International Journal of Power Electronics and Drive System (IJPEDS)
Vol.2, No.2, June 2012, pp. 170~176
ISSN: 2088-8694

A Multilevel Quasi Matrix Converter Design for SRM Drives In EV Applications

Syeda Fatima Ghousia*
* Departement of Electrical and Computer Engineering, University of Windsor, Canada

Article Info

Article history:

Received Feb 9th, 2012
Revised May 24th, 2012
Accepted May 29th, 2012

Keyword:

Electric motor
FE analysis
Matrix converter
Multilevel converter
Switched reluctance motor

ABSTRACT

This paper presents a novel idea of developing an absolute, general choice multilevel asymmetric power converter for switched reluctance motor (SRM) drive suitable specifically in electric vehicle applications. For SRM drives, the suitability of a particular inverter circuit changes with the motor geometry. It is in contrast to the drives operating with sinusoidal voltages and currents where the inverter topology is independent of the motor design. Specifically, in the case of SRM, the number of the stator/rotor poles and the related issues of the dwell angle and current overlap parameters affect the inverter choice. The multilevel power converters open up a great deal of possibilities in control and can be used to achieve flexible current profiling but with the added benefit of lower switching frequencies and hence less converter losses. The idea is to use a matrix converter topology for finer control on flexible current profiling with three terminals of dc voltage source at the input. To illustrate the potential benefits of this converter, with SRM for EV applications, a Simulink model of proposed multilevel matrix converter was tested in interface with finite element model of the SRM.

Corresponding Author:

Syeda Fatima Ghousia
University of Windsor
401 Sunset Ave, Windsor, Ontario, Canada N9B3P4 (519)253-3000
e-mail: sfghousia@gmail.com

1. INTRODUCTION

Two of the major problems associated with overall SRM performance are high torque ripple and excessive machine vibration leading to undesirable acoustic noise. Both issues can be addressed by introducing some form of current profiling when energizing the phase. The multilevel conversion capability offers the possibility of reduced high-frequency torque ripple without excessive power converter switching losses. However, SRM drives have still not yet found broad industry acceptance, they continue to attract research interest, stimulated mainly by the promise of simple and rugged motor construction, the possibility of high motor speeds, high torque-to-inertia ratio, an inverter with a reduced number of power switches, and an overall robust drive. This research activity has resulted in a number of inverter topologies, some of which have been described in the literature [1-6].

For SRM drives, the suitability of a particular inverter circuit changes with the motor geometry. It is in contrast to the drives operating with sinusoidal voltages and currents. where the inverter topology is independent of the motor design. Specifically, in the case of SRM, the number of the stator/rotor poles and the related issues of the dwell angle and current overlap parameters affect the inverter choice. The multilevel power converters open up a great deal of possibilities in control and can be used to achieve flexible current profiling but with the added benefit of lower switching frequencies and hence less converter losses.

Among the popular SRM drive converter choices, if the current overlap can be restricted to speeds where the motor-magnetizing voltage is below approximately one half the dc-link voltages, the most advantageous circuit is Miller Circuit. However, since the majority of SRMs operate with a current overlap over most of their speed range, the classic inverter becomes most attractive topology in that case. Also the SRM starting torque very much influences the inverter rating. In order to provide a rated torque starting for any rotor position, the inverter rating may have to be increased several times over the value required by the motor-rated power. Conversely, if the starting currents are limited to their rated value, the starting torque is severely reduced for worst-case rotor initial position. To achieve operation at higher dc-linkvoltages, a multiple voltage level approach needs to be adopted where a power converter can be realised using lower voltage rated power switches. This approach will also allow operation at higher switching frequencies than would otherwise be possible with much high voltage power switches.

The need for a high PWM frequency is not as strong in SRM drives as in induction motor drives because the total phase inductance-is important than just the leak inductance like in IM. Freewheeling inverter states also permit reduced PWM frequency for the same current ripple. Therefore, in order to make SRM popular on industrial and manufacturing level, the need for improvement in SRM converter drives is direly needed where extremely close design coordination between the motor, the control and the inverter is possible. That coordination has to be much closer than in the case of brushless drives and indicates that SRM applications may be more successful if special purpose or OEM-type drives.

Therefore, a novel multilevel matrix converter is presented in the paper. In order to prove the validity of the proposed topology, a simple output voltage control strategy is described and utilized. Operation principles and current commutation strategies are analyzed in detail. The operation with simulation model developed with experimental results of the 1hp switched reluctance motor is tested experimental results are provided to validate the proposed converter.

2. CLASSICAL SRM MULTILEVEL CONVERTER TOPOLOGIES

Multilevel converters are finding increased attention in industry and academia as one of the preferred choices of electronic power conversion for high-power applications. Although it is an enabling and already proven technology, multilevel converters present a great deal of challenges, and even more importantly, they offer such a wide range of possibilities that their research and development is still growing in depth and width. Researchers all over the world are not only contributing to further improve energy efficiency, reliability, power density, simplicity, and cost of multilevel converters, but also broaden their application field as they become more attractive and competitive than classic topologies.

The matrix converter belongs to the direct conversion family since it directly connects the input ac lines to the output ac lines through bidirectional switches and without need of energy storage devices, such as capacitors or inductors. As a consequence, their strengths are important weight/volume reduction and inherent four-quadrant operation, which are desirable features for transportation systems (electric vehicles, more electric aircraft, military vehicles, etc.). The lack of energy storage devices does not favor the possibility to arrange semiconductors in such a way that higher voltages and more voltage levels can be reached. This is why this topology was limited to low power and a small application scope. However, recently several multilevel matrix converter topologies have been reported. Most of them are actually based on the three classic multilevel topologies: the Classsical Matrix Converter, the Indirect Matrix and the FC matrix converter

3. CONCEPT OF PROPOSED MULTI-LEVEL QUASI MATRIX CONVERTER FOR NON-SINUSOIDAL CURRENT MOTORS

For more than 20 years, the matrix converter has been discussed academically. The traditional matrix converter offers an all silicon solution for AC-AC power conversion as shown in Fig.1. The Sparse Matrix Converter is used to simplify when all of the switching states are not required for supplying loads in which only one current direction is required. The focus of matrix converter drives research has largely been on sinusoidal motors (induction, permanent magnet synchronous and the like). However, it is also possible to use the matrix converter to drive non-sinusoidal output currents, typically with nearly rectangular output current waveforms [7]. Such non-sinusoidal excitation waveforms can also lead to increased torque per ampere realizations with particular motor designs.

For EV applications, the converter is designed to be operated with 3 level DC voltage connected through the battery which is contrary to classic matrix converter design, therefore, the converter is named as “Quasi” matrix converter. 3-level DC to 4-phase matrix converter consists of an array of 16 bi-directional switches arranged so that any of the output lines of the converter can be connected to any of the input lines as shown in Fig. 2. The switches are modulated in such a way as to generate the desired output waveform.

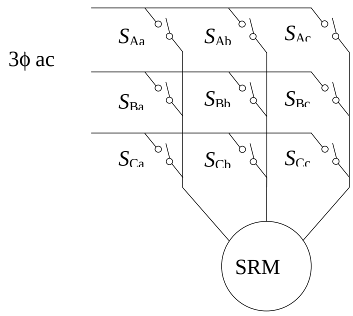

Fig. 1 A Classical AC-AC Matrix Converter Circuit

The inherently bi-directional matrix converter regenerates energy, which is very desirable in EV applications. It draws sinusoidal input current and depending on the modulation technique, it can be arranged that unity displacement factor is seen at the supply side irrespective of the type of load. The size can be greatly reduced compared to conventional technologies since there are no large capacitors or inductors to store energy. Recently there has been considerable interest in the potential benefits of matrix converter technology, especially for applications where size, weight and long term reliability are important factors such as electric powertrains.

Number of phases is not limited. By using nine bidirectional switches, the matrix converter is able to create a variable output voltage system of a desired frequency and magnitude. Normally, a BDS is built by two collector– or emitter-connected insulated gate bipolar transistors (IGBTs). This enables a high switching frequency which is necessary to decouple input and output systems of the matrix converter. Altogether, 18 IGBTs for the BDS are more than 12 IGBTs needed for a dc-voltage link converter with power regeneration. However, it is a fact that the size of IGBT chips needed to build up a comparable matrix converter in power, is reduced[8]. A further aspect is the reduction of unit volume by renunciation of a chopper resistor and a live time limiting dc-link reactance. The input power factor can be adjusted with little reduction to the active power transfer ratio. The sinusoidal voltage transfer ratio is limited to 0.86 on principle. To handle concerning the commutation behaviour and at pulse-off, a reliable protection at pulse-off is required. Multilevel technology is a good solution in medium or high voltage power conversion. However, the existing multilevel converters have their limitations such as cascaded cell multilevel converter requires two split DC supplies while the capacitor clamping converter has to balance the capacitors while diode clamping uses half the DC-link voltage and many of the switching states cannot be used.

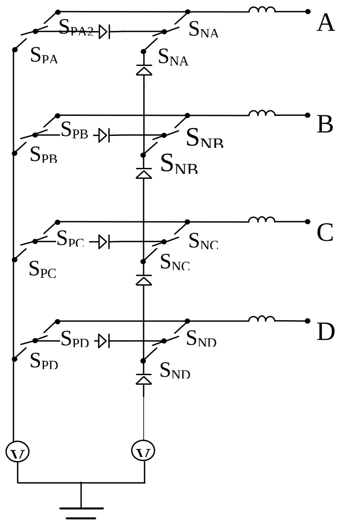

Fig. 2. Configuration of dc-ac sparse matrix Converter.

4. MATHEMATICAL MODEL AND DESIGN OF PROPOSED CONVERTER

This paper demonstrates a technique to drive an open loop 8/6 four-phase Finite Element model of the SRM using a quasi multi-level sparse matrix converter using RB-IGBTs. A simple modulation strategy has been developed to produce the step multi-level output currents for each phase independent of each other keeping the fault-tolerant characteristics of SRM. The configuration of the proposed multilevel matrix converter is shown in Fig 3. Since the inputs of multilevel converter is connected to voltage sources, the input lines must not be short circuit, and due to the inductive nature of the load, the output loops must not left opened. If the switching functions of switches in Fig. 4, are defined as (1) shown at the bottom of the next page. The general direct forms of voltage and current equations of matrix converters are given by (1)-(2). With these constraints, the proposed multilevel matrix converter in Fig. 3 finds 729 available switching modes. The switching schemes can generate the state table. The state tables show the options for each phase.

$$\underbrace{\begin{bmatrix} u \\ v \\ w \end{bmatrix}}_{v_o} = \begin{bmatrix} u^* + v_z \\ v^* + v_z \\ w^* + v_z \end{bmatrix} = \underbrace{\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}}_{M} \underbrace{\begin{bmatrix} R \\ S \\ T \end{bmatrix}}_{v_i} \equiv v_o = \mathbf{M} v_i \ldots (1)$$

$$\underbrace{\begin{bmatrix} i_R \\ i_S \\ i_T \end{bmatrix}}_{i_i} = \underbrace{\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}^T}_{M^T} \underbrace{\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix}}_{i_o} \equiv i_i = \boldsymbol{M^T} i_o \ldots (2)$$

$$where\ 0 \le m_j \le 1, \sum_{j=i}^{3} m_j \quad i = \{1, 2, 3\}, j = \{1, 2, 3\}$$

At any instant, the input voltages can be sorted into the maximum, median and minimum voltages. In the discussion below, a particular combination of enabled switch connections between input lines and the output legs is called a switch state. The switching rule is as follows: During motoring operation, the positive leg is switched between the median and maximum voltages via the forward conducting RB-IGBTs. The negative leg is switched between the median and minimum voltages via vM is the DC output phase voltage and is close to the value of the phase back-emf of the load. During a given switching period, all the voltage levels may be assumed to be invariant. Clearly, at any instant, each of the two legs must be connected to any one of the input lines because they are inductive in nature.

Fig. 3. (a) Configuration of ac-ac sparse matrix Converter. (b) Configuration of dc-ac sparse matrix multi-level Converter

In the discussion below, a particular combination of enabled switch connections between input lines and the output legs is called a switch state. The switching rule is as follows: During motoring operation, the positive leg is switched between the median and maximum voltages via the forward conducting RB-IGBTs. The negative leg is switched between the median and minimum voltages via the backward conducting RB-IGBTs. Let the variable x denote the switch position of the positive leg; x = 0 denotes a connection to the median voltage and x = 1 denotes a connection to the maximum voltage as per the switching rule above. Similarly, let y denote the switch position of the negative leg; y = 0 denotes a connection to the median voltage and y = 1 denotes a connection to the minimum voltage as per the switching rule above.

There are four allowed switch states denoted by (x, y) = (0, 0), (0, 1), (1, 1) and (1, 0). These states are shown in Fig. 5. Let _xy be the duty cycle of the state with the positive leg at x and the negative leg at y. During a switching cycle, the converter goes through all four states. In Fig. 2, one of the output phases is assumed to be inactive, carrying zero current. In this case, one of the other active output phases carries positive current and the other active phase can also carry negative current. At any instant, the desired voltages levels are obtained for different phases into the maximum, median and minimum voltage levels if three levels are desired.

5. ANALYSIS OF COMMUTATION STRATEGIES FOR ALLOWED SWITCHING STATES

The knowledge of matrix converter commutation is fundamental in understanding the difficulties of the converter. On a single output phase, as shown in Fig. 3 the commutation process can be studied. In contrast to the well-known dc-voltage link converter, a commutation cannot be initiated without any knowledge of the commutation conditions. To perform a commutation, the voltage between the involved BDS or the load current must be measured. For a commutation, only the sign of one of the two quantities is important, as the sign determines the commutation sequence. A well-selected sequence enables a commutation without short circuiting the input voltages or breaking the load current. In Fig. 4, all applicable sequences are listed in its legal quadrants for 4-level output. The shown sequences are “four step commutations.” This means that, before a commutation, a whole BDS in an output phase is switched on. After a commutation has passed, this BDS is off and a BDS connected to a different input phase is switched on. There are 12 ways to perform a commutation. Fig. 4 can explain the paths from a starting situation with BDS 11 switched on. In order to deal with the delay times of the IGBTs, a little dead time is kept between each commutation step. The two sequences on the axis only need the evaluation of the sign of the input voltage but are independent of the current sign. These sequences are named “voltage commutation”. The two sequences on the axis only need the evaluation of the sign of the load current and are named “current commutation”.

The remaining sequences need the evaluation of both signs. This fact makes them harder to handle. As a result, voltage or current commutation should be used. Another idea to achieve a commutation is the “two-step commutation.” The basic idea is to switch only the IGBT in a BDS which will lead the load current. In addition, all IGBTs in the matrix which will not conduct are switched on. This will reduce the total time of the commutation and opens additional free-wheeling paths for the load current in case of error. The two-step commutation can be voltage controlled or current controlled. The commutation logic deals only with the switching commands of the PWM generator and the utilized sign of commutation.

The matrix converter should mimic a classical four phase inverter while driving an SRM motor. In a rotation through 360 electrical degrees, each phase of the motor goes through four distinct back-emf regions. These regions determine the conduction mode of the phase leg X (= u, v or w) as shown in Fig 5. Let the variable x denote the switch position of the positive leg; x = 0 denotes a connection to the median voltage and x = 1 denotes a connection to the maximum voltage as per the switching rule above. Similarly, let y denote the switch position of the negative leg; y = 0 denotes a connection to the median voltage and y = 1 denotes a connection to the minimum voltage as per the switching rule above. There are four allowed switch states denoted by (x, y) = (0, 0), (0, 1), (1, 1) and (1, 0). These states are shown in Fig. 4.

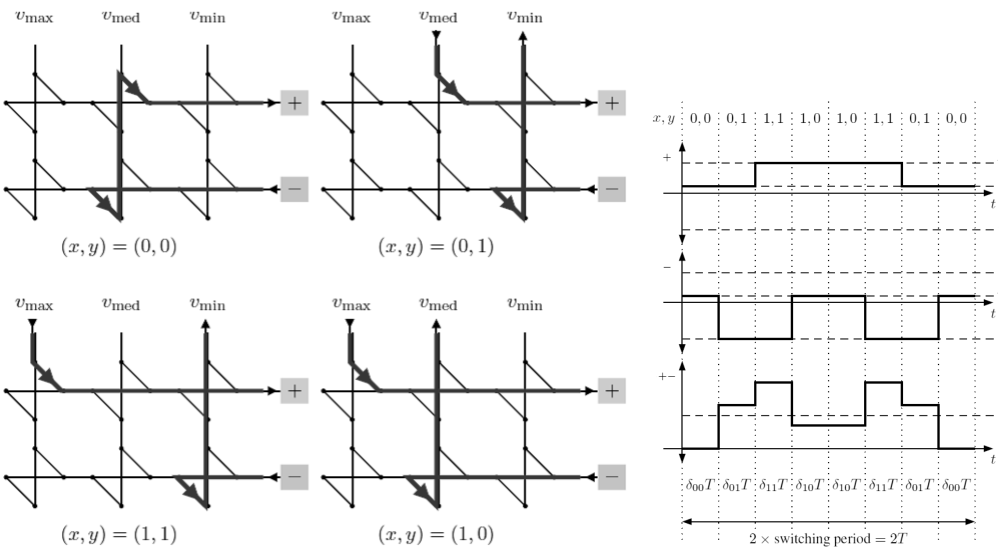

Fig. 4. Theory of commuataion strategies for allowed switching states. a) Transition of switching states diagrams (b) Timing diagrams.

Let *xy* be the duty cycle of the state with the positive leg at x and the negative leg at y. During a switching cycle, the converter goes through all allowed states. In order to get a leg-leg voltage of 2Im at the output, the duty ratios have to be suitably chosen. Kirchhoff’s voltage law is averaged over one switching cycle to give 2Im. where m is the modulation index. These duty ratios ensure that the average of the output voltage is a fixed DC value. This is actually a carrier-based scheme similar to elementary PWM schemes for inverters.

6. TESTING SETUP AND VALIDATION MODES WITH VIRTUAL MACHINE INTERFACE

The proposed sparse matrix converter is used to run the SRM under the conditions stated in Table 1. In this section, a brief description of the implementation of the system in simulations and in the virtual machine interface is given. Fig 5 shows the actual switched reluctance motor which is simulated for Finite Element Analysis. Table 1 states the machine characteristics of the SRM used.

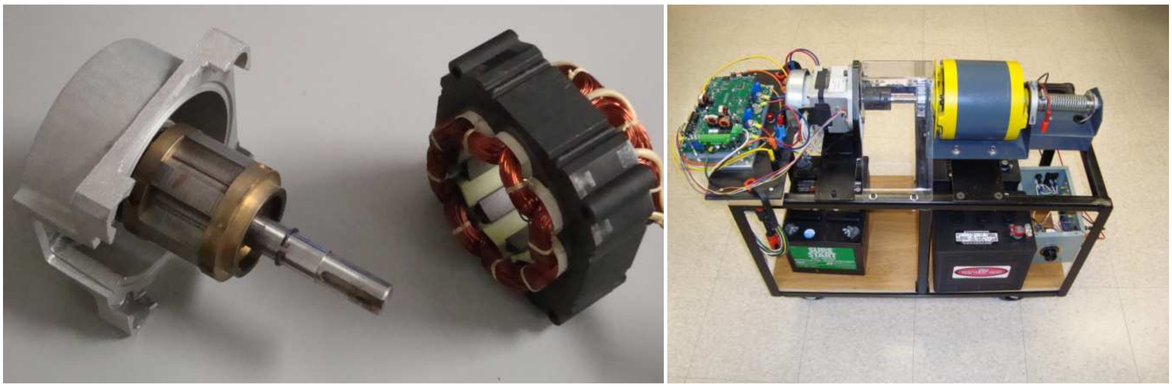

Fig. 5. Experimental Switched Reluctance motor used for simulation model. (a) The rotor and stator snapshots. (b) Experimental setup.

Table 1: Operating Conditions for the testing of the proposed Converter under static and dynamic FE Analysis

Characteristics	Value
No. of Stator/poles	8/6
No. of phases	4
Rated power	1 hp
Rated Current	45A
Rated Speed	3000rpm
Loading conditions	No Load
Input	±24V dc
Output	Step current pulses

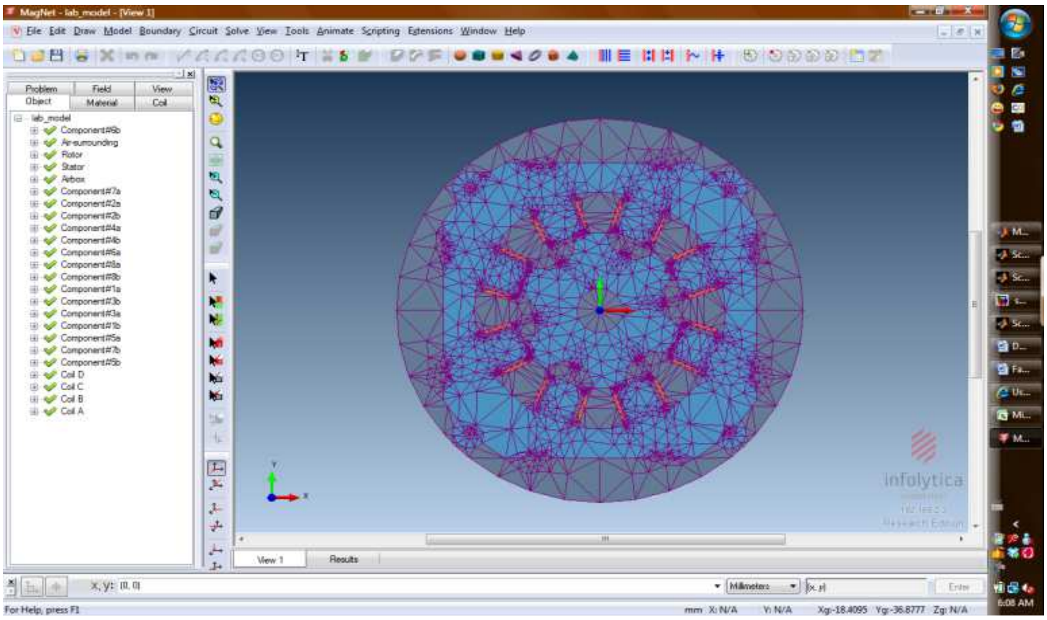

Fig. 6. Switched Reluctance motor simulation model.

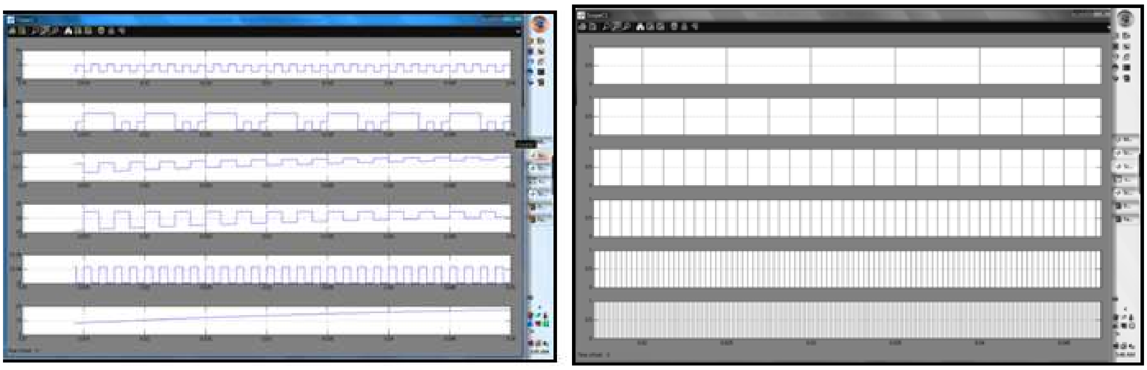

Fig.7. Multi-level output waveforms from the Matrix Converter circuit generated from a single DC power supply (Randomly selected gate signals). (a) A glance at 4 independent phase current profiles. (b) timing diagram of switches.

7. CONCLUSIONS

This paper proposes a multi-level quasi-sparse converter of the SRM that is a modified circuit from an AC-AC sparse matrix converter for lighter weight, battery operated, energy efficient applications such as EV applications. When SRM run, the higher voltage could be also applied to phase windings and obtain faster excitation current and demagnetization current. So it can also improve current tracing effect, dynamic performance and efficiency and reduce the torque ripple similarly without using any bulky short life span passive components.

ACKNOWLEDGEMENTS

I like to acknowledge my Professor Dr. Narayan Kar, Canada Reaserch Chair Tier II at C.H.A.R.G.E. Labs, Department of Electrical and Computer Engineering, University of Windsor for his guidance, facilities, continuous encourgament and motivation

REFERENCES

[1] J. Bauer, "Development of a compact matrix converter," Acta Polytechnica, Vol 49, No. 2-3, 2009.

[2] D. Zhou, K. P. Phillips, G. L. Skibinski, J. L. McCarty, M. W. Loth, B. R. Buchholz, D. H. Braun, R. A. Lukaszweski, "Evaluation of AC-AC Matrix Converter A Manufacturer's Perspective," *Proceedings of Industry Applications Conference*, 37th IAS Annual Meeting., 2002,vol.3, 2002, pp. 1558- 1563.

[3] J. Seok, J. Kim, and S. Sul, "Over-modulation strategy for high-performance torque control," IEEE Transactions on Power Electronics, vol. 13, No. 4, July 1998, pp 786- 792.

[4] C. Hong, and B. Zhou, "Over-modulation strategy of matrix converter driving brushless DC motor systems," proceedings of IEEE-IPEMC Conf. 2009, pp.1907-1912.

[5] P. Kiatsookkanatorn S. Sangwongwanich, "A unified PWM method for Matrix converters and its carrier-based realization using dipolar modulation technique," IEEE Trans. on Industrial Electronics, Issue 99, May 2011.

[6] Bucknall, R. W. G., & Ciaramella, K. M. "On the conceptual design and performance of a matrix converter for marine electric propulsion", Power Electronics, IEEE Transactions on, 25(6), 1497-1508, (2010).

[7] S. Bala, G. Venkataraman, "Matrix Converter BLDC drive using reverse-blocking IGBTs," Proceedings of 21st Annual IEEE- APEC Conf. 2009, pp. 660-666.

BIOGRAPHY OF AUTHOR

Syeda Fatima Ghousia received her Bachelor degree in Electronics Engineering from Dawood College of Engineering and Technology, NED University, Karachi, Pakistan. She received her Master of Engineering degree in Electrical Power Engineering from University of Alberta, Edmonton, Canada. She is currently working toward the PhD degree at the Department of Electrical and Computer Engineering, University of Windsor, Ontario, Canada. Her research interests includes design and control of Switched Reluctance Motors and drives in Electric Vehicle and Wind Energy applications, Matrix Converter topologies and applications in renewable energy generation applications.