

**GRID INTERACTIVE AND STANDALONE PERMANENT
MAGNET BRUSHLESS DC MOTOR DRIVE FOR SOLAR
PV ARRAY FED WATER PUMPING**

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MAGNET BRUSHLESS DC MOTOR DRIVE FOR SOLAR PV
ARRAY FED WATER PUMPING**

by

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Department of Electrical Engineering

Submitted

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to the



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CERTIFICATE

It is certified that the thesis entitled “**Grid Interactive and Standalone PMBLDC Drive and PMBLDC Motor Design for Solar Water Pumping**” being submitted by **Mr. Aryadip Sen** for the 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 **the** award of any other degree or diploma.

Dated: June 18, 2024

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Aryadip Sen

ABSTRACT

The integration of solar photovoltaic (SPV) array energy in irrigation as well as domestic water pumping is very much prudent specially in isolated zones where the utility grid is either impractical or exorbitant. Apart from this, utilization of solar PV array energy in the field of water pumping reduces the utility grid load, carbon footprint and also saves conventional energy. In this research work, different methodologies for solar PV array fed water pumping system are developed using a permanent magnet brushless DC (PMBLDC) motor drive. A highly efficient PMBLDC motor significantly reduces the size of the solar photovoltaic array and so the installation cost. Moreover, unlike an induction motor, the speed of the PMBLDC motor is not limited by frequency of the supply. This reduces the size of the motor. A high efficient compact size optimized PMBLDC motor is investigated and designed here. Efficiency and cost optimization are done in the designed motor in comparison with the available counterpart. Optimization of the magnetic volume in the designed motor leads to optimization of the cost of the designed motor. A prototype of the designed motor is manufactured using industrial manufacturing facility for validation of the design results.

A position sensorless, compact, efficient and cost-effective PMBLDC motor drive is investigated with sensorless speed control. The Hall Effect position sensors, for sensing, the voltage sensor at the DC bus of the VSI and the motor phase current sensors are eliminated in the developed PMBLDC motor drive. In addition, the sensorless speed control is done using virtual position estimation. The system consists of a maximum power point tracking (MPPT) of solar photovoltaic array using VSI, feeding the PMBLDC motor. This developed system is capable of operating the solar photovoltaic array at its maximum available power using the same VSI, which is used for sensorless commutation and speed control. In order to develop a solar photovoltaic array fed water pumping further, reliable and economical, the position

sensorless PMBLDC motor drives are also developed for two-stage water pumping system. The position sensorless control is found the only way to use the PMBLDC motor for submersible water pumping. The work is further extended towards integration of DC-DC converter in the design system and a double stage solar PV array powered PMBLDC motor drive is also investigated for water pumping. Different DC-DC converters are placed for MPP and performances are analysed based on their simplicity, cost, design challenge and efficiency.

A challenging case of interaction in the solar PV array powered water pumping due to the intermittency of solar PV array power generation is resolved by using a battery integration and a single-phase grid as an external power backup. A battery integrated solar PV array and its control are evaluated to get a high reliable and fully utilised water pumping with PMBLDC motor. A grid interactive solar PV array and its control are demonstrated to get a well-engineered and fully utilised water pumping with PMBLDC motor such that the water pumping is not affected by the intermittency of the solar PV generation. The power is drawn from the single-phase grid in case the solar PV array is not able meet the power demand required by the water pumping system. Bi-directional power flow control is implemented for grid integrated water pumping system. The bi-directional power flow control gives an additional flexibility to feed the extra power to the utility grid by the installed solar PV array, which is not utilised for the water pumping system. This concept leads to a full utilization of the installed resources. Moreover, it is found as a source of earning by feeding electricity to the utility grid. The power quality (PQ) standard such as total harmonic distortion (THD) and power factor of grid current are met by the developed system as per the IEEE-519 standard.

All the developed configurations are modelled and analysed using MATLAB/ Simulink tool in order to exhibit their performances under various operating conditions during steady state, starting and dynamic conditions. Simulated results are validated through experimental results obtained from the developed hardware laboratory prototype along with an industrial

product prototype. The commercial viability of the developed system is justified from the developed industrial product prototype by their in-depth analysis considering cost, efficiency, size, reliability and performance.

सारांश

सिंचाई के साथ-साथ घरेलू जल पंपिंग में सौर फोटोवोल्टिक (एसपीवी) सरणी ऊर्जा का एकीकरण विशेष रूप से पृथक क्षेत्रों में बहुत विवेकपूर्ण है जहां उपयोगिता ग्रिड या तो अव्यावहारिक है या अत्यधिक है। इसके अलावा, जल पंपिंग के क्षेत्र में सौर पीवी सरणी ऊर्जा का उपयोग उपयोगिता ग्रिड लोड, कार्बन पदचिह्न को कम करता है और पारंपरिक ऊर्जा की भी बचत करता है। इस शोध कार्य में, स्थायी चुंबक ब्रशलेस डीसी (पीएमबीएलडीसी) मोटर ड्राइव का उपयोग करके सौर पीवी ऐरे फेड वॉटर पंपिंग सिस्टम के लिए विभिन्न पद्धतियां विकसित की गई हैं। एक अत्यधिक कुशल पीएमबीएलडीसी मोटर सौर फोटोवोल्टिक सरणी के आकार और इसलिए स्थापना लागत को काफी कम कर देती है। इसके अलावा, एक इंडक्शन मोटर के विपरीत, पीएमबीएलडीसी मोटर की गति आपूर्ति की आवृत्ति तक सीमित नहीं है। इससे मोटर का आकार कम हो जाता है। एक उच्च कुशल कॉम्पैक्ट आकार अनुकूलित पीएमबीएलडीसी मोटर की जांच और डिजाइन यहां किया गया है। उपलब्ध समकक्ष की तुलना में डिज़ाइन की गई मोटर में दक्षता और लागत अनुकूलन किया जाता है। डिज़ाइन की गई मोटर में चुंबकीय मात्रा के अनुकूलन से डिज़ाइन की गई मोटर की लागत का अनुकूलन होता है। डिज़ाइन परिणामों के सत्यापन के लिए औद्योगिक विनिर्माण सुविधा का उपयोग करके डिज़ाइन की गई मोटर का एक प्रोटोटाइप निर्मित किया जाता है।

एक स्थिति सेंसर रहित, कॉम्पैक्ट, कुशल और लागत प्रभावी पीएमबीएलडीसी मोटर ड्राइव की जांच सेंसर रहित गति नियंत्रण के साथ की जाती है। हॉल इफ़ेक्ट स्थिति सेंसर, सेंसिंग के लिए, वीएसआई के डीसी बस में वोल्टेज सेंसर और मोटर चरण वर्तमान सेंसर विकसित पीएमबीएलडीसी मोटर ड्राइव में समाप्त हो जाते हैं। इसके अलावा, सेंसर रहित गति नियंत्रण आभासी स्थिति अनुमान का उपयोग करके किया जाता है। सिस्टम में वीएसआई का उपयोग करके पीएमबीएलडीसी मोटर को फीड करते हुए सौर फोटोवोल्टिक सरणी की अधिकतम पावर प्वाइंट ट्रैकिंग (एमपीपीटी) शामिल है। यह विकसित

प्रणाली उसी वीएसआई का उपयोग करके अपनी अधिकतम उपलब्ध शक्ति पर सौर फोटोवोल्टिक सरणी को संचालित करने में सक्षम है, जिसका उपयोग सेंसर रहित कम्प्यूटेशन और गति नियंत्रण के लिए किया जाता है। सौर फोटोवोल्टिक ऐरे से संचालित जल पंपिंग को और अधिक विश्वसनीय और किफायती विकसित करने के लिए, दो-चरणीय जल पंपिंग प्रणाली के लिए स्थिति सेंसर रहित पीएमबीएलडीसी मोटर ड्राइव भी विकसित की गई है। सबमर्सिबल पानी पंपिंग के लिए पीएमबीएलडीसी मोटर का उपयोग करने का एकमात्र तरीका स्थिति सेंसर रहित नियंत्रण पाया गया है। डिजाइन प्रणाली में डीसी-डीसी कनवर्टर के एकीकरण की दिशा में काम को आगे बढ़ाया गया है और पानी पंपिंग के लिए एक डबल स्टेज सौर पीवी सरणी संचालित पीएमबीएलडीसी मोटर ड्राइव की भी जांच की जा रही है। एमपीपी के लिए अलग-अलग डीसी-डीसी कनवर्टर रखे गए हैं और उनकी सादगी, लागत, डिजाइन चुनौती और दक्षता के आधार पर प्रदर्शन का विश्लेषण किया जाता है।

सौर पीवी सरणी बिजली उत्पादन की रुक-रुक कर होने वाली सौर पीवी सरणी संचालित जल पंपिंग में बातचीत का एक चुनौतीपूर्ण मामला बैटरी एकीकरण और बाहरी पावर बैकअप के रूप में एकल चरण ग्रिड का उपयोग करके हल किया गया है। पीएमबीएलडीसी मोटर के साथ उच्च विश्वसनीय और पूरी तरह से उपयोग की जाने वाली जल पंपिंग प्राप्त करने के लिए एक बैटरी एकीकृत सौर पीवी सरणी और इसके नियंत्रण का मूल्यांकन किया जाता है। एक ग्रिड इंटरैक्टिव सौर पीवी सरणी और इसके नियंत्रण को पीएमबीएलडीसी मोटर के साथ एक अच्छी तरह से इंजीनियर और पूरी तरह से उपयोग की जाने वाली जल पंपिंग प्राप्त करने के लिए प्रदर्शित किया जाता है ताकि जल पंपिंग सौर पीवी पीढ़ी की रुक-रुक कर प्रभावित न हो। यदि सौर पीवी सरणी जल पंपिंग प्रणाली के लिए आवश्यक बिजली की मांग को पूरा करने में सक्षम नहीं है, तो बिजली एकल-चरण ग्रिड से ली जाती है। ग्रिड एकीकृत जल पंपिंग प्रणाली के लिए द्वि-दिशात्मक विद्युत प्रवाह नियंत्रण लागू किया गया है। द्वि-दिशात्मक बिजली प्रवाह नियंत्रण स्थापित सौर पीवी सरणी द्वारा उपयोगिता ग्रिड को अतिरिक्त बिजली खिलाने के लिए अतिरिक्त लचीलापन देता है, जिसका उपयोग जल पंपिंग प्रणाली के लिए नहीं किया जाता है। यह

अवधारणा स्थापित संसाधनों के पूर्ण उपयोग की ओर ले जाती है। इसके अलावा, यह उपयोगिता ग्रिड को बिजली खिलाकर कमाई के स्रोत के रूप में पाया जाता है। बिजली की गुणवत्ता (पीक्यू) मानक जैसे कि कुल हार्मोनिक विरूपण (टीएचडी) और ग्रिड करंट के पावर फैक्टर को आईईईई-519 मानक के अनुसार विकसित प्रणाली द्वारा समायोजित किया जाता है।

सभी विकसित कॉन्फ़िगरेशन को स्थिर स्थिति, प्रारंभिक और गतिशील स्थितियों के दौरान विभिन्न परिचालन स्थितियों के तहत उनके प्रदर्शन को प्रदर्शित करने के लिए MATLAB/Simulink टूल का उपयोग करके मॉडलिंग और विश्लेषण किया जाता है। सिमुलेटेड परिणामों को औद्योगिक उत्पाद प्रोटोटाइप के साथ विकसित हार्डवेयर प्रयोगशाला प्रोटोटाइप से प्राप्त प्रयोगात्मक परिणामों के माध्यम से मान्य किया जाता है। विकसित प्रणाली की व्यावसायिक व्यवहार्यता को लागत, दक्षता, आकार, विश्वसनीयता और प्रदर्शन पर विचार करते हुए उनके गहन विश्लेषण द्वारा विकसित औद्योगिक उत्पाद प्रोटोटाइप से उचित ठहराया जाता है।

TABLE OF CONTENTS

	Page No
Certificate	i
Acknowledgement	ii
Abstract	v
Table of Contents	xi
List of Figures	xix
List of Tables	xxiv
List of Abbreviations	xxv
List of Symbols	xxvii

CHAPTER –I	INTRODUCTION	1-12
-------------------	---------------------	-------------

1.1	General	1
1.2	Solar Photovoltaic Array Connected Aqua Pumping Technology	3
1.2.1	Solar Photovoltaic Array Connected PMBLDC Motor Design for Water Pumping	3
1.2.2	State of Art of Solar Energy Powered PMBLDCM Controller for Water Pumping	5
1.3	Objectives and Scope	7
1.3.1	Solar Energy Powered PMBLDC Motor Design for Aqua Pumping	7
1.3.2	Sensorless Standalone One Stage Solar Energy Powered PMBLDCM Controller for Aqua Pumps	7
1.3.3	Sensorless Standalone Double Stage Solar Energy Pow PMBLDC Motor Drive for Controller for Water Pumps	8
1.3.4	Battery Integrated Sensorless Solar Energy fed PMBLDCM Drive for Water Pumps	8
1.3.5	Sensorless Single Stage Grid Interactive Solar Energy fed PMBLDC Motor Drive for Water Pumps	9
1.3.6	Sensorless Two Stage Grid Connected Solar Energy powered PMBLDCM Controller for Aqua Pumps	9
1.4	Thesis Organization	9

CHAPTER -II	LITERATURE REVIEW	13-32
--------------------	--------------------------	--------------

2.1	General	13
2.2	Solar PV Technology Development and History	15

2.3	PMBLDC Motor Development and History	17
2.4	Literature Review	18
2.4.1	Review of PMBLDC Motor Development and Technology for Water Pumping	19
2.4.1.1	Surface Mounted PMBLDC Motor Development and Technology for Water Pumping	20
2.4.1.2	Submersible PMBLDC Motor Development and Technology for Water Pumping	21
2.4.2	Review of Solar Energy Powered Water Pumps	21
2.4.2.1	Solar PV Energy Powered DC Motor Coupled Water Pumps	22
2.4.2.2	Solar Energy Powered BLDCM Coupled WPS	23
2.4.2.3	Solar Energy Powered IM Coupled WPS	23
2.4.3	Review of Different MPPT technologies for Solar Powered WPS	24
2.4.4	Review of DC-DC Converter Topologies for MPPT of Solar Energy	26
2.4.5	Review of Grid Interfaced Solar PV Systems for Solar Powered Water Pumping System	27
2.4.6	Review of Battery Integrated Solar PV Systems for Solar Powered Water Pumping System	28
2.4.7	Review of BLDC Motor Controller for Solar Energy powered WPS	28
2.4.8	Review of Different Sensorless Technologies of BLDC Motor Controller for Solar Energy Water pumping	29
2.5	Challenges in PMBLDC Motor Development for Solar Powered Water Pumping System	30
2.6	Challenges in Grid-Interfaced and Off-Grid Solar PV Systems for Solar Powered Water Pumping System	31
2.7	Identified Research Areas	31
2.8	Conclusions	32

CHAPTER -III DESIGN AND DEVELOPMENT OF PMBLDC MOTOR FOR SOLAR PV FED WATER PUMPING 33-61

3.1	General	33
3.2	Configuration and Operating Principle of PMBLDC Motor	34
3.3	Selection of Design Parameters of PMBLDC Motor for Solar Energy Powered Water Pumping	35
3.4	Design and Analytical Modeling of PMBLDC Motor	36
3.5	Parameter Optimization of the Designed Motor	45
3.6	System Simulation in Ansys Rmxprt/MAXWELL Environment	48
3.7	Prototype Development Procedure as per Industry Standard	50
3.7.1	Stamping Grade Selection and Stamping Cutting	50
3.7.2	Stator and Rotor Stack Development	52
3.7.3	Winding Wire Gauge Selection and Stator Winding	52

3.7.4	Permanent Magnet Grade Selection and Permanent Magnet Sizing	52
3.7.5	Varnishing for Insulation and Moisture Protection	53
3.7.6	PMBLDC Motor Parts Assembling	53
3.7.7	External Frame Housing	53
3.8	Results and Discussion	
3.8.1	FE Analysis based Performance Evaluation	54
3.8.1.1	Stable State Analysis	55
3.8.1.2	Starting Performance Analysis	56
3.8.1.3	Magnetic Flux Density Distribution of the designed PMBLDC Motor	57
3.8.1.4	FE based Optimization	58
3.8.1.5	No Load Performance evaluation of the designed PMBLDC Motor	59
3.8.2	Performance Comparison of the Designed PMBLDC motor with Conventional Motor	60
3.9	Conclusions	61

CHAPTER -IV DESIGN AND DEVELOPMENT OF SINGLE STAGE SOLAR ENERGY POWERED SENSOR FREE BLDC MOTOR CONTROLLER FOR WATER PUMPING 62-105

4.1	General	62
4.2	LAYOUT OF One Stage Solar Energy Powered Sensor free PMBLDCM Controller for WPS	63
4.2.1	Single Stage Sensorless PMBLDC motor Controller for Solar powered Water Pumping	63
4.2.2	One Stage Sensor free PMBLDC Motor controller for Solar energy powered Aqua Pumping with Two way Power Transmission Control	64
4.3	Design and Modeling of One Stage Solar PV Energy Powered Sensorless BLDCM Controller for Water Pumping	65
4.3.1	Design and Selection of Solar PV Array	65
4.3.2	Design of Direct Current Link Capacitor of VSI	66
4.3.3	Design of VSI	67
4.3.4	Selection of Battery	68
4.3.5	Selection of Water Pump and BLDC Motor	68
4.4	Control Strategy for One Stage Solar Energy Powered Sensor free BLDC Controller for Aqua Pumping	68
4.4.1	MPPT Control for Solar Energy with VSI	69
4.4.2	Sensorless Control of PMBLDC Motor	72
4.4.2.1	Sensorless Starting Control	73
4.4.2.2	Sensorless Commutation Control	77
4.4.2.3	Varying Low Pass Filter Design and DSP Implementation	80

4.4.3	Speed Control of PMBLDC Motor-pump	84
4.4.4	Control of Battery Charging	85
4.5	System Simulation in Matlab®/Simulink Environment	85
4.6	Experimental System Description	86
4.6.1	Hardware Configuration	87
4.6.2	DSP d-SPACE 1104	89
4.6.3	Auxiliary Circuit for Current Sensors	90
4.6.4	Interfacing Circuit for Hall Effect Voltage Sensors	91
4.6.5	Interfacing Circuit for Gate Driver	92
4.7	Results and Discussion	93
4.7.1	Performance of Single Stage Sensorless PMBLDC Motor Drive for Solar powered Water Pumping	93
4.7.1.1	Simulated Performance	93
4.7.1.1.1	Steady State Performance	93
4.7.1.1.2	Starting Performance	95
4.7.1.1.3	Dynamic Performance	95
4.7.1.2	Experimental Results	96
4.7.1.2.1	Steady State Performance	96
4.7.1.2.2	Starting Performance	97
4.7.1.2.3	Dynamic Performance	98
4.7.2	Performance of Single Stage Sensorless PMBLDC Motor Controller for Solar powered Water Pumping with Battery Integration	98
4.7.2.1	Simulated Performance	99
4.7.2.1.1	Steady State Performance	99
4.7.2.1.2	Starting Performance	99
4.7.2.1.3	Dynamic Performance	99
4.7.2.2	Experimental Results	100
4.7.2.2.1	Steady State Performance	100
4.7.2.2.2	Starting Performance	100
4.7.2.2.3	Dynamic Performance	100
4.8	Comparison of Proposed and Conventional Drive Systems	102
4.9	Conclusions	104

CHAPTER -V DEVELOPMENT OF TWO STAGE SENSORLESS SOLAR PV POWERED BLDC MOTOR CONTROLLER FOR WATER PUMPING

106-124

5.1	General	106
5.2	Configurations of Two Stage Sensorless Solar Energy powered BLDC Motor Controller for Water Pumping	107

5.2.1	Layout of Double Stage Boost Converter fed Sensorless PMBLDCM Controller for Solar powered pumping	107
5.2.2	Configuration of Double Stage Sensorless PMBLDC Motor Controller for Solar powered Water Pumping with Battery Interfaced and Local Loads	107
5.3	Design and Modeling of Two Stage Sensorless Solar Energy Energized BLDC Motor Controller for Aqua Pumping	108
5.3.1	Design and Selection of Solar PV Array	109
5.3.2	Design of Boost Converter	109
5.3.3	Design of Direct Current Linked Capacitor of VFI	110
5.3.4	Design of VSI	110
5.3.5	Selection of Battery	110
5.3.6	Selection of BLDC Motor and Water Pump	110
5.4	Control Strategy for Double Stage Sensorless Solar PV Energized BLDCM Controller for Aqua Pumping	110
5.4.1	Solar Maximum Power Control with Boost Converter	111
5.4.2	Sensorless Control of PMBLDC Motor	111
5.4.3	Speed Control of PMBLDC Motor-pump	111
5.4.4	Control of Battery Charging	112
5.5	System Simulation using Simulation Tool	112
5.6	Experimental System Description	114
5.7	Results and Discussion	112
5.7.1	Performance of Double Stage Boost Converter fed Sensorless PMBLDC Motor Drive for Solar powered Water Pumping	114
5.7.1.1	Simulated Performance	114
5.7.1.1.1	Steady State Performance	115
5.7.1.1.2	Starting Performance	115
5.7.1.1.3	Dynamic Performance	115
5.7.1.2	Experimental Results	116
5.7.1.2.1	Steady State Performance	117
5.7.1.2.2	Starting Performance	118
5.7.1.2.3	Dynamic Performance	119
5.7.2	Performance of Double Stage Sensor free PMBLDC Motor Controller for Solar powered Water Pumping with Battery Integration	120
5.7.2.1	Simulated Performance	120
5.7.2.1.1	Steady State Performance	120
5.7.2.1.2	Starting Performance	120
5.7.2.1.3	Dynamic Performance	120
5.7.2.2	Experimental Results	121
5.7.2.2.1	Steady State Performance	121

5.7.2.2.2	Starting Performance	121
5.7.2.2.3	Dynamic Performance	122
5.8	Comparison between One Stage and two Stage Solar Energy powered BLDCM Drive for Aqua Pumping	122
5.9	Conclusions	123
CHAPTER -VI	DEVELOPMENT OF SENSORLESS SOLAR PV POWERED BLDC MOTOR DRIVE FOR WATER PUMPING USING BUCK-BOOST CONVERTER	125-137
6.1	General	125
6.2	Layout of Sensorless Solar Power Energized BLDCM Controller for Pumping using B-B Converter	125
6.3	Design and Modeling of Double Stage Sensorless Solar PV powered BLDC Motor Controller for Water Pumping	125
6.3.1	Design and Selection of Solar PV Array	126
6.3.2	Design of Buck-Boost Converter	126
6.3.3	Design of DC Bus Capacitor of VSI	127
6.3.4	Design of VSI	127
6.3.5	Selection of Battery	127
6.3.6	Selection of BLDC Motor and Water Pump	127
6.4	Control Strategy for Sensorless Solar Power Energized BLDCM for Aqua Pumping Using Buck-Boost Converter	128
6.4.1	MPP Control for Solar Power with B-B Converter	128
6.4.2	Sensorless Control of PMBLDC Motor	129
6.4.3	Speed Control of PMBLDC Motor-pump	129
6.5	System Simulation in Matlab®/Simulink Environment	129
6.6	Experimental System Description	129
6.7	Results and Discussion	130
6.7.1	Performance of Double Stage Sensorless PMBLDC Motor Drive for Solar powered Water Pumping	131
6.7.1.1	Simulated Performance	131
6.7.1.1.1	Steady State Performance	131
6.7.1.1.2	Starting Performance	132
6.7.1.1.3	Dynamic Performance	132
6.7.1.2	Experimental Results	133
6.7.1.2.1	Steady State Performance	133
6.7.1.2.2	Starting Performance	135
6.7.1.2.3	Dynamic Performance	135
6.8	Comparison between Single Stage and Double Stage Solar Power Energized BLDCM for Aqua Pumping	136

6.9	Conclusions	137
-----	-------------	-----

CHAPTER -VII DESIGN AND DEVELOPMENT OF ONE STAGE SINGLE PHASE GRID INTERFACED SOLAR ENERGY POWERED SENSORLESS BLDC MOTOR DRIVE FOR WATER PUMPING 138-157

7.1	General	138
7.2	Configuration of One Stage Single Phase Grid Interfaced Solar Energy powered Sensorless BLDCM Drive for WPS	139
7.3	Design and Modeling of Single Stage Single Phase Grid Connected Solar PV Energy Sensorless BLDC Controller for Water Pumping	141
	7.3.1 Design of Direct Current Linked Capacitor of VSI	141
	7.3.2 Design of R-C filter	141
	7.3.3 Design of Voltage Source Converter	142
	7.3.4 Design of Interfacing Inductor	143
7.4	Control Strategy for One Stage Grid Connected Solar Energy feed Sensorless BLDC Controller for Water Pumping	143
7.5	System Simulation in Matlab®/Simulink Environment	144
7.6	Experimental System Description	145
7.7	Results and Discussion	146
	7.7.1 Output of Grid Interfaced Sensorless PMBLDC Motor Controller for Solar Power Energized WPS with Two Way Power Flow Control	146
	7.7.1.1 Simulated Performance	147
	7.7.1.1.1 Steady State Performance	148
	7.7.1.1.2 Starting Performance	146
	7.7.1.1.3 Dynamic Performance	150
	7.7.1.2 Experimental Results	153
	7.7.1.2.1 Single-Phase Grid Fed PMBLDC Motor Pump	154
	7.7.1.2.2 The PMBLDC Motor Pump is Fed by Solar PV Array and Single-Phase Grid	155
7.9	Conclusions	157

CHAPTER -VIII DESIGN AND DEVELOPMENT OF SINGLE PHASE GRID INTERFACED SOLAR PV FED SENSORLESS BLDC MOTOR DRIVE FOR WATER PUMPING USING BOOST CONVERTER 158-177

8.1	General	158
8.2	Layout of Single Phase Grid Interactive Solar Energy powered Sensorless BLDCM Controller for WPS Boost Converter	159
8.3	Design and Modeling of Single Phase Grid Interfaced Solar PV fed Sensorless BLDC Motor Controller for Water Pumping Using Boost Converter	159

8.4	Control Strategy for Single Phase Grid Interfaced Solar Energy Powered Sensorless BLDCM Controller for WPS Using Boost Converter	161
8.5	System Simulation in Matlab®/Simulink Environment	162
8.6	Experimental System Description	163
8.7	Results and Discussion	164
8.7.1	Performance of Single Phase Grid Interactive Solar PV powered Sensorless BLDCM for WPS using Boost Converter	164
8.7.1.1	Simulated Performance	164
8.7.1.1.1	Steady State Performance	165
8.7.1.1.2	Starting Performance	166
8.7.1.1.3	Dynamic Performance	167
8.7.1.2	Experimental Results	171
8.7.1.2.1	Single-Phase Grid Fed PMBLDC Motor Pump	172
8.7.1.2.2	Solar PV Array Fed Utility Grid	173
8.7.1.2.3	PMBLDC Motor Pump is Fed by Solar PV Array and Single- Phase Grid	174
8.9	Conclusions	176

CHAPTER -IX MAIN CONCLUSIONS AND SUGRESSIONS FOR FURTHER WORK

9.1	General	178
9.2	Main Conclusions	179
9.3	Main Contributions of Research Work	181
9.4	Scope of Further Work	183

REFERENCES	185-202
-------------------	---------

APPENDICES	203-204
-------------------	---------

LIST OF PUBLICATIONS	205-206
-----------------------------	---------

AUTHOR BIO-DATA	207
------------------------	-----

LIST OF FIGURES

Fig. 3.1	Configuration of the PMBLDC motor (a) Surface mounted PMBLDC motor (b) Interior permanent magnet PMBLDC motor
Fig. 3.2	Operating point of Neodymium Permanent Magnet B_m with demagnetizing effect
Fig.3.3	Pole Magnet Thickness Optimization
Fig.3.4	(a) Stator Stamping (b) Rotor Stamping
Fig.3.5	Stack development using hydraulic pressing
Fig.3.6	(a) Stator Winding Insertion (b) Complete Stator Winding
Fig.3.7	Different assembled part of the manufactured PMBLDC motor
Fig.3.8	Complete assembled manufactured PMBLDC motor
Fig.3.9	Power to speed characteristics
Fig.3.10	Efficiency versus speed characteristics
Fig.3.11	Moving torque characteristics
Fig.3.12	Phase currents of the designed PMBLDC motor
Fig.3.13	Starting to moving torque profile of the designed PMBLDC motor
Fig.3.14	Magnetic flux distribution inside the designed PMBLDC motor
Fig.3.15	Electrical flux distribution inside the designed PMBLDC motor
Fig.3.16	Magnetic volume optimization considering maximum efficiency response
Fig.3.17	Phase Back EMF of designed PMBLDC Motor at generating mode (a) Peak amplitude 100 V (b) Peak Amplitude 200 V
Fig. 4.1	Single stage sensorless PMBLDC motor drive for Solar powered water pumping
Fig. 4.2	Single stage sensorless PMBLDC Motor drive for Solar powered Water Pumping with battery and Local Loads
Fig. 4.3	State flow of incremental conductance method
Fig. 4.4	Detailed control diagram of the solar MPPT and position sensorless control
Fig. 4.5	Control scheme for estimation of sensorless position and virtual Hall signal generation
Fig. 4.6	Phase currents and induced EMF PMBLDC motor under test
Fig. 4.7	Direction-defined starting algorithm flowchart

- Fig. 4.8 Phase Plot along with magnitude plot of before and after compensation in sensed line voltage
- Fig. 4.9 Bidirectional power flow control of integrated Battery
- Fig. 4.10 MATLAB/Simulink model of single Stage sensorless PMBLDC Motor controller for solar energy powered water pumping
- Fig. 4.11 MATLAB/Simulink model of single Stage Sensorless PMBLDC Motor Drive for Solar powered Water Pumping with integrated battery and local load
- Fig. 4.12 Laboratory Prototype of the developed PMBLDC motor drive
- Fig. 4.13 Industrial Product Prototype of the developed PMBLDC motor drive
- Fig. 4.14 dSPACE 1104 architecture (a) Control algorithm execution (b) CLP 1104
- Fig. 4.15 Auxiliary circuit for current sensor (a) Schematics (b) PCB of current sensor
- Fig. 4.16 Auxiliary circuit for voltage sensor (a) Schematics (b) PCB of voltage sensor
- Fig. 4.17 Auxillary circuit for gate drivers (a) Schematics (b) Photograph of opto-isolation and amplification board
- Fig. 4.18 Simulated steady state and starting performance of a (a) Solar PV array (b) PMBLDC motor -pump
- Fig. 4.19 Performance during transition (a) Solar PV array (b) PMBLDC motor –pump
- Fig. 4.20 Experimental MPPT performance recorded at insolation at (a) 1000 W/m² (b) 500 W/m²
- Fig. 4.21 Steady-state performance of the solar PV array
- Fig. 4.22 Steady-state performance of the PMBLDC motor-pump at 1000 W/m² insolation
- Fig. 4.23 4.23 PMBLDC motor's starting performance
- Fig. 4.24 PMBLDC motor-pump's dynamic performance (a) Insolation varies from 1000 W/m² to 500 W/m² (b) 500 W/m² to 1000 W/m²
- Fig. 4.25 Dynamic performance of the battery integrated PMBLDC motor-pump system
- Fig. 4.26 Dynamic performance of the battery integrated PMBLDC motor-pump system when solar insolation increased
- Fig. 4.27 Simulated steady state and starting performance of a (a) Solar PV array (b) PMBLDC motor –pump
- Fig. 4.28 Dynamic performance of the battery integrated PMBLDC motor-pump system when solar insolation decreased
- Fig. 5.1 Double Stage Boost Converter fed Sensorless PMBLDC Motor Drive for Solar powered water pumping

- Fig. 5.2 Double Stage Sensorless PMBLDC Motor controller for Solar powered water Pumping with Battery and local loads interfaced
- Fig. 5.3 Control diagram of boost converter fed double stage PMBLDC motor drive
- Fig 5.4 Double Stage Sensorless PMBLDC Motor Drive for Solar powered Water Pumping (a)MATLAB /SIMULINK model with Boost converter (b) with battery and local load (c) Experimental set-up
- Fig. 5.5 PMBLDC motor-pump performance (a) starting and steady state (b) dynamic performance
- Fig. 5.6 Solar PV array performance (a) starting and steady state (b) dynamic performance
- Fig. 5.7 Experimental MPPT performance recorded at insolation at (a) 1000 W/m² (b) 200 W/m²
- Fig. 5.8 Steady-state performance of (a) PMBLDC motor (b) PMBLDC motor with virtual Hall sensor's signal (c) Boost converter
- Fig. 5.9 Starting performance of PMBLDC motor-pump
- Fig. 5.10 Experimental dynamic performance recorded at insolation variation (a) 500 W/m² -1000 W/m² (b) 1000 W/m²-500 W/m²
- Fig.5.11 Dynamic performance of the battery integrated PMBLDC motor-pump system
- Fig. 5.12 Dynamic performance of the battery integrated PMBLDC motor-pump system when solar insolation increased
- Fig. 5.13 Dynamic performance of the battery integrated PMBLDC motor-pump system when solar insolation decreased
- Fig.6.1 Double Stage Boost Converter fed Sensorless PMBLDC Motor Drive for Solar powered water pumping
- Fig. 6.2 Control diagram of the buck-boost converter fed double stage PMBLDC motor controller
- Fig. 6.3 MATLAB/SIMULINK Model of Double Stage Sensorless PMBLDC Motor controller for Solar powered Water Pumping with Buck-Boost converter.
- Fig. 6.4 Laboratory Prototype of the developed PMBLDC motor drive.
- Fig. 6.5 PMBLDC motor-pump performance (a) starting and steady state (b) dynamic performance
- Fig. 6.6 Solar PV array performance (a) starting and steady state (b) dynamic performance
- Fig. 6.7 Experimental MPPT performance recorded at insolation at (a) 1000 W/m² (b) 200 W/m²
- Fig. 6.8 Steady-state performance (a) PMBLDC motor-pump (b) Solar PV array (c) Buck-boost converter

- Fig. 6.9 Starting performance of PMBLDC motor-pump
- Fig. 6.10 Experimental dynamic performance recorded at insolation variation (a) 500 W/m²-1000 W/m² (b) 1000 W/m²-500 W/m²
- Fig. 7.1 Single Stage Single Phase Grid Interfaced Solar PV fed Sensorless BLDC Motor Drive for Water Pumping
- Fig. 7.2 Control diagram of the grid side converter section of grid integrated PMBLDC motor drive
- Fig. 7.3 MATLAB/SIMULINK model of single stage single phase grid interfaced Solar PV feed sensorless PMBLDC Drive for water pumping
- Fig. 7.4 Laboratory Prototype of the developed PMBLDC motor drive
- Fig. 7.5 PMBLDC motor-pump performance (a) starting and steady state (b) dynamic performance
- Fig. 7.6 Solar PV array performance (a) starting and steady state (b) dynamic performance
- Fig. 7.7 PMBLDC motor-pump performance (a) Single phase grid performance (b) PMBLDC motor steady-state performance (c) FFT analysis
- Fig. 7.8 PMBLDC motor-pump dynamic performance (a) PMBLDC-motor pump turns off (b) Solar –PV array power fed single phase grid (c) FFT analysis of grid fed current
- Fig. 7.9 Dynamic performance (a) Solar PV array insolation reduces from 800 W/m² to 600 W/m² (b) Single phase grid fed PMBLDC motor pump (c) FFT analysis of grid fed current (d) PMBLDC motor –pump performance
- Fig. 7.10 Experimental MPPT performance recorded at insolation of 1000 W/m²
- Fig. 7.11 Single phase grid fed PMBLDC motor-pump (a) grid indices (b) power quality of single phase grid (c) PMBLDC motor pump indices
- Fig. 7.12 Solar PV array fed PMBLDC motor-pump to both solar PV array and grid fed PMBLDC motor pump (a) solar PV array indices (b) PMBLDC motor pump indices (c) power quality of single phase grid
- Fig. 8.1 Double Stage single phase grid Interfaced solar PV fed sensorless PMBLDC Motor controller for water pumping
- Fig. 8.2 Control diagram (a) grid side converter section (b) boost converter section of the grid integrated double stage PMBLDC motor drive
- Fig. 8.3 MATLAB/SIMULINK model of double stage single phase grid interfaced Solar PV feed sensorless PMBLDC Drive for water pumping
- Fig. 8.4 Laboratory Prototype of the developed PMBLDC motor drive

- Fig. 8.5 PMBLDC motor-pump performance (a) starting and steady state (b) dynamic performance
- Fig. 8.6 Solar PV array performance (a) starting and steady state (b) dynamic performance
- Fig. 8.7 PMBLDC motor-pump performance (a) Single phase grid performance (b) PMBLDC motor steady-state performance (c) FFT analysis
- Fig. 8.8 PMBLDC motor-pump dynamic performance (a) PMBLDC-motor pump turns off (b) Solar –PV array power fed single phase grid (c) FFT analysis of grid fed
- Fig. 8.9 Dynamic performance (a) Solar PV array insolation reduces from 800 W/m^2 to 600 W/m^2 (b) Single phase grid fed PMBLDC motor pump (c) FFT analysis of grid fed current (d) PMBLDC motor –pump performance
- Fig. 8.10 Experimental MPPT performance recorded at insolation of 1000 W/m^2
- Fig. 8.11 Single phase grid fed PMBLDC motor-pump (a) grid indices (b) power quality of single phase grid (c) PMBLDC motor pump indices
- Fig. 8.12 Dynamic performance of the grid current with the PMBLDC motor speed variation
- Fig. 8.13 Solar PV array fed single phase grid
- Fig. 8.14 Solar PV array fed single phase grid with enhances solar insolation
- Fig. 8.15 Variation of the solar insolation (a) 1000 W/m^2 to 500 W/m^2 (b) 500 W/m^2 to 1000 W/m^2 (c) power quality indices of the grid current

LIST OF TABLES

Table 3.1	Different Electro-Steel Grades and Details
Table 3.2	PMBLDC Motor Phase and Approximate Torque Ripple
Table 4.1	Forward direction Starting Switching combination
Table 4.2	Reverse direction Starting Switching combination
Table 4.3	Cost of developed PMBLDCM Drive in comparison to Existing available PMBLDCM Drive

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
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
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
VFI	Voltage Fed Inverter
ZSI	Z-Source Inverter
WPS	Water Pumping System