DESIGN AND DEVELOPMENT OF SOLAR PV FED BLDC MOTOR DRIVES FOR WATER PUMPING

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by

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CERTIFICATE

It is certified that the thesis entitled "**Design and Development of Solar PV Fed BLDC Motor Drives For Water Pumping**," being submitted by **Mr. Rajan Kumar** 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: September 27, 2017

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Rajan Kumar

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 fed water pumping are developed using a brushless DC (BLDC) motor drive. A high efficiency BLDC motor substantially reduces the size of PV array and hence its installation cost. Moreover, its high power factor results in a reduced capacity of the used voltage source inverter (VSI). Besides these, unlike an induction motor, the speed of a BLDC motor is not limited by power frequency. This leads to a reduced size of the motor.

A reduced sensor based simple, efficient and cost-effective BLDC motor drive is investigated with fast control of its speed. The voltage sensor at the DC bus of VSI and the motor phase current sensors are eliminated in the proposed drive. In addition, the speed control loop is not required, as the speed of BLDC motor-pump is adjusted by the DC bus voltage of VSI. The VSI is switched at fundamental frequency, which offers a high conversion efficiency by reducing the switching losses in VSI. The system possesses a maximum power point tracking (MPPT) of PV array by introducing a DC-DC converter between the PV array and a VSI, feeding the motor. The various DC-DC converters are placed for MPPT, and analyzed based on their performance, simplicity, design, cost and efficiency. The work is extended towards an elimination of DC-DC converter and a single stage PV array fed BLDC motor drive is also investigated for water pumping. This system is capable of operating the solar PV array at its optimum power using the same VSI, which is used for motor control. In order to make a PV water pumping further economical and compact, the position sensor-less BLDC motor drives are also developed for both two stage and single stage PV based water pumping. The sensorless control is the only reliable way to operate the BLDC motor for applications in submersible water pumping.

A promising case of interruption in the water pumping due to the intermittency of PV power generation is resolved by using a single phase utility grid as an external power backup. A grid interacted PV array and its control are demonstrated to get a reliable and fully utilized water pumping with BLDC motor such that the pumping is not affected by an intermittency of PV generation. The power is drawn from the grid in case the PV array is unable to meet the required power demand. Both unidirectional and bidirectional power flow control are implemented for a grid interfaced PV fed BLDC motor driven water pump. 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. This practice leads to a full utilization of installed resources. Moreover, it emerges as a source of earning by 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 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

वाटर पंपिंग में सोलर फोटोवोल्टेइक (पीवी) ऊर्जा का प्रयोग ऊर्जा संरक्षण की दृष्टि से श्रेयस्कर है, विशेषकर दूरवर्ती क्षेत्रों में जहाँ बिजली का संचरण आज भी या तो अव्यावहारिक है या अमितव्ययी है। इस शोध कार्य में ब्रशलेस डीसी (बीएलडीसी) मोटर ड्राइव के प्रयोग से सोलर पीवी चालित वाटर पंपिंग के लिए विभिन्न पद्धतियाँ विकसित की गई हैं। उच्च दक्षता का बीएलडीसी मोटर पीवी पैनल के आकार तथा लागत को कम करता है। इसका उत्तम पावर फैक्टर वोल्टेज सोर्स इन्वर्टर (वीएसआई) के मान को भी कम कर देता है। इसके अतिरिक्त, इंडक्शन मोटर से भिन्न, बीएलडीसी मोटर की गति पावर ग्रिड की आवृत्ति से संबंधित नहीं होती। अतः मोटर का आकार और भी छोटा हो जाता है।

प्रस्तुत शोध में कम सेंसर युक्त सरल, दक्ष और किफायती बीएलडीसी मोटर ड्राइव की खोज की गई है, जिसमें इसकी गति को तेजी से नियंत्रित किया जाता है। प्रस्तावित ड्राइव में वीएसआई के डीसी लिंक वोल्टेज सेंसर और मोटर के फेस करेंट सेंसर को हटा दिया गया है। इसके अलावा, गति नियंत्रक लूप की आवश्यकता नहीं है, क्योंकि बीएलडीसी मोटर-पंप की गति को वीएसआई के डीसी लिंक वोल्टेज द्वारा समायोजित किया जाता है। वीएसआई को मूल आवृत्ति से संचालित किया जाता है, जो वीएसआई में स्विचिंग क्षति को कम करके उच्च रूपांतरण दक्षता प्रदान करता है। प्रस्तावित प्रणाली में पीवी पैनल और वीएसआई के मध्य एक डीसी-डीसी कन्वर्टर का प्रयोग करके पीवी पैनल के मैक्सिमम पावर प्वाइंट ट्रैकिंग (एमपीपीटी) को सिद्ध किया गया है। विभिन्न डीसी-डीसी कन्वर्टर्स को एमपीपीटी के लिए प्रयुक्त किया गया है, तथा प्रदर्शन, सरलता, रचना, लागत और दक्षता के आधार पर उनका विश्लेषण किया गया है। इस शोध के अगले भाग में डीसी-डीसी कन्वर्टर को निष्कासित किया गया है तथा एक सिंगल स्टेज पीवी चालित बीएलडीसी मोटर ड्राइव को भी वाटर पंपिंग के लिए उपयोग में लाया गया है। यह प्रणाली उसी वीएसआई का प्रयोग करके सोलर पीवी पैनल को उसके इष्टतम शक्ति पर संचालित करने में सक्षम है, जिसका प्रयोग मोटर नियंत्रण के लिए किया जाता है। पीवी-वाटर पम्पिंग को और अधिक किफायती और सुगठित करने हेतु डबल स्टेज और सिंगल स्टेज पीवी पर आधारित वाटर पंपिंग के लिए पोजिसन सेंसर रहित बीएलडीसी मोटर ड्राइव्स भी विकसित किए गए हैं। सेंसर रहित नियंत्रण ही सब्मर्सिबल वाटर पंपिंग के लिए बीएलडीसी मोटर संचालित करने का एकमात्र विश्वसनीय तरीका है।

सोलर पीवी पर आधारित बिजली उत्पादन की अनिरंतरता के कारण वाटर पंपिंग में व्यवधान उत्पन्न होने की समस्या से निजात पाने के लिए सिंगल फेस ग्रिड को बैकअप के रूप में प्रयोग किया गया है। ग्रिड-संयोजित पीवी पैनल तथा उसके नियंत्रण के द्वारा एक विश्वसनीय और पूर्णतः उपयोग किए हुए बीएलडीसी मोटर-वाटर पम्पिंग को सिध्द किया

गया है, ताकि पीवी उत्पादन की अनिरंतरता से वाटर पम्पिंग प्रभावित न हो। जब पीवी पैनल वाटर पम्पिंग के लिए आवश्यक ऊर्जा की पूर्ति नहीं कर पाता तब शेष ऊर्जा ग्रिड से ले ली जाती है। ग्रिड-संयोजित पीवी-बीएलडीसी मोटर चालित वाटर पंप के लिए यूनिडिरेक्शनल और बाइडिरेक्शनल-दोनों ही पर आधारित ऊर्जा प्रवाह के नियंत्रण को कार्यान्वित किया गया है। बाइडिरेक्शनल ऊर्जा प्रवाह के नियंत्रण पर आधारित प्रणाली, जब वाटर पंपिंग की आवश्यकता न हो, स्थापित पीवी पैनल की ऊर्जा को ग्रिड में स्थानांतरित करने की अतिरिक्त योग्यता रखती है। इससे स्थापित संसाधनों का संपूर्ण उपयोग सुनिश्चित होता है। साथ ही साथ, ग्रिड को ऊर्जा का विक्रय करके यह प्रणाली आय के एक श्रोत के रूप में उभर आई है। इन दोनों प्रणालियों (यूनिडिरेक्शनल और बाइडिरेक्शनल ऊर्जा प्रवाह पर आधारित) में भी पीवी पैनल का मैक्सिमम पावर प्वाइंट (एमपीपी) नियंत्रित किया गया है, तथा विभिन्न पावर क्वालिटी (पीक्यू) मानकें, जैसे ग्रिड करेंट का पावर फैक्टर और टोटल हार्मोनिक डिस्टोर्शन (टीएचडी) आईईईई-५१९ मानक के अनुरूप हैं।

प्रारंभिक, गतिशील और स्थिर अवस्थाओं में उनकी प्रतिक्रियाओं को सिध्द करने हेतु उपरोक्त सभी प्रस्तावित प्रणालियों का मैट्लैब/सिमुलिंक द्वारा मॉडलिंग तथा सिमुलेशन किया गया है। प्रयोगशाला में तैयार की गई हार्डवेयर प्रतिकृति द्वारा परीक्षण से प्राप्त परिणामों के आधार पर सिमुलेशन-परिणामों को सत्यापित किया गया है। सभी प्रस्तावित प्रणालियों की उपयोगिता और व्यावसायिक संभावनाओं को दक्षता, लागत, सरलता और प्रदर्शन के आधार पर उनका गहराई से विश्लेषण करके उपयुक्त साबित किया गया 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
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
DSP	Digital Signal Processor
DTC	Direct Torque Control
EMF	Electromotive Force
EMI	Electro-magnetic Interference
FL	Fuzzy Logic
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	Single Ended Primary Inductor Converter
Si	Silicon
SRM	Switched Reluctance Motor
STC	Standard Test Condition
SyRM	Synchronous Reluctance Motor
TCDIC	Transformer Coupled Dual Input Converter
THD	Total Harmonic Distortion
TIBC	Two Inductor Boost Converter
TIBuck	Two Input Buck
UPF	Unity Power Factor
UVT	Unit Vector Template
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
ZSI	Z-Source Inverter

LIST OF SYMBOLS

a	Overloading factor
C	Capacitor at the DC bus of VSI (μF)
C_1	Intermediate capacitor (μF)
C_f	Capacitor of the R-C ripple filter (μF)
C_pv	Capacitor across the PV array (μF)
D, D_1, D_2	Duty ratios
e_a, e_b, e_c	Back-EMFs of BLDC motor (V)
e_af, e_bf, e_cf	Filtered estimated back-EMFs of BLDC motor (V)
e_an, e_bn, e_cn	Estimated back-EMFs of BLDC motor (V)
e_ap, e_bp, e_cp	Phase lead compensated back-EMFs of BLDC motor (V)
f_rated	Frequency of input voltage corresponding to the rated speed (Hz)
f_sw, f_sw1, f_sw2	Switching frequencies (Hz)
$G(s)$	Transfer function of the phase lead compensator
H_1, H_2, H_3	Hall-effect signals
i_C	Current through the DC bus capacitor of VSI (A)
I_dc	Current at the DC bus of VSI (A)
I_L, I_L1, I_L2	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_s	Utility grid current (A)
i_s^*	Reference utility grid current (A)
i_sa, i_sb, i_sc	Stator currents of BLDC motor (A)
I_sp	Amplitude of fundamental component of utility grid current (A)
J	Moment of inertia of the BLDC motor (kg.cm^2)
k	Magnitude constant of the phase lead compensator
k_1	Pump constant [W/(rad/sec)^3]
K_e	Voltage constant of BLDC motor (V/krpm)
K_t	Torque constant of BLDC motor (Nm/A)
L, L_1, L_2	Inductors (mH)
L_f	Interfacing inductor (mH)

L_s	Inductance of stator windings of BLDC motor (mH)
m	Modulation index
N	Instantaneous speed of BLDC motor-pump (rpm)
N_{rated}	Rated speed of BLDC motor-pump (rpm)
N_s, N_P	Numbers of PV modules connected in series and parallel
P	Number of poles
P_m	Power (rated) of BLDC motor (W)
R_f	Resistance of the R-C ripple filter (Ω)
R_s	Resistance of stator windings of BLDC motor (Ω)
S	Solar irradiance (W/m^2)
S_1, S_2,.....,S_6	Switching pulses to the VSI
S_1', S_2',.....,S_6'	Fundamental frequency pulses
T	Time constant of the phase lead compensator
T_e	Electro-magnetic torque (Nm)
T_L	Pump load torque (Nm)
$\mathrm{T_s}$	Sampling rate
T_{sw2}	Switching time of the PFC boost converter (s)
v_{ab}, v_{bc}, v_{ca}	Line voltages of VSI (V)
v_{an}, v_{bn}, v_{cn}	Phase voltages of VSI (V)
V_{C1}	Voltage across intermediate capacitor (V)
v_d	Output DC voltage of the bridge rectifier (V)
V_{dc}	Voltage at the DC bus of VSI (V)
V_{dc}^*	Reference voltage at the DC bus of VSI (V)
v_s	Utility grid voltage (V)
V_{VSC}, 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
z_a, z_b, z_c	Commutation signals for gating signals' generation
ΔD	Perturbation in the duty ratio
ΔI_L, ΔI_{L1}, ΔI_{L2}	Permitted ripples in the currents through the inductors (A)
ΔI_{VSC}	Permitted ripple in the current through the interfacing inductor (A)
ΔV_{C1}	Permitted ripple in the voltage across intermediate capacitor (V)
ΔV_{dc}	Permitted ripple in the voltage at the DC bus of VSI (V)
η	Efficiency (%)
θ	Rotor position (º)

θ_1	Phase angle of utility grid voltage at fundamental frequency (º)
θ_d	Delay angle of filtered estimated back-EMF (º)
ω	Speed or frequency (rated) of BLDC motor (rad/sec.)
ω_c	Cut-off frequency of the low pass filter (rad/sec.)
ω_{c1}	Zero crossover frequency of the phase lead compensator (rad/sec.)
ω_{c2}	Pole crossover frequency of the phase lead compensator (rad/sec.)
ω_L	Line frequency of the utility grid (rad/sec.)
ω_{rated}	Frequency of input voltage corresponding to the rated speed (rad/sec.)