IMPROVED SPACE VECTOR MODULATION WITH REDUCED SWITCHING VECTORS FOR MULTI-PHASE MATRIX CONVERTER

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Specially dedicated to my beloved *Mom, Dad and my Wife*
for their enduring love, care and motivation.

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ABSTRACT

Multi-phase converter inherits numerous advantages, namely superior fault tolerance, lower per-leg power rating and higher degree of freedom in control. With these advantages, this thesis proposes an improved space vector modulation (SVM) technique to enhance the ac-to-ac power conversion capability of the multi-phase matrix converter. The work is set to achieve two objectives. First is to improve the SVM of a three-to-seven phase single end matrix converter by reducing number of space vector combinations. Second is to use the active vector of the SVM to eliminate the common-mode voltage due to the heterogeneous switching combination of a dual three-to-five phase matrix converter. In the first part, the proposed technique utilizes only 129 out of 2,187 possible active space vectors. With the reduction, the SVM switching sequence is greatly simplified and the execution time is shortened. Despite this, no significant degradation in the output and the input waveform quality is observed from the MATLAB/Simulink simulation and the hardware prototype. The results show that the output voltage can reach up to 76.93% of the input voltage, which is the maximum physical limit of a three-to-seven phase matrix converter. In addition, the total harmonics distortion (THD) for the output voltage is measured to be below 5% over the operating frequency range of 0.1 Hz to 300 Hz. For the second part, the common-mode voltage elimination is based on the cancellation of the resultant vectors (that causes the common-mode to be formed), using a specially derived active vectors of the dual matrix converter. The elimination strategy is coupled with the ability to control the input power factor to unity. The proposed concept is verified by the MATLAB/Simulink simulation and is validated using a 5 kW three-to-five phase matrix converter prototype. The SVM switching algorithm itself is implemented on a dSPACE-1006 digital signal processor platform. The results prove that the common-mode voltage is successfully eliminated from the five-phase induction motor winding. Furthermore, the output phase voltage is boosted up to 150% of the input voltage in linear modulation range.

ABSTRAK

Penukar pelbagai fasa memiliki beberapa kelebihan iaitu bertoleransi tinggi terhadap kesilapan, mempunyai kadar kuasa yang rendah bagi setiap fasa dan tahap kebebasan yang tinggi dalam sistem kawalan. Dengan kelebihan-kelebihan ini, tesis ini mencadangkan penambahbaikan dalam teknik modulasi vektor ruang (SVM) untuk meningkatkan keupayaan penukar kuasa *ac-to-ac* untuk penukar matriks pelbagai fasa. Projek ini menetapkan untuk mencapai dua objektif. Pertama untuk menambahbaik SVM bagi penukar matriks tunggal tiga-ke-tujuh fasa dengan mengurangkan bilangan gabungan vektor ruang. Kedua ialah untuk menggunakan vektor aktif SVM untuk menyahkan voltan mod sepunya akibat daripada ketidakseragaman pengsuisan daripada sebuah penukar dwi-matriks tiga-ke-lima fasa. Dalam bahagian pertama, teknik yang dicadangkan menggunakan hanya 129 daripada 2,187 vektor ruang yang aktif. Oleh kerana pengurangan vektor yang besar, maka aturan pengsuisan SVM dapat dipermudahkan dan masa pemprosesan algoritma dapat diringkaskan. Walaupun bilangan vektor aktif dikurangkan dengan banyaknya, kualiti gelombang input dan output tidak terjejas seperti yang terbukti dari simulasi MATLAB/Simulink dan prototaip perkakasan. Keputusan menunjukkan bahawa voltan output boleh mencecah sehingga 76.93% daripada voltan input, yang mana adalah limit fizikal bagi penukar matriks tiga-ke-tujuh fasa. Tambahan pula, herotan harmoniks total (THD) bagi voltan output diukur di bawah 5% dalam julat frekuensi 0.1 Hz ke 300 Hz. Bagi bahagian yang kedua, penghapusan voltan mod sepunya adalah berdasarkan penyahan vektor paduan dengan menggunakan vektor aktif khusus yang terhasil daripada penukar dwi-matriks. Strategi penghapusan disertakan dengan keupayaan untuk mengawal faktor kuasa masukan kepada uniti. Konsep yang dicadangkan disahkan dengan simulasi MATLAB/Simulink dan dibuktikan menggunakan sebuah prototaip 5 kW penukar matriks tiga-ke-lima fasa. Algoritma pengsuisan SVM itu sendiri diimplementasikan oleh pemprosesan isyarat signal digital dSPACE-1006. Keputusan menunjukkan bahawa voltan mod sepunya berjaya dihapuskan daripada lilitan motor berinduksi lima fasa. Tambahan lagi, fasa voltan output dinaikkan ke 150% daripada voltan input di dalam julat modulasi linear.

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LIST OF ABBREVIATION

SVM	-	Space vector modulation
THD	-	Total harmonics distortion
MC	-	Matrix converter
PWM	-	Pulse width modulation
SPWM	-	Sinusoidal pulse width modulation
IGBT	-	Insulated gate bipolar transistor
FFT	-	Fast Fourier Transform
R	-	Resistor
L	-	Inductor
C	-	Capacitor
EMI	-	Electromagnetic interference
VSBBC	-	Voltage source back-to-back converter
SVM	-	Space vector modulation

LIST OF SYMBOLS

I	-	Current
V	-	Voltage
P	-	Power
δ	-	Pulse width of the SVM pulse
v_i	-	Input voltage
v_o	-	Output voltage
i_i	-	Input current
i_o	-	Output current
α	-	Input side displacement angle
v_{cm}	-	Common-mode voltage
q	-	Voltage transfer ratio (or modulation index)

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CHAPTER 1

INTRODUCTION

1.1 Overview of Multi-phase Matrix Converter

Matrix converter is a direct ac-to-ac power converter which allows power flow in two directions. This functionality is achieved by the aid of fully controlled semiconductor switches, arranged in a form of matrix array. Nowadays, matrix converter is steadily gaining popularity and is considered as a reliable future alternative to the more established voltage source inverter, for a number of reasons. Firstly, it does not require an intermediate (dc link) energy storage element. Secondly, regardless of any load, the input power factor can be fully controlled at any instant. Thirdly, it has an inherent four-quadrant operation mode, which enables for a fast and flexible performance—particularly for motor drive applications. Some of the practical applications of the converter are multi-phase drives for aircraft, marine applications, electric vehicles and on-board traction propulsion systems.

The most common matrix converter is the three-phase (input) to three-phase (output) [1-2] configuration. This topology is mainly utilized for the traditional variable speed drive [2-4]. Notwithstanding the widespread usage of the three-phase based system, there is a growing interest for multi-phase (more than three phases) converter for certain niche applications [5-14]. The multi-phase systems inherit numerous advantages; these include the higher degree of freedom in control, greater system redundancy (thus greater fault tolerance) and lower per-leg converter rating. Furthermore, the operation of the multi-phase motor is quieter and it allows for an independent control of two or more series/parallel connected motors [5-7].

The voltage-source inverter is the most widely used in the multi-phase motor drive. Despite its popularity, it does not allow for a reversible power flow due to the uncontrollable diode bridge rectifier at the input stage. Furthermore, it is based on a two-stage conversion process, with an energy storage element in between the stages. Hence its efficiency is greatly compromised. For certain application that requires reversed power flow (e.g. dynamic braking), a resistor is provided at the dc link to dissipate the power. An alternative to the voltage-source inverter is the voltage source back-to-back converter (VSBBC). This topology uses a controlled rectifier at the input stage, feeding a conventional inverter with multi-phase output. The major advantage of the VSBBC is that it offers a bidirectional power flow with almost the same number of power switches as the voltage-source inverter. However, it is still considered as a two-stage power converter, as the input and the output converters are coupled with a dc link capacitor.

In contrast, the matrix converter is considered as a direct ac-to-ac power conversion, i.e. without intermediate energy storage element. The absence of the dc link capacitor decreases its footprint and improves the system lifetime. Moreover, the matrix converter is essentially a single stage converter with an inherent quasi three-level property. This characteristic enables all the three instantaneous line-to-line input voltages to appear at the output voltages simultaneously. As far as per switch conduction current is concerned, the matrix converter is lower; thus it is better suited for high current, low-frequency as well as start-up applications. Above all, the power density and the power-to-mass ratio of the matrix converter is significantly higher than the voltage-source inverter or the VSBBC for a wide range of switching frequencies [15-18].

1.2 Modulation Techniques for Multi-phase Matrix Converter

Modulation is the switching strategy imposed on the power switches to efficiently transfer the power from the input to the load. The effectiveness of the modulation methods is measured based on several objectives: 1) to obtain the highest value of fundamental voltage for a given input, 2) to minimize the number of switching instants in order to achieve certain output waveform quality, 2) to be able to maintain zero displacement angle between the input voltage and the current (unity power factor). For a given converter topology, these objectives may contradict; hence the necessary compromises.

Despite the numerous merits of the multi-phase matrix converter, little attention is given to the advancement of its modulation strategy. Whilst there exists quite a number of modulation techniques developed for the multi-phase voltage-source inverter [5-7] and the VSBBC [19-21], there appears to be very limited (similar) work carried out on the multi-phase matrix converter. To date, most of the established modulation strategies for matrix converter are based on the carrier-based PWM—primarily the sinusoidal PWM (SPWM) switching strategies [11-14, 22-23]. Besides these, there are several work on the matrix converter involving the space vector modulation (SVM) for motor drives [24-29] and distributed generation [30-31] applications. The SVM is more adaptable for digital implementation because the switching angles are formulated by simple vector calculations. It has freedom to generate independent gating signals at low modulation ratio and its performance is superior than the carrier based PWM [33-34]. Furthermore, the SVM can be utilized to achieve different control goals such as fault tolerance, common mode voltage elimination and switching frequency reduction [32]. In addition, it also exhibits better harmonic profile, which is particularly advantageous for high power converters.

Several variations of the SVM have been utilized for three-to-three phase matrix converter [24-29]. Recently, the SVM has been implemented in a three-to-five phase matrix converter too [10]. Despite these successes, there is no attempt to apply the SVM to a matrix converter with five phases or more. The main advantage of using a higher number of phases is the reduction in pulsating torque (ripple). The lower pulsation results in smoother machine operation, lower oscillation, reduced mechanical fatigue and acoustic noise. Additionally, the rotor harmonic currents losses are lessened, due to the reduced power drawn by the motor. There are several works on the SVM for the three-to-three phase matrix converter, but they are only limited to single ended motor drives [35-40]. It would be interesting if these converters can be applied to open-end motors as well.

1.3 Issues on Common-mode Voltage

For a motor that is fed by the pulse width modulated switching converters, the common-mode voltage is bound to be formulated at the output. The-common-mode voltage is detrimental and has been identified as a main source of premature motor failures [41-43]. It is also known to cause overvoltage stress to the winding insulation—affecting its lifetime and contributes to a host of EMI-related problems. Furthermore, the presence of high frequency common-mode voltage component with large magnitude at the motor neutral point, generates high frequency leakage current to ground path, as well as induced shaft voltage [41].

There are numerous efforts to reduce or eliminate the common-mode voltage in the three- and five-phase motor drives [44-48]. Expectedly, most of them are related to the conventional voltage-source inverter. A high frequency AC-link with single stage bidirectional power electronic transformer is used to suppress the common-mode voltage at the load end [49]. In [50], a hybrid 81-level multilevel voltage-source inverter that implements space vector modulation (SVM) to eliminate the common-mode voltage in the three-phase drive is proposed, while in [51], the zero vectors of the SVM are used. In another work [52], a hybrid PWM is proposed to reduce the bearing currents, shaft voltage and common-mode voltage in a dual voltage-source inverter-fed, three-phase open-end motor drive. In [53], two SVM switching techniques with common-mode voltage reduction capability are described for a five-phase, and in [54] the algorithm is enhanced by allowing for over-modulation. A two-level voltage-source inverter feeding a five-phase drive to eliminate the common-mode voltage is investigated in [55]; it is based on the vector space decomposition concept. A carrier based PWM scheme to eliminate the common-mode voltage in five-phase and six-phase voltage-source inverter-fed drive with open-end stator winding are proposed in [56, 57]. In [58-59], various SVM techniques are applied to multi-level voltage-source inverter with multi-phase open-end winding drive topologies. The interest in the dual open-end drive is due to the fact that it can deliver much higher power than the single ended type.

Despite extensive works on three-phase as well as multi-phase voltage-source inverter drives [50-59], little attention is given to the common-mode voltage elimination for multi-phase matrix converter. This is crucial because one of the factor to increase reliability of the drive system is to eliminate the circulating common-mode current, which is the consequence of the common-mode voltage. However, there are some effort and works in that directions, but mostly they are focused on the three-phase matrix converter. For example, authors in [60] have applied a predictive control to reduce the common-mode voltage in the three-phase system, which results in a 50% increase in the overall efficiency. Recently, several contributions on common-mode voltage mitigation [61-69] are reported on square-type matrix converter[1] open-end drive system. In general, the objective of such work is two-fold: 1) to eliminate the common-mode voltage across the windings of the open-end motor and 2) to increase the output voltage range by extending the linear modulation range.

1.4 Problem Statements

In view of the literary gap and considering the clear advantages of higher number of output phases, this work attempts to utilize the SVM for the multi-phase matrix converter with a higher number of phase e.g. seven. The main problem of the SVM implementation for the higher phases is the large number of switching states that must be considered. Thus one of the challenges of this work is to reduce the number of switching vectors to a manageable level. This in turn, will decrease the execution time, thereby increasing the efficiency of the algorithm. Notwithstanding the fewer switching states, the modulation must exhibit an improvement or at least maintain the harmonic profile, compared to the carrier based PWM. Furthermore, the SVM should be able to generate a balanced sinusoidal input currents with unity power factor—both at high and low output frequency. This is a major concern in matrix converter, as it is quite difficult to achieve sinusoidal input current with controllable power factor.

Another issue to be addressed by this work is the elimination of the common-mode voltage from the output of the matrix converter. Note that, for the case of the

[1]Square matrix converter means 3 × 3 or 5 × 5 or $n \times n$ phase. In other words, the input is multiple of output or vice versa. Non-square matrix converter means number of input and output phases are different in the form of $n \times m$, where n and m are not multiple of each other.

square-type matrix converter, the common-mode voltage is readily eliminated by utilizing the rotating vectors [61-69]. In particular, for the three-to-three phase matrix converter, all the different input phases correspond to all the three output phases' positions, thus actively nullifying the instantaneous common-mode voltage. This is because, ideally, the sum of the voltages formed by the input-output rotating vectors at the motor terminal at any instant is always zero. On the contrary, for the non-square matrix converter (since the number of input phases differ from the output phases), it is not possible to take advantage of the same rotating vectors, as the input-output space vector positions are always asymmetrical. This situation is known as heterogeneous switching. However, there are opportunities for the common-mode voltage to be eliminated by applying ingenious modulation techniques. One possibility to be explored is to introduce appropriate active vectors in the SVM switching sequence.

1.5 Objective of the Research

The proposed research work has the following specific objectives:

1) To develop an improved SVM modulation strategy for the three-to-seven matrix converter. The desirable features of the proposed technique is the reduction of the SVM switching states and improved harmonic profile compared to the carrier based PWM. Furthermore, the proposed SVM is able to generate a balanced sinusoidal input currents with a near unity power factor—both at high and low output frequencies.

2) To eliminate the common-mode voltage across the windings of the open-end motor by using the active vectors. The common-mode voltage elimination must also be coupled with the ability to control the input power factor to unity. Furthermore, the use of dual open-end drive is expected to boost the output phase voltage up to 150% of the input phase voltage in the linear modulation range.

1.6 Scope of Work

The work carried out in this thesis are mainly bounded by the following scopes:

A large part of the work deals with the formulation of switching strategies of the SVM. This involves the mathematical formulation of switching instants to increase the performance of the matrix converter. The first scope is to design the SVM for the three-to-seven phase matrix converter with reduced switching vectors. The second scope is to use the SVM to eliminate the common-mode voltage in an open-end motor driven by the dual three-to-five phase matrix converter.

The ideas are to be verified by MATLAB/Simulink simulation. In addition, to validate the simulation results, the experimental work is carried out. The experiments are done with matrix converter rated at approximately 5 kW (peak). The SVM algorithms are implemented on a digital signal processor platform.

1.7 Thesis Organization

The content of this thesis is divided into five chapters, including the Introduction. It is organized as follows:

Chapter 2 is the literature review. It serves as the pre-requisite reading for the reader to follow through the thesis effectively. Thus it mainly focuses on the background information of the matrix converter topology, its characteristics and operation. It also describes the detail of the SVM modulation. Note that, since the nature of this work can be distinctly divided into two parts, the specific literature review and the definition of the research gaps (or the problem statements) are not formulated here; rather they are described in the respective chapter.

Chapter 3 covers the SVM strategy for the five-to-seven phase matrix converter. It begins with a review on the previous modulation strategies for the SVM published in the literature. From the review, the need for an improved SVM for the three-to-seven phase matrix converter is established. The complete space vector model for the converter is developed. Hence, the proposed idea of the switching vector reduction is analyzed. The concept is verified by using the MATLAB/Simulink. Finally, an experimental test rig is set up to validate the simulation results.

Chapter 4 deals with the elimination of the common-mode voltage. The topology under study is the open-end five-phase induction motor fed by a dual matrix converter. Initially, the discussion revolves around the causes and the effects of the common-mode voltage on the drive performance. Then the SVM strategy to eliminate the common-mode voltage is proposed. The idea is verified by simulation and validated by experiments.

Chapter 5 draws the overall conclusion of the work and highlights its contribution to the research field. It also suggests some future research that can be taken up as continuation of this work.

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