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MULTI-DIRECTIONAL MATRIX CONVERTER FOR LOW POWER APPLICATION USING FIELD-PROGRAMMABLE GATE ARRAY

SAMAN TOOSI

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By

SAMAN TOOSI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

July 2015

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DEDICATION

Dedication to:

My dear wife, Nooshin, without whose mind and heart this project could ever have been written. I also dedicated this to my parents and my family. My goals could never come true without all of you.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

MULTI-DIRECTIONAL MATRIX CONVERTER FOR LOW POWER APPLICATION USING FIELD-PROGRAMMABLE GATE ARRAY

By

SAMAN TOOSI

July 2015

Chairman: **Norhisam Misron, PhD**
Faculty: **Engineering**

With high robustness nature and simplicity design, the stand alone battery based systems found their way to supplies a remote local village or individual users. In modern stand-alone power system, power electronic converters have significant effect on system performance. Due to the rapid progress in power electronic component and integrated power modules, the power converters become a commercial alternative for modern low power applications. This evolution encourages a progressive development of Stand-Alone Battery Based System (SABBS) by reducing the number of converters and using the power of input sources in different operation modes.

In this study, the Multi-Directional Matrix Converter (MDMC) was developed using the five expected operation mode of stand-alone battery based system. Based on the conventional matrix converter structure, five configurations were proposed to control the power direction from power sources to loads. The indirect method with Space Vector Pulse Width Modulation (SVPWM) technique applied to the proposed MDMC configurations. However, the SVPWM could not inject power from generator and battery at the same time, since several vectors were utilized in one switching period.

Therefore, a novel modulation method introduced to change the function of MDMC from inverter to PWM rectifier, PWM rectifier to inverter, or inverter and PWM rectifier to inverter or PWM rectifier. The proposed modulation method acts based on average voltage over one switching period concept. Hence, in order to determine the duty ratio for each switch, the instantaneous input voltages are captured and compared with triangular waveform continuously. By selecting the proper switching pattern and changing the slope of the carriers, the sinusoidal input current can be synthesized with high power factor and desired output voltage. In the proposed model named Extended Direct Duty Pulse Width Modulation (EDDPWM) method, the number of time subinterval was increased to inject the power from the AC and DC sources to the load simultaneously. Thus, it increased the performance of the system and save more energy.

These five configurations and two modulation methods were simulated using MATLAB software and the results compared in term of THD, DC current ripple and ability to work in different operation modes. Based on the simulation results, the neutral connection MDMC with EDDPWM technique generated a set of digital commutation signals which are applicable for all operation modes. While, the switching signal set of SVPWM run the MDMC in one Mode at a time. The main emphasis in proposed full-silicon MDMC structure was minimizing the total number of bidirectional switches and subsystems to achieve higher operating efficiency and more compact designs, and to reduce weight and volume of the resultant systems.

On the other hand, in this study the Xilinx's System Generator development tool was used to implement the EDDPWM method in FPGA. Moreover, high level design tools were employed to decrease the development time required for implementing the modulation methods in FPGA. This study also derived necessary equation for proposed modulation method as well as detail of analysis and modulation algorithm. The theoretical and modulation concepts have been verified in MATLAB simulation and experimental test.

Abstrak thesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENUKAR MATRIKS PELBAGAI HALA UNTUK APLIKASI KUASA RENDAH DENGAN MENGGUNAKAN FIELD-PROGRAMMABLE GATE ARRAY

Oleh

SAMAN TOOSI

Julai 2015

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Sifat ketahanan yang tinggi dan reka bentuk ringkas membolehkan sistem bateri berdiri sendiri mampu membekalkan kuasa sebuah kampung tempatan yang terpencil dan juga pengguna individu. Dalam sistem kuasa berdiri sendiri moden, penukar kuasa elektronik memberi impak ke atas prestasi sistem tersebut. Kemajuan pesat dalam kuasa komponen elektronik dan modul kuasa bersepadu membolehkan penukar kuasa menjadi alternatif komersial untuk aplikasi kuasa rendah yang canggih. Evolusi ini menggalakkan perkembangan progresif dalam Sistem Bateri Berdiri Sendiri (SABBS) melalui peningkatan prestasi sistem menggunakan kuasa input kepada semua kaedah operasi.

Penukar Matriks Pelbagai Hala (MDMC) telah dibangunkan berdasarkan lima jangkaan mod operasi sistem bateri berdiri sendiri. Berdasarkan penukar matriks pelbagai hala konvensional, lima konfigurasi telah dicadangkan untuk mengawal arah kuasa daripada sumber kepada beban. Kaedah tidak langsung dengan teknik Space Vector Pulse Width Modulation (SVPWM) digunakan untuk konfigurasi MDMC yang dicadangkan. Walaubagaimanapun, SVPWM tidak dapat menyuntik kuasa dari generator dan bateri pada masa yang sama, memandangkan beberapa vektor digunakan dalam satu tempoh pensuisan.

Oleh sebab itu, satu kaedah baru telah diperkenalkan untuk menukar fungsi MDMC daripada penyongsang kepada penerus, penerus kepada penyongsang atau penyongsang dan penerus kepada penyongsang atau penerus. Kaedah modulasi yang dicadangkan adalah berdasarkan konsep voltan purata lebih daripada satu tempoh pensuisan. Oleh yang demikian, untuk menentukan nisbah duti untuk setiap pertukaran, voltan input dapat diambil dan dibandingkan dengan bentuk gelombang segi tiga secara berterusan. Dengan memilih corak pensuisan yang betul dan menukar penghantaran lereng , input sinus boleh disintesis dengan faktor kuasa yang tinggi dan voltan keluaran yang diingini. Sistem yang dicadangkan ini dapat meningkatkan prestasi sistem dengan

menyuntik sumber kuasa untuk sistem dari AC dan DC pada masa yang sama. Oleh itu, sistem ini dapat memanjangkan jangka hayat bateri dan menjimatkan tenaga.

Kelima-lima konfigurasi dan dua kaedah modulasi telah disimulasikan oleh perisian MATLAB dan hasil kajian telah dibandingkan dalam terma THD, riak arus DC dan kebolehan untuk bertindak dalam mod operasi yang berbeza. Berdasarkan hasil kajian daripada simulasi, teknik sambungan neutral MDMC dengan EDDPWM telah menghasilkan satu set penggantian isyarat digital yang boleh diaplikasi kepada semua mod operasi. Di samping itu, isyarat pensuisan daripada SVPWM mengaktifkan MDMC dalam satu mod pada satu masa. Penekanan utama dalam cadangan sepenuh silikon struktur adalah untuk mengurangkan jumlah suis dua hala dan subsistem agar dapat meningkatkan kecekapan operasi dan lebih padat dalam reka bentuk dan mengurangkan berat serta isi padu sistem.

Selain itu, dalam kajian ini *Sistem Penjana pembangunan Xilinx* telah digunakan untuk melaksanakan kaedah EDDPWM dalam FPGA. Tambahan pula, kajian ini juga menggunakann alat rekabentuk bertahap tinggi yang dapat mengurangkan masa pembangunan yang diperlukan untuk melaksanakan kaedah modulasi penukar kuasa menggunakan FPGA Kajian ini juga memperoleh persamaan yang diperlukan untuk kaedah modulasi dicadangkan secara terperinci daripada analisis dan algoritma modulasi. Teori dan modulasi konsep yang dikemukakan telah disahkan dalam simulasi MATLAB dan eksperimen.

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I would like to thank to my dear wife Nooshin, whose supports and continued encouragements have helped me to achieve and to accomplish my dream. I also would like to thank my parents and my family for their support to achieve my goal.

I certify that a Thesis Examination Committee has met on 10th July 2015 to conduct the final examination of Saman Toosi on his thesis entitled "Multi-Directional Matrix Converter for Low Power Application Using Field-Programmable Gate Array" in accordance with Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the candidate be awarded the Doctor of Philosophy.

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Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
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LIST OF ABBREVIATIONS

AC	Alternating current
ADC	Analog-to-digital converter
BBPHS	Battery Based Pico-Hydropower Systems
CSR	Current-Source Rectifier
DC	Direct current
DDPWM	Direct Duty ratio Pulse-Width Modulation
DSP	Digital Signal Processor
EDDPWM	Extended Direct Duty Pulse-Width Modulation
ELCs	Electronic Load Controllers
EV	Electric Vehicles
FiT	Fit-in Tariff
FPGA	Field-Programmable Gate Array
GHGs	Greenhouse Gases
IGBT	Insulated-gate bipolar transistor
kW	Kilo Watt
MC	Matrix converter
MDC	Multi Directional Converter
MDMC	Multi-Directional Matrix Converter
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
MW	Mega Watt
PLL	phase locked loop
PV	Photovoltaic
PWM	Pulse-Width Modulation
RE	Renewable Energy
RM	Ringgit Malaysia
SABBS	Stand-Alone Battery Based System
SEDA	Sustainable Energy Development Authority
SOC	State-Of-Charge
SVM	Space Vector Modulation
SVPWM	Space Vector Pulse-Width Modulation
THD	Total Harmonic Distortion
VHDL	Hardware Description Language
VLBBC	Voltage DC-Link Back-to-Back Converter
VSC	Voltage-Source Converters
C_f	Input filter capacitor per phase per phase
d_{ij} $(i=a,b,c, j=R,S,T)$:	Duty cycle between phase i and phase j
D	Transformation matrix
D^{-1}	Inverse transformation matrix of the MC
$D_I(\omega_o)$	Inverter transfer matrix
$D_R(\omega_i)$	Rectifier transfer matrix
i_{or}, i_{os} , i_{ot}	Three phase output currents of MDMC
$I_{s\text{-}ref}$	Reference current
$i_{\alpha\beta}$	Current vector transferred to the MC output frequency frame
i_{abc}	three-phase MC input voltages
i_{RST}	three-phase MC output voltages
L_f	Input source plus filter inductance per phase

L_l	Output load inductance
$L_{L\text{-}dc}$	Inductor load at DC side of MDMC
$L_{L\text{-}ac}$	Inductor load at AC side of MDMC
m_v	Modulation index of voltage source inverter
m_c	Modulation index of current source rectifier
MN	Instant minimum value of AC input phase of MDMC
MX	Instant maximum value of AC input phase of MDMC
MD	Instant medium value of AC input phase of MDMC
NEG	Instant negative value of DC input phase of MDMC
POS	Instant positive value of DC input phase of MDMC
q	Voltage ratio
R_f	Input source resistance per phase
R_l	Output load resistance
$R_{L\text{-}dc}$	Resistor load at DC side of MDMC
$R_{L\text{-}ac}$	Resistor load at AC side of MDMC
S	instantaneous switching function matrix
S^T	transpose of matrix S
S_{ij} $(i=a, b, c, j=R, S, T)$	Switch between phase i and phase j
T_α	time spent in vector I_α
T_β	is the time spent in vector I_β
T_s	Switching period
T_{R2}, T_{R3}, T_{R4}, T_{R5}, T_{R6},	Switching pattern time subintervals
Vpn	Imaginary dc-link voltage
V_{ab}, V_{bc} V_{ca}	Line-to-line Three-phase input ac voltages of generator
V_{RS}, V_{ST}, V_{TR}	Line-to-line Three-phase output voltages of MDMC
V_{Batt}	Battery terminal voltage
V_j, i_j $(j=R,S,T)$	Three-phase MC output voltage
Vs_i, i_i $(i=a,b,c)$	Three-phase MC input voltages
v_{sab} , v_{sbc}, v_{sca}	Three phase input line-to-line voltages of MDMC
ω_o	MC output angular speed
ω_i	MC input angular speed
ω_c	Cut-off angular speed
X_{0q}	q-axis voltages or current
X_{0d}	d-axis voltages or current
$\bar{X}_{RST}$	Three-phase MC output voltage or current
$\bar{X}_{abc}$	Three-phase MC input voltages or current
αi	Input voltage angle
θ_{CSR}	Angle between the reference vector and the closest clockwise state vector in current source rectifier
θ_{VSI}	Angle between the reference vector and the closest clockwise state vector in voltage source inverter
δ_{DT}	dead-time of the single commutation

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Stand-alone renewable power systems have recently increased in demand for low power application such as local village or individual users that are not connected to a national grid [1-3]. Battery banks are required in a stand-alone renewable power system to supply the load continuously, where several separate power electronic converters are conventionally utilized [4]. Higher system efficiency, faster response time, lower cost, and compact packaging with central controller algorithm are the most significant feature of SABBS. Therefore, many multi-port power converters have been suggested recently for several different applications such as hybrid electric vehicles [5], aerospace power systems [6], and hybrid energy storage systems [7]. However, the size, cost increased and efficiency decreased due to multiple-stage conversion through the converters and transformers. These converters utilize a different switching pulse width modulation (PWM) signal in different operation modes, resulting in complicated driving and control circuitry. This evolution encourages a progressive development in Stand-Alone Battery Based System (SABBS) with replacing all the rectifier, and inverter with single multi directional power converter that can control the power flow direction.

Multi Directional Converters (MDC) has been proposed to reduce the number of converter and control the power flow direction in SABBS. The number of inverter and converter has been changed based on the variety in load type and number of power supply that are connected to the system [7-11]. DC-link back-to-back converter and matrix converter are the most common type of converters used in hybrid system and SABBS with variable speed turbines [12-15]. Most desired feature of multi directional converter can be fulfilled by using Matrix Converter (MC) structure. In the MC, several bidirectional switches are used to couple the power sources to load side. With proper switching method, the bidirectional switches in MC can be utilized as inverter or rectifier. Therefore, in this study the multi directional converter was developed based on matrix converter structure.

Specially, this study is dedicated to analyse and derive the necessary equation of new carrier based pulse-width modulation for proposed Multi Directional Matrix Converter (MDMC) structure. The preliminary concepts of a new carrier based PWM strategy, named direct duty ratio PWM (DDPWM), is presented by Li et al. (2008) [16]. This study aims to control the power flow direction and to inject the power from DC and AC power supplies to the loads at the same time by proposing the suitable MDMC structure and increasing the number of time intervals of direct duty pulse width modulation method. The novel switching method is expected to change the function of converter in different operation modes from inverter to rectifier, rectifier to inverter, and rectifier and inverter to inverter or rectifier.

The proposed converter topology and new modulation method are expected to reduce the number of power converters in battery based systems when the proposed converter can act as rectifier and inverter at same time. Based on the above concept, the objectives and methodology of the study are defined. An outline of the thesis concludes this introductory chapter.

1.2 Problem Statement

In SABBS, previous studies have proposed Multi Directional Converter (MDC) based on two or three types of conventional rectifier and inverter with high-frequency transformer to control the power flow from input supplies to the loads. The number of inverter and converter has been changed based on the variety of load type and number of power supply that are connected to the system [7-11]. However, the size and the cost are increased and the efficiency is decreased by multiple-stage conversion through the converters and transformers. These converters utilized a different switching signal in different operation modes, resulting in complicated driving and control circuitry. [3, 8, 17-19]. The size and the volume of a system can be reduced to 1/2 or more, and the efficiency can be increased to 1/3 or more by combining the characteristic of all power converters in one simple full-silicon structure in a compact design converter. In addition, the system driver and control circuit complexity can be reduced to 1/2 or more using a general switching signal for all operation modes.

The main purpose of this study is to develop a multi-directional matrix converter based on the stand-alone battery based system to control the power flow direction from each power supplies to each loads. This study also proposed a new modulation method to change the function of multi-directional matrix converter from inverter to rectifier, rectifier to inverter, and rectifier and inverter to rectifier or inverter.

1.3 Objectives

In terms of knowledge creation, the project involves research into design of a novel multi-directional matrix converter and novel carrier based pulse-width modulation method. In order to achieve this, the research work is divided into the following specific research objectives:

1 To develop a multi-directional matrix converter based on stand-alone battery based system operation modes.

2 To design a simple and compact multi-directional matrix converter to control the power flow between each individual input and output with minimum number of switching devices and their driver circuit components.

3 To change the function of multi-directional matrix converter as an inverter, a rectifier or inverter and rectifier in different operation modes by developing a new modulation method.

4 To synthesize the input current and output voltage to control the input power factor and to inject the power from AC and DC sources, simultaneously by using the proper switching pattern.

5 To impliment the proposed modulation method in FPGA and to examine the multi-directional matrix converter in different operation modes.

1.4 Scope of Work

The focus of this research is to develop a multi-directional matrix converter which can control power flow from generator to load, generator to battery and battery to load in standalone battery based system. Since the system needs to be design based on the generator characteristic, the system ratings and performance limits are referred to the previous researcher study that developed the generator.

Initially, in this study, the expected operation modes of stand-alone battery based have been derived. Then, based on the conventional matrix converter configuration, a few possible configurations have been proposed and simulated in MATLAB software. The space vector pulse with modulation (SVPWM) is a well-known modulation method for matrix converter. Thus, this method was used to control the switching state of proposed MDMCs in the current study. Then, the output waveform results were compared in term of THD, DC current ripple and ability to work in different operation modes.

To inject the power from generator and battery simultaneously and generate a set of switching signal for all operation modes, a novel carrier based PWM strategy is developed without complex calculations and lookup tables. In addition, the number of bidirectional switches in MC structre has been increasd based on the type and number of output and input which are connected to the system. The proposed modulation method determines the switching state of each output phases by employing the input DC phase voltages and input AC phase voltages based on the average voltage over one switching cycle concept. At the first step of each switching period, in order to generate the corresponding switching signals, the duty ratio values for each output phase was calculated and the results compared with the continuous triangular waveform.

In this study the Xilinx virtex-6 FPGA DSP development kit is used as the main controller and six 12bit ADC chip (LTC2366) is employed to monitor the voltage and current of the system instantaneously. The integrated software design platform containing System Generator 14.7 for DSP, ISE 14.7 from Xilinx, and MATLAB with Simulink from MathWorks was used to generate the bit file for FPGA.

Based on the stand-alone battery based system behavior, five different operation modes have been considered in this study. Therefore, the implemented modulation method on MDMC experimental setup was tested in these five operating mode. Since the switching frequency of the MDMC is high and two different frequency sources supply

the loads, simultaneously, the real challenge in generating the signal is to prevent the short circuit in source side and open circuit in load side. In addition, the AC source leg and DC source leg should not connect to the loads at the same time. This means that the SABBS has to switch between the sources with a continuous power flow without interrupting the loads and misstep.

1.5 Contribution of the Thesis

1. Based on the average voltage over one switching cycle concept, the extended direct duty pulse-width modulation (EDDPWM) approach was introduced. The procedure outlined herewith is one of the major developments in this study. In this study, essential equation for proposed switching method as well as the detail of analysis and modulation algorithm was derived. This modulation method was used to control the power flow direction in novel multi-directional matrix converter in all operation modes.

2. None of the previous researchers attempt to control the direction of power flow with single converter in stand-alone battery based system due to the structure and modulation constrains. This work could pave way for further research in the stand alone battery based system design and the design aspects also can be extended to the design of other battery based application. This study covers the design procedure of five difference configuration of MDMC with two well-known modulation methods. Principles and limitations of matrix converter have been considered in these designs.

3. The proposed MDMC reduced the size and volume of system by combining the characteristic of all power converters in one simple and compact power converter.In this study, the proposed MDMC acted as rectifier, inverter, and rectifier and inverter at different operation modes. In addition, demand in AC load was supplied by injecting the power from the AC source and DC source at the same time. Thus, increase the performance and save more energy.

4. Lastly, Verification of the proposed EDDPWM algorithm is obtained for a multi-directional matrix converter, both through the simulations and experiments. In experimental verification, the EDDPWM algorithm is implemented in FPGA using integrated software design platform containing System Generator 14.7 for DSP, ISE 14.7 from Xilinx, and MATLAB with Simulink from Math Works.

1.6 Thesis Outline

The thesis consists of five chapters in which each chapter has continuous flow of the research study. The overview of each chapter is described as followed:

Chapter one gives a brief introduction on the research topic which is discussed on the foundation of the research topic. It is followed by problem statement and objectives of the study to set the focus of the research. Subsequently, the scope of work is highlighted to give a clearer picture of the study.
Chapter two provides the explanation on the basic theory and principle that is related to the research along with reviews on research related published works. This chapter begins with introduction of the stand-alone renewable power system as the subjective of the design, and continues with the introduction on the MC topology and its switching method. The overview on the matrix converter commutation strategy is described to understand the switching behavior of system. Finally, an overview of multi directional converter and practical issues that applied in this study is briefly described. The chapter ends with the summary of the chapter.

Chapter three presents the theory, modulation method, and methodology which is employed in this research and derives the results for the succeeding chapter. The chapter starts with the introduction of the variable speed power system and then followed by the overview of the research flow. The design and construction of the multi-directional matrix converter is described by presenting the sub-circuits and sub-control systems. The description followed by the theory of EDDPWM which is proposed by researcher in order to satisfied the objective. Furthermore, this chapter highlighted the development of MDMC system for SABBS from circuit design until the built of prototype.

Chapter four presents the results obtained from the Matlab simulink and experimental prototype of the research. This chapter analysis and compare the simulation result for both SVPWM and Extended direct duty PWM. Finally, the experimental setup has been run in different operation modes. In order to evaluate the dynamic response of system, the output reference voltage and input frequency of generator have been varied during the experimental test.

Chapter five represents the conclusion of research findings for the Multi-directional matrix converter. This chapter also summarizes the thesis main points and contributions, and proposes future directions for research.

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