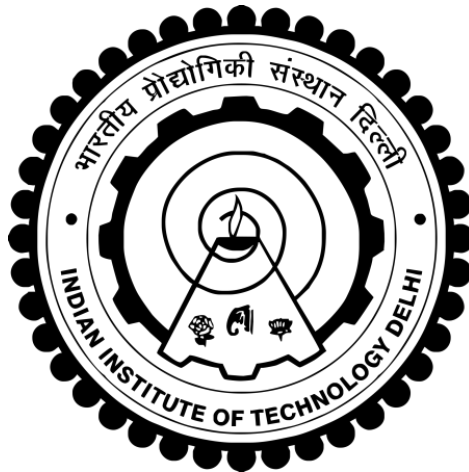


DESIGN AND DEVELOPMENT OF SOLAR PV FED BLDC MOTOR DRIVES FOR WATER PUMPING

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
SEPTEMBER 2017**

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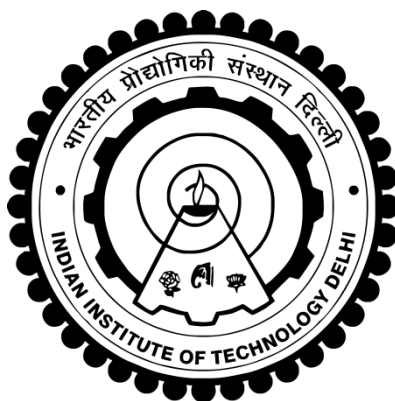
by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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SEPTEMBER 2017

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 पंपिंग 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 सम्बन्धित 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 पंपिंग को सिद्ध 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 स्रोत 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 सिद्ध करने हेतु उपरोक्त सभी प्रस्तावित प्रणालियों का मैटलैब/सिमुलिक 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।

TABLE OF CONTENTS

	Page No.
Certificate	i
Acknowledgements	ii
Abstract	v
Table of Contents	vii
List of Figures	xxii
List of Tables	xxiv
List of Abbreviations	xxv
List of Symbols	xxvii
 CHAPTER I INTRODUCTION	 1-9
1.1 General	1
1.2 State of Art on Solar PV Fed Water Pumping Systems	2
1.3 Objectives and Scope of Work	4
1.3.1 Two Stage Solar PV Based BLDC Motor Drive for Water Pumping	4
1.3.2 Single Stage Solar PV Based BLDC Motor Drive for Water Pumping	4
1.3.3 Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Unidirectional Power Flow Control	5
1.3.4 Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	5
1.3.5 Sensorless BLDC motor Drive for Solar PV Fed Water Pumping	5
1.4 Outline of Chapters	5
 CHAPTER II LITERATURE REVIEW	 10-26
2.1 General	10
2.2 History and Development of Solar PV Technology	11
2.3 Standards, Testing and Quality Certification for Solar PV Systems	14
2.4 Literature Survey	16
2.4.1 Review of Solar PV Fed Water Pumping Systems	16
2.4.1.1 Solar PV Fed DC Motor Driven Water Pumping	17
2.4.1.2 Solar PV Fed BLDC Motor Driven Water Pumping	18
2.4.1.3 Solar PV Fed Induction Motor Driven Water Pumping	18
2.4.1.4 Solar PV Fed PMSM Driven Water Pumping	20
2.4.1.5 Solar PV Fed SRM Driven Water Pumping	20
2.4.1.6 Solar PV Fed SyRM Driven Water Pumping	21
2.4.2 Review of MPPT Techniques for Solar PV Fed Water Pumping	21

2.4.3	Review of DC-DC Converter Topologies for MPPT of Solar PV Array	23
2.4.4	Review of BLDC Motor Drives for Solar PV fed Water Pumping	24
2.5	Identified Research Areas	25
2.6	Conclusions	26
CHAPTER III	CLASSIFICATION AND CONFIGURATIONS OF SOLAR PV FED BLDC MOTOR DRIVES FOR WATER PUMPING	27-35
3.1	General	27
3.2	Classification of Solar PV Fed BLDC Motor Drives for Water Pumping	27
3.3	Configurations of Solar PV Fed BLDC Motor Drives for Water Pumping	29
3.3.1	Configurations of Off-Grid Solar PV Fed BLDC Motor Drive for Water Pumping	29
3.3.1.1	Two Stage Solar PV Fed BLDC Motor Drives for Water Pumping	29
3.3.1.2	Single Stage Solar PV Fed BLDC Motor Drive for Water Pumping	31
3.3.2	Configurations of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping	32
3.3.2.1	Unidirectional Power Flow Control Based Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping	33
3.3.2.2	Bidirectional Power Flow Control Based Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping	34
3.3.3	Configurations of Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	34
3.3.3.1	Configuration of Two Stage Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	35
3.3.3.2	Configuration of Single Stage Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	35
3.4	Conclusions	35
CHAPTER IV	SOLAR PV-BOOST CONVERTER FED BLDC MOTOR DRIVE FOR WATER PUMPING	36-61
4.1	General	36
4.2	Configuration of Solar PV Fed BLDC Motor Drive for Water Pumping Using Boost Converter	36
4.3	Design of Solar PV Fed BLDC Motor Drive for Water Pumping Using Boost Converter	38
4.3.1	Design and Selection of Solar PV Array	38
4.3.2	Design of Boost Converter	39
4.3.3	Design of DC Bus Capacitor of VSI	40
4.3.4	Design of VSI	41

4.3.5	Selection of BLDC Motor	41
4.3.6	Design of Water Pump	41
4.4	Control of Solar PV Fed BLDC Motor Drive for Water Pumping Using Boost Converter	42
4.4.1	MPPT Control of Solar PV Array with Boost Converter	42
4.4.2	Electronic Commutation of BLDC Motor	45
4.4.3	Speed Control of BLDC Motor-Pump	46
4.4.4	Soft Starting of BLDC Motor	46
4.5	MATLAB Based Modeling and Simulation of PV Fed BLDC Motor Drive for Water Pumping Using Boost Converter	47
4.6	Hardware Implementation of Solar PV Fed BLDC Motor Drive for Water Pumping Using Boost Converter	48
4.6.1	Development of Signal Conditioning Circuit for Voltage Sensors	49
4.6.2	Development of Signal Conditioning Circuit for Current Sensors	50
4.6.3	Development of Isolation and Amplification Circuit for Gate Drivers	51
4.6.4	Execution of Control Algorithm on DSP-dSPACE 1104	51
4.7	Results and Discussion	53
4.7.1	Simulated Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Boost Converter	53
4.7.1.1	Steady State Performance	53
4.7.1.2	Starting Performance	55
4.7.1.3	Dynamic Performance	55
4.7.2	Experimental Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Boost Converter	56
4.7.2.1	Steady State Performance	56
4.7.2.2	Dynamic Performance	57
4.7.2.3	Starting Performance	59
4.7.3	Comparison of Proposed and Conventional Drive Systems	59
4.8	Conclusions	61
CHAPTER V	SOLAR PV-BUCK CONVERTER FED BLDC MOTOR DRIVE FOR WATER PUMPING	62-73
5.1	General	62
5.2	Configuration of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck Converter	62
5.3	Design of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck Converter	62
5.3.1	Design and Selection of Solar PV Array	63
5.3.2	Design of Buck Converter	64
5.3.3	Design of DC Bus Capacitor of VSI	64
5.3.4	Design of VSI	64
5.3.5	Selection of BLDC Motor	64

5.3.6	Design of Water Pump	65
5.4	Control of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck Converter	65
5.5	MATLAB Based Modeling and Simulation of PV Fed BLDC Motor Drive for Water Pumping Using Buck Converter	65
5.6	Hardware Implementation of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck Converter	66
5.7	Results and Discussion	66
5.7.1	Simulated Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck Converter	66
5.7.1.1	Steady State Performance	66
5.7.1.2	Starting Performance	68
5.7.1.3	Dynamic Performance	68
5.7.2	Experimental Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck Converter	70
5.7.2.1	Steady State Performance	70
5.7.2.2	Dynamic Performance	71
5.7.2.3	Starting Performance	72
5.7.3	Comparison of Proposed and Conventional Systems	72
5.8	Conclusions	73
CHAPTER VI	SOLAR PV FED BLDC MOTOR DRIVE FOR WATER PUMPING USING BUCK-BOOST CONVERTERS	74-117
6.1	General	74
6.2	Classification of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck-Boost Converters	74
6.3	Configurations of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck-Boost Converters	75
6.3.1	Configuration of Solar PV Fed BLDC Motor Drive With Buck-Boost Converter	75
6.3.2	Configuration of Solar PV Fed BLDC Motor Drive With Cuk Converter	76
6.3.3	Configuration of Solar PV Fed BLDC Motor Drive With Zeta Converter	76
6.3.4	Configuration of Solar PV Fed BLDC Motor Drive With SEPIC	76
6.3.5	Configuration of Solar PV Fed BLDC Motor Drive With Landsman Converter	77
6.4	Design of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck-Boost Converters	78
6.4.1	Design and Selection of Solar PV Array	78
6.4.2	Design of Buck-Boost Converters	79

6.4.2.1	Design of Buck-Boost Converter	79
6.4.2.2	Design of Cuk Converter	80
6.4.2.3	Design of Zeta Converter	80
6.4.2.4	Design of SEPIC	81
6.4.2.5	Design of Landsman Converter	81
6.4.3	Design of DC Bus Capacitor of VSI	81
6.4.4	Design of VSI	82
6.4.5	Selection of BLDC Motor	82
6.4.6	Design of Water Pump	82
6.5	Control of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck-Boost Converters	82
6.6	MATLAB Based Modeling and Simulation of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck-Boost Converters	82
6.7	Hardware Implementation of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck-Boost Converters	83
6.8	Results and Discussion	83
6.8.1	Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Buck-Boost Converter	83
6.8.1.1	Simulated Performance	84
6.8.1.2	Experimental Performance	87
6.8.2	Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Cuk Converter	90
6.8.2.1	Simulated Performance	90
6.8.2.2	Experimental Performance	93
6.8.3	Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Zeta Converter	96
6.8.3.1	Simulated Performance	96
6.8.3.2	Experimental Performance	99
6.8.4	Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using SEPIC	102
6.8.4.1	Simulated Performance	102
6.8.4.2	Experimental Performance	105
6.8.5	Performance of Solar PV Fed BLDC Motor Drive for Water Pumping Using Landsman Converter	109
6.8.5.1	Simulated Performance	109
6.8.5.2	Experimental Performance	112
6.9	Comparative Evaluation of Various DC-DC Converters for Solar PV Fed BLDC Motor Driven Water Pumping	115
6.10	Conclusions	117

CHAPTER VII	SINGLE STAGE SOLAR PV FED BLDC MOTOR DRIVE FOR WATER PUMPING	118-136
7.1	General	118
7.2	Configuration of Single Stage Solar PV Fed BLDC Motor Drive for Water Pumping	118
7.3	Design of Single Stage Solar PV Fed BLDC Motor Drive for Water Pumping	120
7.3.1	Design and Selection of Solar PV Array	120
7.3.2	Design of DC Link Capacitor of VSI	121
7.3.3	Design of VSI	122
7.3.4	Selection of BLDC Motor	122
7.3.5	Design of Water Pump	122
7.4	Control of Single Stage Solar PV Fed BLDC Motor Driven Water Pumping	122
7.4.1	MPPT of Solar PV Array	124
7.4.2	Electronic Commutation of BLDC Motor	124
7.4.3	Switching Pulse Generation for VSI	124
7.4.4	Speed Control of BLDC Motor-pump	125
7.4.5	Soft Starting of BLDC Motor	125
7.5	MATLAB Based Modeling and Simulation of Single Stage Solar PV Fed BLDC Motor Drive for Water Pumping	125
7.6	Hardware Implementation of Single Stage Solar PV Fed BLDC Motor Drive for Water Pumping	126
7.7	Results and Discussion	127
7.7.1	Simulated Performance of Single Stage Solar PV Fed BLDC Motor Drive for Water Pumping	127
7.7.1.1	Steady State Performance	127
7.7.1.2	Starting Performance	130
7.7.1.3	Dynamic Performance	130
7.7.2	Experimental Performance of Single Stage Solar PV Fed BLDC Motor Drive for Water Pumping	131
7.7.2.1	Steady State Performance	132
7.7.2.2	Dynamic Performance	132
7.7.2.3	Starting Performance	134
7.8	Comparative Evaluation of Single Stage and Two Stage Solar PV Fed BLDC Motor Drives for Water Pumping	135
7.9	Conclusions	136
CHAPTER VIII	UNIDIRECTIONAL POWER FLOW CONTROL BASED GRID INTERFACED SOLAR PV FED BLDC MOTOR DRIVE FOR WATER PUMPING	137-160

8.1	General	137
8.2	Configuration of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Unidirectional Power Flow Control	138
8.3	Design of Grid Interfaced Solar PV Fed BLDC Motor Driven Water Pumping Based on Unidirectional Power Flow Control	139
8.3.1	Design and Selection of Solar PV Array	140
8.3.2	Design of Boost Converter	141
8.3.3	Design of VSI	142
8.3.4	Design of PFC Boost Converter	142
8.3.5	Design of Common DC Link Capacitor	142
8.3.6	Design of R-C Filter	143
8.3.7	Selection of BLDC Motor	143
8.3.8	Design of Water Pump	143
8.4	Control of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Unidirectional Power Flow Control	144
8.4.1	Unidirectional Power Flow Control	144
8.4.2	Speed Control of BLDC Motor	145
8.5	MATLAB Based Modeling and Simulation of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Unidirectional Power Flow Control	145
8.6	Hardware Implementation of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Unidirectional Power Flow Control	146
8.7	Results and Discussion	147
8.7.1	Simulated Performance of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Unidirectional Power Flow Control	148
8.7.1.1	Steady State Performance	148
8.7.1.2	Starting Performance	149
8.7.1.3	Dynamic Performance	149
8.7.2	Experimental Performance of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Unidirectional Power Flow Control	152
8.7.2.1	Steady State Performance	152
8.7.2.2	Dynamic Performance	157
8.7.2.3	Starting Performance	159
8.8	Conclusions	159
CHAPTER IX	BIDIRECTIONAL POWER FLOW CONTROL BASED GRID INTERFACED SOLAR PV FED BLDC MOTOR DRIVE FOR WATER PUMPING	161-182
9.1	General	161

9.2	Configuration of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	162
9.3	Design of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	163
9.3.1	Design of Voltage Source Converter	163
9.3.2	Design of Interfacing Inductor	164
9.4	Control of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	164
9.5	MATLAB Based Modeling and Simulation of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	165
9.6	Hardware Implementation of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	166
9.7	Results and Discussion	167
9.7.1	Simulated Performance of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	167
9.7.1.1	Steady State Performance	167
9.7.1.2	Starting Performance	170
9.7.1.3	Dynamic Performance	170
9.7.2	Experimental Performance of Grid Interfaced Solar PV Fed BLDC Motor Drive for Water Pumping Based on Bidirectional Power Flow Control	173
9.7.2.1	BLDC Motor-pump is Fed by Grid Only	173
9.7.2.2	Grid is Fed by PV Array	175
9.7.2.3	BLDC Motor-Pump is Fed by Both PV Array and Grid	178
9.7.2.4	Transition from PV Array and Grid Feeding Pump to PV Array Feeding Grid	179
9.7.2.5	Grid Failure Condition	181
9.8	Conclusions	181

CHAPTER X SOLAR PV FED SENSORLESS BLDC MOTOR DRIVE FOR WATER PUMPING 183-226

10.1	General	183
10.2	Classification of Solar PV Fed Sensorless BLDC Motor Drives For Water Pumping	184
10.3	Configurations of Solar PV Fed Sensorless BLDC Motor Drives For Water Pumping	184
10.3.1	Configuration of Two Stage Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	184
10.3.2	Configuration of Single Stage Solar PV Fed Sensorless BLDC Motor	185

	Drive for Water Pumping	
10.4	Design of Solar PV Fed Sensorless BLDC Motor Drives For Water Pumping	185
10.4.1	Design of Two Stage Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	186
10.4.1.1	Estimation of Back EMFs from Line Voltages	187
10.4.1.2	Elimination of False Zero-Crossing Detection	188
10.4.1.3	Design of Phase Lead Compensator	191
10.4.1.4	Generation of Commutation Signals	192
10.4.1.5	Generation of Gating Signals	193
10.4.2	Design of Single Stage Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	195
10.4.2.1	Elimination of False Zero-Crossing Detection	195
10.4.2.2	Design of Phase Lead Compensator	196
10.5	Control of Solar PV Fed Sensorless BLDC Motor Drives for Water Pumping	197
10.5.1	Control of Two Stage Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	197
10.5.1.1	Alignment of Rotor Position	198
10.5.1.2	Sensorless Starting	199
10.5.2	Control of Single Stage Solar PV Fed Sensorless BLDC Motor Drive for Water Pumping	199
10.6	MATLAB Based Modeling and Simulation of Sensorless BLDC Motor Drives for Solar PV Fed Water Pumping	199
10.7	Hardware Implementation of Sensorless BLDC Motor Drives for Solar PV Fed Water Pumping	201
10.8	Results and Discussion	201
10.8.1	Performance of Position Sensorless BLDC Motor Drive	201
10.8.2	Performance of Sensorless BLDC Motor Drive for Two Stage Solar PV Fed Water Pumping	203
10.8.2.1	Simulated Performance	203
10.8.2.2	Experimental Performance	208
10.8.3	Performance of Sensorless BLDC Motor Drive for Single Stage Solar PV Fed Water Pumping	213
10.8.3.1	Simulated Performance	214
10.8.3.2	Experimental Performance	219
10.9	Conclusions	225

CHAPTER XI MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK 227-233

11.1	General	227
11.2	Main Conclusions	228

11.3	Suggestions for Further Work	232
	REFERENCES	234-249
	APPENDICES	250-255
	LIST OF PUBLICATIONS	256-257
	BIO-DATA	258-258

LIST OF FIGURES

- Fig. 2.1 Historical development of solar technology
- Fig. 3.1 Classification of solar PV fed BLDC motor driven water pumping systems
- Fig. 3.2 Solar PV-boost converter fed water pumping using BLDC motor drive
- Fig. 3.3 Solar PV-buck converter fed water pumping using BLDC motor drive
- Fig. 3.4 Solar PV-buck-boost converter fed water pumping using BLDC motor drive
- Fig. 3.5 Solar PV-Cuk converter fed water pumping using BLDC motor drive
- Fig. 3.6 Solar PV-SEPIC fed water pumping using BLDC motor drive
- Fig. 3.7 Solar PV-zeta converter fed water pumping using BLDC motor drive
- Fig. 3.8 Solar PV-Landsman converter fed water pumping using BLDC motor drive
- Fig. 3.9 Solar PV-ZSI fed water pumping using BLDC motor drive
- Fig. 3.10 Single stage solar PV fed water pumping using BLDC motor drive
- Fig. 3.11 Unidirectional power flow control based grid interfaced solar PV fed BLDC motor drive for water pumping
- Fig. 3.12 Bidirectional power flow control based grid interfaced solar PV fed BLDC motor drive for water pumping
- Fig. 4.1 Proposed PV-boost-BLDC motor-pump
- Fig. 4.2 Conventional topology of PV-boost-BLDC motor-pump
- Fig. 4.3 Illustration of INC-MPPT with PV array p_{pv} - v_{pv} characteristics
- Fig. 4.4 Flow diagram of INC-MPPT algorithm
- Fig. 4.5 MATLAB/Simulink model of solar PV fed BLDC motor drive for water pumping
- Fig. 4.6 Developed hardware prototype of the proposed system
- Fig. 4.7 Signal conditioning circuit for voltage sensors (a) Schematic diagram (b) Photograph of voltage sensor board
- Fig. 4.8 Signal conditioning circuit for current sensors (a) Schematic diagram (b) Photograph of current sensor board
- Fig. 4.9 Isolation and amplification circuit for gate drivers (a) Schematic diagram (b) Photograph of opto-isolation and amplification board
- Fig. 4.10 Architecture of dSPACE 1104 (a) Execution of control algorithm (b) CLP 1104
- Fig. 4.11 Steady state and starting performances of (a) PV array (c) BLDC motor-pump, and (b) steady state performance of boost converter
- Fig. 4.12 Dynamic performances of (a) PV array (b) BLDC motor-pump
- Fig. 4.13 PV array characteristics and MPPT performance at 1000 W/m^2

- Fig. 4.14 Steady state performance of (a) PV array (b) boost converter (c) motor-pump, at 1 kW/m², and (d) motor-pump, at 200 W/m²
- Fig. 4.15 Dynamic performances when the irradiance is (a) decreased from 1000 W/m² to 500 W/m², and (b) increased from 500 W/m² to 1000 W/m²
- Fig. 4.16 Starting performance of motor-pump at 1 kW/m²
- Fig. 4.17 Efficiency comparison of proposed and conventional schemes
- Fig. 4.18 Price distribution of proposed system in comparison with conventional systems
- Fig. 5.1 Proposed PV-buck-BLDC motor-pump
- Fig. 5.2 Steady state and starting performances of (a) PV array (c) BLDC motor-pump, and (b) steady state performance of buck converter
- Fig. 5.3 Dynamic performances of (a) PV array (b) BLDC motor-pump
- Fig. 5.4 PV array characteristics and MPPT performance at 1000 W/m²
- Fig. 5.5 Steady state performance of (a) PV array (b) buck converter (c) motor-pump, at 1 kW/m², and (d) motor-pump, at 200 W/m²
- Fig. 5.6 Dynamic performances when the irradiance is (a) decreased from 1000 W/m² to 500 W/m², and (b) increased from 500 W/m² to 1000 W/m²
- Fig. 5.7 Starting performance of motor-pump at 1 kW/m²
- Fig. 6.1 Configuration of proposed PV-buck-boost-BLDC motor-pump
- Fig. 6.2 Configuration of proposed PV-Cuk-BLDC motor-pump
- Fig. 6.3 Configuration of proposed PV-zeta-BLDC motor-pump
- Fig. 6.4 Configuration of proposed PV-SEPIC-BLDC motor-pump
- Fig. 6.5 Configuration of proposed PV-Landsman-BLDC motor-pump
- Fig. 6.6 Performance of proposed water pumping at 1000 W/m², (a) PV array variables, (b) Buck-boost converter variables, (c) BLDC motor-pump variables
- Fig. 6.7 Performance of proposed water pumping under varying solar insolation level, (a) PV array variables, (b) Buck-boost converter variables, (c) BLDC motor-pump variables
- Fig. 6.8 PV array characteristics and MPPT performance at 1000 W/m²
- Fig. 6.9 Steady state performance of (a) PV array (b) buck-boost converter (c) motor-pump, at 1 kW/m², and (d) motor-pump, at 200 W/m²
- Fig. 6.10 Starting performance of motor-pump at 1 kW/m²
- Fig. 6.11 Dynamic performance of proposed system under varying insolation level (a) 200 W/m² to 1000 W/m², (b) 1000 W/m² to 200 W/m²
- Fig. 6.12 Performance of proposed water pumping at 1000 W/m², (a) PV array variables, (b) Cuk converter variables, (c) BLDC motor-pump variables
- Fig. 6.13 Performance of proposed water pumping under varying solar insolation level, (a)

(a-b)	PV array variables, (b) BLDC motor-pump variables
Fig. 6.14	PV array characteristics and MPPT performance at 1000 W/m^2
Fig. 6.15	Steady state performance of (a) PV array (b)-(c) Cuk converter (d) motor-pump, at 1 kW/m^2 , and (e) motor-pump, at 200 W/m^2
Fig. 6.16	Starting performance of motor-pump at 1 kW/m^2
Fig. 6.17	Dynamic performance of proposed system under varying insolation level (a) 500 W/m^2 to 1000 W/m^2 , (b) 1000 W/m^2 to 500 W/m^2
Fig. 6.18	Performance of proposed water pumping at 1000 W/m^2 , (a) PV array variables, (a-c) (b) Zeta converter variables, (c) BLDC motor-pump variables
Fig. 6.19	Performance of proposed water pumping under varying solar insolation level, (a) (a-b) PV array variables, (b) BLDC motor-pump variables
Fig. 6.20	PV array characteristics and MPPT performance at 1 kW/m^2
Fig. 6.21	Steady state performance of (a) PV array (b)-(c) Zeta converter (d) motor-pump, at 1 kW/m^2 , and (e) motor-pump, at 200 W/m^2
Fig. 6.22	Dynamic performance of proposed system under varying insolation level (a) 200 W/m^2 to 1000 W/m^2 , (a-b) (b) 1000 W/m^2 to 200 W/m^2
Fig. 6.23	Starting performance of motor-pump at 1 kW/m^2
Fig. 6.24	Performance of proposed water pumping at 1000 W/m^2 , (a) PV array variables, (a-c) (b) SEPIC variables, (c) BLDC motor-pump variables
Fig. 6.25	Performance of proposed water pumping under varying solar insolation level, (a) (a-b) PV array variables, (b) BLDC motor-pump variables
Fig. 6.26	PV array characteristics and MPPT performance at 1 kW/m^2
Fig. 6.27	Steady state performance of (a) PV array (b)-(c) SEPIC (d) motor-pump, at 1 kW/m^2 , and (e) motor-pump, at 200 W/m^2
Fig. 6.28	Dynamic performance of proposed system under varying insolation level (a) 500 W/m^2 to 1000 W/m^2 , (a-b) (b) 1000 W/m^2 to 500 W/m^2
Fig. 6.29	Starting performance of motor-pump at 1 kW/m^2
Fig. 6.30	Performance of proposed water pumping at 1000 W/m^2 , (a) PV array variables, (a-c) (b) Landsman converter variables, (c) BLDC motor-pump variables
Fig. 6.31	Performance of proposed water pumping under varying solar insolation level, (a) (a-b) PV array variables, (b) BLDC motor-pump variables
Fig. 6.32	PV array characteristics and MPPT performance at 1 kW/m^2
Fig. 6.33	Steady state performance of (a) PV array (b)-(c) Landsman converter (d) motor-pump, at 1000 W/m^2 , and (e) motor-pump, at 200 W/m^2
Fig. 6.34	Starting performance of motor-pump at 1000 W/m^2
Fig. 6.35	Dynamic performance of proposed system under varying insolation level (a) 400 W/m^2 to 1000 W/m^2 , (a-b) (b) 1000 W/m^2 to 400 W/m^2

- Fig.7.1 BLDC motor driven water pumping based on a single stage solar PV energy conversion system
- Fig.7.2 Solar PV-ZSI fed BLDC motor driven water pumping system
- Fig. 7.3 Control structure of proposed BLDC motor drive for water pumping based on a single stage solar PV energy conversion system
- Fig. 7.4 MATLAB/Simulink model of single stage solar PV fed BLDC motor drive for water pumping
- Fig. 7.5 Developed hardware prototype of the proposed system
- Fig. 7.6 Steady state and starting performance of (a) PV array and (b) motor-pump, of proposed system at 1 kW/m^2
- Fig. 7.7 Dynamic performance of (a) PV array and (b) BLDC motor, of proposed system (a-b)
- Fig. 7.8 Test results for v_{pv} - p_{pv} & v_{pv} - i_{pv} characteristics of solar PV array at (a) 1000 W/m^2 (b) 200 W/m^2
- Fig. 7.9 Test results of proposed system under steady state condition (a) PV array indices (b) BLDC motor indices (c) Hall sensor indices (d) Hall signals and switching pulse, at 1000 W/m^2 , and (e) BLDC motor indices (f) Hall signals and switching pulse, at 200 W/m^2
- Fig. 7.10 Test results of proposed system under dynamic variation in irradiance from (a) 400 W/m^2 to 1 kW/m^2 and (b) 1 kW/m^2 to 400 W/m^2
- Fig. 7.11 Test results of proposed system under starting condition at 1 kW/m^2
- Fig. 7.12 Efficiency comparison of two stage and single stage PV based schemes
- Fig. 8.1 Schematic of proposed water pumping system
- Fig. 8.2 Structure of the proposed unidirectional power flow control
- Fig. 8.3 MATLAB/Simulink model of proposed solar PV fed water pumping
- Fig. 8.4 Developed hardware prototype of the proposed system
- Fig. 8.5 Starting and steady state behavior of (a) PV array and (b) BLDC motor-pump, when only PV array feeds BLDC motor-pump
- Fig. 8.6 Steady state behavior of (a) utility grid and (b) BLDC motor-pump, and (c) THD and harmonic spectrum of supply current, when only utility grid feeds BLDC motor-pump
- Fig. 8.7 Dynamic behavior of (a) PV array (b) utility grid and (c) BLDC motor-pump, and (d) THD and harmonic spectrum of supply current, under a transition from PV feeding pump to both PV and grid feeding pump
- Fig. 8.8 Dynamic behavior of (a) PV array (b) utility grid and (c) motor-pump, under a transition from grid feeding pump to PV array feeding pump
- Fig. 8.9 PV array characteristics and MPPT performance at 1000 W/m^2
- Fig. 8.10 Steady state performance when only the PV array feeds motor-pump

- Fig. 8.11 Steady state performance when both PV array and utility grid feed motor-pump (a-d)
- Fig. 8.12 Steady state performance when only utility grid feeds motor-pump (a-c)
- Fig. 8.13 Dynamic performance under (a) rise in radiation level (b) drop in radiation level (a-c) (c) grid failure
- Fig. 8.14 Starting performance of BLDC motor-pump
- Fig. 9.1 Schematic of the grid interactive PV array based water pumping using a BLDC motor drive
- Fig. 9.2 UVT based bi-directional power flow control of VSC
- Fig. 9.3 MATLAB/Simulink model of proposed grid interactive solar PV fed water pumping
- Fig. 9.4 Steady state and starting performance of (a) PV array, and (b) BLDC motor-pump, when only PV array feeds BLDC motor-pump (a-b)
- Fig. 9.5 Steady state performance of (a) utility grid and (b) BLDC motor-pump, and (c) harmonic spectrum of supply current, when only utility grid feeds water pump (a-c)
- Fig. 9.6 Steady state response of (a) PV array and (b) utility grid, when water pumping is not required (a-b)
- Fig. 9.7 Dynamic response of (a) PV array (b) utility grid and (c) BLDC motor-pump, under a transition from grid feeding pump to PV array feeding grid (a-c)
- Fig. 9.8 Dynamic performance of (a) PV array (b) utility grid and (d) BLDC motor-pump, and (c) harmonic spectrum of supply current, under a transition from PV array feeding pump to both PV array and grid feeding pump (a-d)
- Fig. 9.9 PV array characteristics and MPPT performance at 1000 W/m^2
- Fig. 9.10 Steady state performance, when the BLDC motor-pump is fed by grid only (a) grid indices (b) grid and motor-pump indices (c) power quality at utility grid (a-c)
- Fig. 9.11 Steady state performance of (a) PV array (b)-(c) utility grid, and (d) power quality at utility grid, when PV array feeds grid at 1000 W/m^2 (a-d)
- Fig. 9.12 Steady state performance of (a) PV array (b) utility grid, and (c) power quality at utility grid, when PV array feeds grid at 400 W/m^2 (a-c)
- Fig. 9.13 Dynamic performance of (a) PV array and (b)-(c) utility grid, when PV array feeds grid under a variation in radiation level from 1000 W/m^2 to 700 W/m^2 (a-c)
- Fig. 9.14 Dynamic performance of (a) PV array and (b) utility grid, when PV array feeds grid under a variation in radiation level from 700 W/m^2 to 1000 W/m^2 (a-b)
- Fig. 9.15 Steady state performance, when BLDC motor-pump is fed by both PV array and grid (a) PV array, grid and BLDC motor indices (b) power quality indices of utility grid (a-b)

- Fig. 9.16 (a-b) Dynamic performance, when BLDC motor-pump is fed by both PV array and grid (a) radiation reduces from 1000 W/m^2 to 400 W/m^2 (b) radiation increases from 400 W/m^2 to 1000 W/m^2
- Fig. 9.17 (a-b) Dynamic performance under the transition from PV array and grid feeding pump to PV array feeding grid (a) grid indices (b) grid and motor-pump indices
- Fig. 9.18 Dynamic performance under grid failure
- Fig. 10.1 Configuration of position sensorless BLDC motor drive for two stage solar PV fed water pumping
- Fig. 10.2 Configuration of position sensorless BLDC motor drive for single stage solar PV fed water pumping
- Fig. 10.3 Functional sequence of the back-EMF zero-crossing based sensorless technique
- Fig. 10.4 Experimental waveforms of estimated back EMF, filtered back EMF and compensated back EMF of phase 'a'
- Fig. 10.5 Plot of phase lag with the cut-off frequency of LPF
- Fig. 10.6 Plot of phase lag with the speed
- Fig. 10.7 Experimentally recorded phase lag
- Fig. 10.8 Bode plot of phase lead compensator
- Fig. 10.9 Experimentally recorded phase lag with phase lead compensator
- Fig. 10.10 Validation of phase lag compensation using the recorded waveforms of estimated back-EMF (e_{an}), filtered estimated back-EMF (e_{af}) and compensated estimated back-EMF (e_{ap})
- Fig. 10.11 Generation of commutation signals
- Fig. 10.12 Generation of gating signals
- Fig. 10.13 Experimentally recorded phase lag
- Fig. 10.14 Experimentally recorded phase lag with phase lead compensator
- Fig. 10.15 MATLAB/Simulink model of sensorless BLDC motor drive for two stage solar PV fed water pumping
- Fig. 10.16 MATLAB/Simulink model of sensorless BLDC motor drive for single stage solar PV fed water pumping
- Fig. 10.17 Simulation results for the position sensorless operation of BLDC motor
- Fig. 10.18 Experimental results for start-up and sensorless running of BLDC motor drive
- Fig. 10.19 (a-b) Starting and steady state performance of sensorless BLDC motor drive for two stage PV fed water pumping, at 1000 W/m^2 (a) PV array indices (b) BLDC motor indices
- Fig. 10.20 Intermediate signals of sensorless BLDC motor drive for two stage PV fed water pumping, under starting and steady state condition at 1000 W/m^2
- Fig. 10.21 (a-b) Dynamic performance of sensorless BLDC motor drive for two stage solar PV fed water pumping (a) PV array indices (b) BLDC motor-pump indices
- Fig. 10.22 Intermediate signals of sensorless BLDC motor drive for two stage PV fed water

pumping, under dynamic condition at 1000 W/m^2

- Fig. 10.23 PV array power-voltage and current-voltage characteristics at (a) 1 kW/m^2 and (a-b) 200 W/m^2
- Fig. 10.24 Experimental starting performance of sensorless BLDC motor drive for two stage solar PV fed water pumping at (a)-(g) 1 kW/m^2 and (h) 200 W/m^2
- Fig. 10.25 Experimental steady state performance of sensorless BLDC motor drive for two stage solar PV fed water pumping at 1 kW/m^2
- Fig. 10.26 Experimental steady state performance of sensorless BLDC motor drive for two stage solar PV fed water pumping at 200 W/m^2
- Fig. 10.27 Experimental dynamic performance of sensorless BLDC motor drive for two stage solar PV fed water pumping under the variation of irradiance level from (a)-(c) 400 W/m^2 to 700 W/m^2 and (d)-(f) 900 W/m^2 to 600 W/m^2
- Fig. 10.28 Starting and steady state performance of sensorless BLDC motor drive for single stage solar PV fed water pumping, at 1000 W/m^2 (a) PV array indices (b) BLDC motor-pump indices
- Fig. 10.29 Intermediate signals of sensorless BLDC motor drive for single stage PV fed water pumping, under starting and steady state condition at 1000 W/m^2
- Fig. 10.30 Dynamic performance of sensorless BLDC motor drive for single stage solar PV fed water pumping (a) PV array indices (b) BLDC motor-pump indices
- Fig. 10.31 Intermediate signals of sensorless BLDC motor drive for single stage PV fed water pumping, under dynamic condition at 1000 W/m^2
- Fig. 10.32 Experimental starting performance of sensorless BLDC motor drive for single stage solar PV fed water pumping at 1 kW/m^2
- Fig. 10.33 PV array power-voltage and current-voltage characteristics at (a) 1 kW/m^2 and (a-b) 200 W/m^2
- Fig. 10.34 Experimental steady state performance of sensorless BLDC motor drive for single stage solar PV fed water pumping at 1000 W/m^2
- Fig. 10.35 Experimental steady state performance of sensorless BLDC motor drive for single stage solar PV fed water pumping at 200 W/m^2
- Fig. 10.36 Experimental dynamic performance of sensorless BLDC motor drive for single stage solar PV fed water pumping under the variation of irradiance level from (a)-(c) 600 W/m^2 to 900 W/m^2 and (d)-(f) 900 W/m^2 to 600 W/m^2

LIST OF TABLES

Table 2.1	Standards, Testing and Quality Requirements for Solar PV Systems
Table 4.1	Switching States for Electronic Commutation of BLDC Motor
Table 4.2	Comparison of Conventional and Proposed Scheme
Table 6.1	Estimation of Cuk Converter Parameters
Table 6.2	Comparison of DC-DC Converters

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 ($\text{kg}\cdot\text{cm}^2$)
k	Magnitude constant of the phase lead compensator
k_1	Pump constant [$\text{W}/(\text{rad}/\text{sec})^3$]
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)
$S_1, S_2, \dots, S_6$	Switching pulses to the VSI
$S_1', S_2', \dots, S_6'$	Fundamental frequency pulses
T	Time constant of the phase lead compensator
T_e	Electro-magnetic torque (Nm)
T_L	Pump load torque (Nm)
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
$\Delta I_L, \Delta I_{L1}, \Delta I_{L2}$	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 ($^\circ$)

θ_1	Phase angle of utility grid voltage at fundamental frequency (°)
θ_d	Delay angle of filtered estimated back-EMF (°)
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.)