pgc}$	Filtered grid phase voltages
v_{pa}, v_{pb}, v_{pc}	Phase voltages at PCC
\mathcal{G}_{pv}	SPV feedforward term
e_{dc}	Voltage error
\mathcal{G}_L	Average active load component
\mathcal{G}_{net}	Net component of the grid currents

$i_{ga}^*, i_{gb}^*, i_{gc}^*$	Reference grid currents
i_{ga}, i_{gb}, i_{gc}	Sensed grid currents
P_g, Q_g	Grid active power, Reactive power
$I_{f_La}, I_{f_Lb}, I_{f_Lc}$	Fundamental component of load current
I_{La}, I_{Lb}, I_{Lc}	Nonlinear Load Current
V_{gab}, V_{gbc}	Grid line voltages