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Review

Issues of matrix converters: Technical review

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Matrix converter is a powerful AC-AC converter for the application of induction motor drives with sinusoidal input currents and no DC-link capacitor. It offers remarkable advantages over other alternatives in applications requiring improved utility interaction and critical weight/volume reduction. This paper presents a technical review on related issues of induction motor drive fed by matrix converters (MC). The first discussions presented the special difficulties involved in matrix converters. These are partly conceptual, partly concerning circuit topology, and current commutation technique. The second discussion analyzes the control and modulation which are of particular interest. The third discussion describes the hardware development modes studies.

Key words: Matrix converter, topologies, current commutation, modulation, control, harmonic losses.

INTRODUCTION

As the output performances of the induction motor drives have continued to improve, the research trends in recent years have been focused on improved interaction with the utility to provide clean power distribution system.

Matrix converter (MC) has recently received considerable interests, because it possesses the topological and operational features to fulfil these current trends for the drives (Venturini, 1980; Huber and Borojevic, 1995; Kazmierkowski, Krishnan et al., 2002; Kwak, 2007). The converter has also attracted the industry application and the technical development has been further accelerated because of a strong demand in power quality, energy efficiency and downsizing of the converters (Roth-Deblon, 2006). Alesina and Venturini (1989) introduce a mathematical approach of main issues. It gives an analytical expression of duty-ratio values as functions of input voltages and desired output voltages but still has two major limitations; the knowledge of the load power factor is required and the maximum input-output voltage ratio decreases severely when input and output power factors differ. Montazeri and Khaburi (2010) introduce method to select the most appropriate voltage vector with respect to the error of the torque. The standard look-up table for direct torque control by matrix converters is improved in order to include the small, medium and large voltage vectors of Matrix Converters. With the new look-up table and new hysteresis comparator with seven levels output the system will differentiate between small, medium and large torque errors and consequently reduce the electromagnetic torque ripple and output current THD. Braun and Stahl (2008) increase the control range of the input reactive current to the same value as reached with the conventional matrix converter. (Ortega and Arias, 2009) a predictive algorithm for Matrix Converters fed Induction Motors is proposed which ensures minimum torque ripple is employed for the selection of the appropriate voltage vector from the Matrix Converter. A new look-up table for Direct Torque Control using Matrix Converters has been developed which delivers a set of three vectors, at every sample period, that fulfill the torque and flux demands. Before attacking the many technical problems involved, one ought to have a clear concept about what one wants to achieve by studying issues of Matrix convertor. In this paper, the current trend of MC is covered. These include:

(i) Study the main crucial aspects in developing MC circuit.
(ii) Study the topologies of MC and the protection issues.
(iii) Study various control and modulation of MC.

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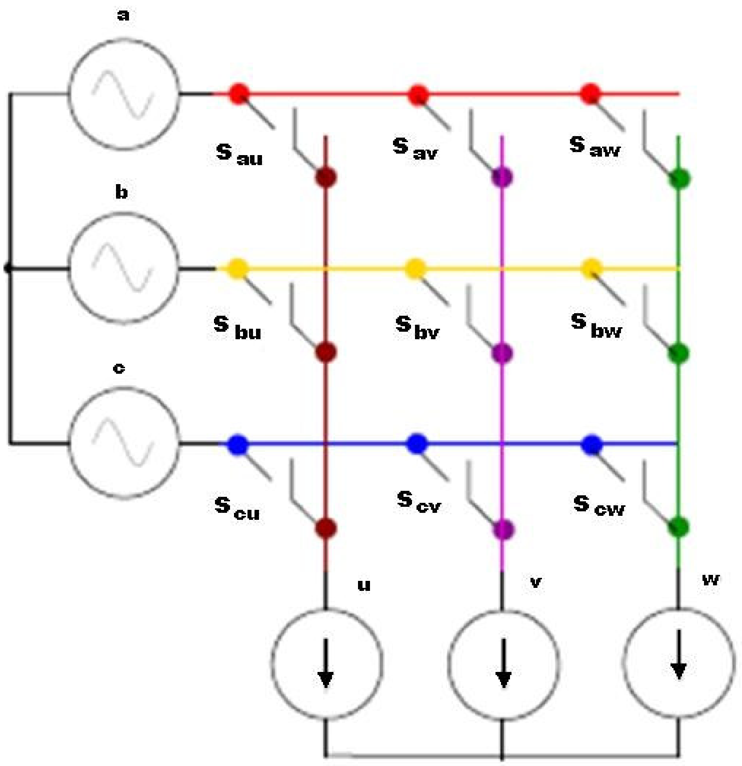


Figure 1. Direct matrix converter.

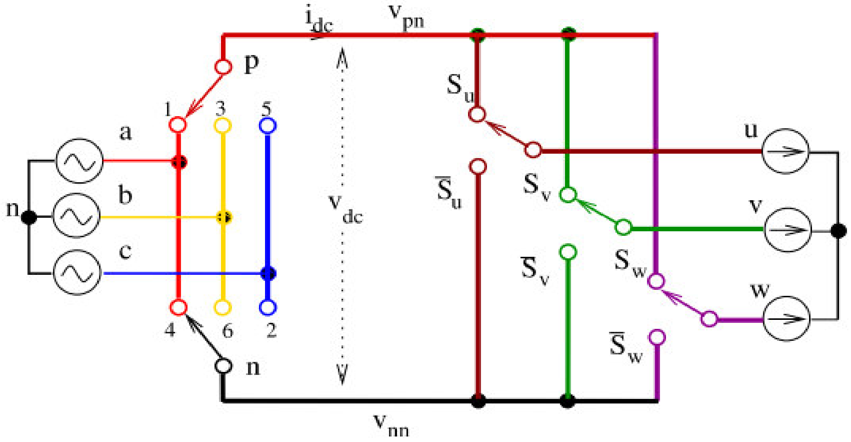


Figure 2. Indirect matrix conversion.

CIRCUIT TOPOLOGIES

Various MC topologies have been studied since 1970 (Gyugyi, 1970). The research is not only concerned on conventional direct matrix converters (DMC), presented in Figure 1, but an indirect matrix converter (IMC), presented in Figure 2 has also been studied (Minari et al., 1993; Kolar et al., 2002; Jussila et al., 2004; Klumpner, 2005; Takeshita and Andou, 2010; Klumpner and Blaabjerg, 2005) and can be considered an option for the DMC. Comparison of space vector modulated DMC and IMC supplying induction motor drives has been done in Jussila et al. (2004). In an ideal case DMC and IMC provide similar performance with identical control system. However,in real motor drives some differences in output voltages and power losses occur caused by different main circuits, whose effects are increased by different commutation methods needed to provide safe operation

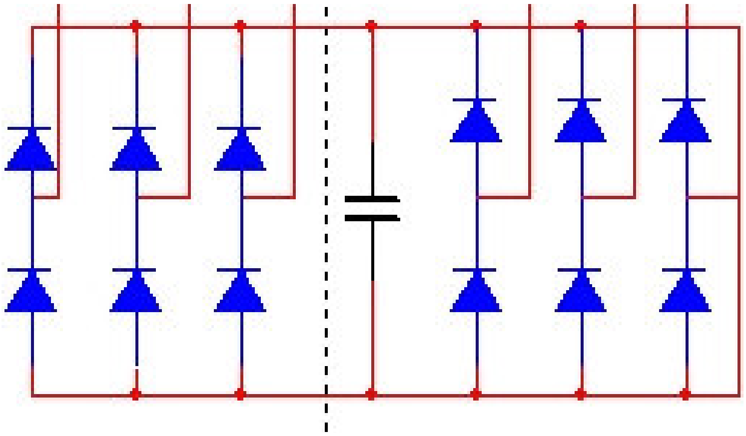


Figure 3. Clamp circuit.

in both cases.Thus the output voltages of the converters do not follow their references similarly but the effects of non-idealities are more severe in the IMC than in the DMC. In addition, the efficiency of the IMC is smaller than DMC under most loading situations tested.

Other derivative topologies of MC is the sparse matrix converter (SMC) (Kolar et al., 2007). SMC offers a reduced number of components, a low complexity modulation scheme, and low realization effort (Kolar et al., 2002; Wheeler et al., 2002; Kolar et al., 2007). Invented in 2001, SMC avoid the multistep commutation procedure of the conventional MC, improving system reliability in industrial operations. Its principal application is in highly compact integrated AC drives. SMC topology is constructed from 15 transistors, 18 diodes, and 7 isolated driver potentials (IDP). Compared to the DMC topology provides identical functionality, but with a reduced number of power switches and the option of employing an improved zero DC-link current commutation scheme, which provides lower control complexity and higher safety and reliability. The very sparse matrix converter (VSMC) topology is developed from 12 transistors, 30 diodes, and 10 isolated driver potentials. There are no limitations in functionality compared to the DMC and SMC. Compared to SMC there are fewer transistors but higher conduction losses due to the increased number of diodes in the conduction paths. Meanwhile the ultra sparse matrix converter (USMC) topology is 9 transistors, 18 diodes, and 7 isolated driver potentials. The significant limitation of this converter topology compared to SMC is the restriction of its maximal phase displacement between input voltage and input current which is restricted to ± 30°

The other topology is Z-source matrix converter which comprises of two types structure; voltage-fed and current-fed. (Zhang et al., 2009) proposed a type of three phase AC-AC Z-Source converters which are derived from MC theories. It overcomes the voltage transfer limitation of MC and also exhibits the inherent benefits of MC. Only additional passive components are required without any increase in the number of power semiconductor switches which can increase the complexity of control. Fang and Chen (2009) proposed a current-fed Z-source matrix converter topology. It combines the current-fed Z-source AC-AC converter with traditional current-fed matrix converter, and can overcome the conceptual and theoretical barriers and limitations of the traditional matrix converter. It can output lower voltage and has higher reliability.

PROTECTION ISSUES

Likewise any other static converter, the MC needs to be protected against the over voltages and the over currents that might be destructive for its semiconductor devices. An effective and robust protection scheme plays an important role in the implementation of a stable and reliable power converter. In (Klumpner and Blaabjerg, 2002; Klumpner et al., 2002) a type of protection circuit was proposed, which consists of input and output diode bridges, an electrolytic capacitor, and its charge and discharge circuit. The electrolytic capacitor not only has a large volume but also constrains the lifetime of the system, and the discharge circuit by a DC chopper increases the number of parts.On the other hand, a varistor protection and a suppressor diode protection were proposed in Mahlein et al.(2002).Those protections are very useful for a small capacity system, but not suitable for a large capacity system.The strategy offers an additional possibility to remove the needed varistors. The protection strategy with excellent overvoltage protection allows the removal of the large and expensive diode clamp. In addition, a varistor with unusual ratings is needed to be applied to the MC. (Itoh et al., 2004) proposed a protection circuit which consists of a small capacitor an 'dynamic clamp circuit' using an IGBT and a resistor. This clamp circuit (Figure 3) does not need a drive and control circuit for the IGBT.A shutdown strategy for MC under normal or fault condition was proposed (Wang et al., 2005). It provides a controlled freewheeling path for the load currents. Using the proposed strategy, the motor currents can be reduced to zero as soon as possible, while without causing over voltages. Even one of the switches is at fault and cannot be used; the proposed strategy is still useful. In order to avoid unexpected over voltages under a switch open-circuit fault condition, a small-capacity clamping circuit is necessary. Different from the usual clamping circuit, a small capacitor is competent here, instead of a large one.

CURRENT COMMUTATION

The main problem related to the bidirectional switches implementation in MC is the commutation problem. The commutation issue basically rises from the absence of static freewheeling paths in the MC. As consequence it becomes a difficult task to safely commutate the current from one bidirectional switch to another, since a particular care is required in the timing and synchronization of the switches command signals.

Wheeler et al. (2002) considered the minimization of the commutation time in order to achieve the optimum output waveform quality which is particularly useful in applications where the controller may demand very low output voltages. Zhou et al. (2005) proposed a commutation method for reducing the losses caused by the reverse leakage current. The realization of this method is based on output current direction and certain voltage polarities of bidirectional switches and it is featured as a two step commutation. Tabone et al. (2004) used four step current commutations for switching between two bidirectional switches.

CONTROL AND MODULATION

The control strategy of MC was proposed by an Italian Venturini in 1979. The maximum line-to-line output voltage of the MC must not be greater than the minimum line-to-line input voltage. This condition gives the maximum output voltage intrinsic limit of 0.866 (Wheeler et al., 2002). The objective of any MC modulation strategy is to obtain the target output voltages and sinusoidal input currents at a controlled input power factor subject to the constraints of not open circuiting any output phase and of not short circuiting any two input phases. Various modulation strategies have been formulated to meet this objective. The modulation is mainly divided into the following four kinds: direct transformation method, hysteresis current method, two voltage method, and space vector modulation (SVM) method. (Bachir and Bendiabdellah, 2009) presented a detailed comparative study between the two different scalar approaches namely, Venturini and Roy applied to the control of an induction motor. The study dealt with the motor current, speed and torque performance response with respect to both techniques. Djahbar et al. (2005) proposed a control strategy of scalar modulation with three intervals and vector control technique. The advantages of MC and vector control are combined in this technique.

Most researchers focus on the SVM method (Kabasta, 2008), which is a more mature control strategy. SVM technique is utilized to calculate the duty cycles of the active voltage vectors that must be applied in each switching cycle period, in order to satisfy the input and output requirements. SVM technique use simpler algorithm compared with the proposed technique by Venturini.The SVM technique allows a direct understanding of switching patterns and their characteristics from the viewpoint of analysis and control.The modulation strategy is capable of controlling not only the output wave, but also the input current wave, as well as modifying the input power factor. Ahmed et al. (2011) proposed the SVM algorithm derived from Indirect Transfer approach (ITF) to yield higher rms output voltage. The modulation of input current is shown in Figure 4; the output voltage modulation is similar to VSI.

The improvement of the pulse pattern for the output phase voltage during carrier cycle was proposed in Yamamoto et al. (2008). In the proposed modulation method, the duty factors of the output pattern obtained by SVM are converted into the duty factor of every switch of the MC. Xiaohong et al. (2009) presented double SVM technique based SVM method (OSVM). It uses direct modulation method which maximizes the modulation capability for reference vectors by using available input voltages and output currents. The modified direct SVM method without using zero space vector was proposed to reduce the common mode voltage which currently exists in the entire modern converters. Sun et al. (2003) proposed a combined controller to implement both SVM and direct field oriented control (DFOC). SVM is employed to regulate the input/output sinusoidal currents of MC and the DFOC to ensure the good performance of induction motor. Bradaschia et al. (2009) derived a particular set of parameters of the generalized scalar pulse width modulation (GSPWM) resulting in the common mode voltage reduction (CMVR) technique. The technique uses the three possible zero vectors switching configurations to minimize the common mode voltage in the MC in all range of the voltage ratio (up to 86.6%), without significant increase of the input currents harmonic and without the complex algebraic and trigonometric calculations inherent of the (direct space-vector modulation) DSVM. Kwak (2009) proposed a fault resilient structure based on the MC and post fault modulation techniques, which allows for continuous operation even after faults in the converter. Cai et al. (2009) studied an over modulation

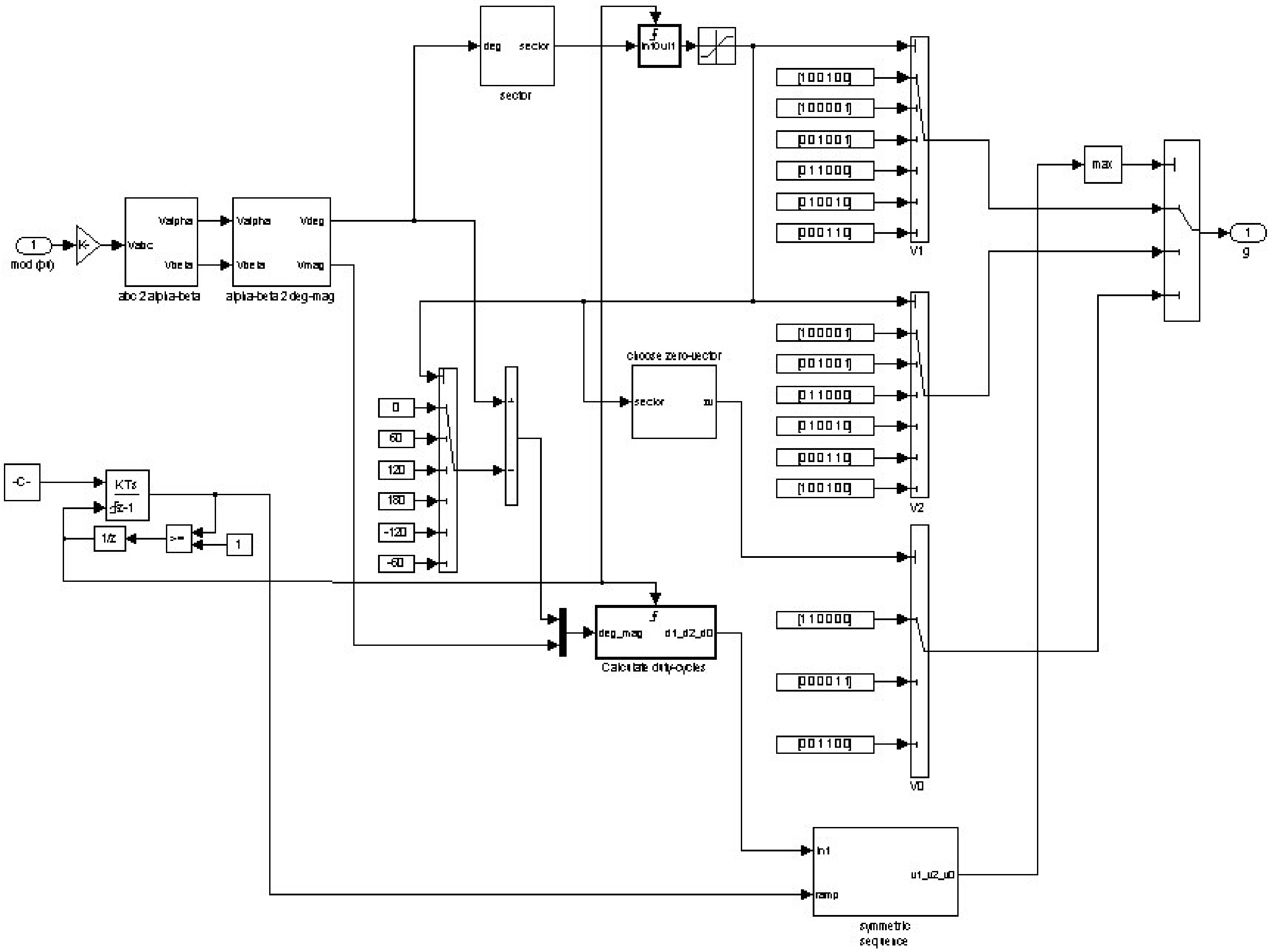


Figure 4. Input current modulation.

strategy for dual bridge MC. Rivera et al. (2009) presented a control scheme applied to the DMC, which combines the advantages of the predictive control and active damping to reduce the resonance of the input filter. Jun and Ming (2009) combined the SVM-MC with the rotor field oriented vector control of induction motor. A two degree of freedom controller was proposed by Joshi et al. (2007) in an adjustable speed control system and a position control system to obtain good transient responses and good load dis-turbance rejection abilities. The study of the high dynamic performance speed-flux tracking field oriented control algorithm was presented in Chekhet et al. (2003). High performance speed tracking is achieved under heavy dynamic conditions of operation. High quality input/output current waveforms of the MC obtained during steady state conditions of operations for both directions of the power flow. A nonlinear robust auto disturbance rejection controller (ADRC) is employed which taking the place of conventional proportional-integral (PI) regulator.This nonlinear robust controller consists of tracking differentiator, extended state observer and nonlinear state error feedback control law. Yang et al. (2007) established the model of MC in d-q frame via PARK transformation. Since the closed loop controller is relatively independent of the power electronic circuits, an ADRC for output current tracking is designed by applying ADRC algorithm to a MC modulated by SVM. The results indicate that the controller has the advent-ages of good steady and dynamic performances, and it is strongly robust.

Direct torque control (DTC) has becomes one of the high performance control strategies for AC machine for providing a very fast torque and flux control without any requirements for coordinate transformation, PWM generation and current regulators. It has been proposed in the middle of 1980's. It is widely known to produce a quick and fast response in AC drives by selecting the proper voltage space vector according to the switching status of inverter which is determined by the error signal of reference flux linkage and torque with their estimated values and the position of the estimated stator flux. For such advanced reasons, the combination of the MC with those of the DTC method is effectively possible. Lee et al. (2007) described the operation of induction motor under the DTC-MC method in steady state and transient conditions. Mohapatra et al. (2006) proposed a DTC-MC with simplified carrier-based PWM scheme of MC for generation of PWM voltages. Ortega et al. (2005) investigated the use of short voltage vectors of MC to reduce the electromagnetic torque ripple which appears when DTC technique is used in induction motors. Meanwhile Chen et al. (2007) proposed a pseudo dc-link to effectively reduced electromagnetic torque ripple presented a DTC-SVM method for direct space vector modulation (DSVM) technique. The proposed method provides a precious input power factor control capability beside the high control performances. Furthermore, the FFT spectrum analysis of the input current shows the better harmonic contents as compared to the conventional DTC method.

Dzung and Phuong (2005) proposed an artificial neural network (ANN) of DTC-MC to decrease the time of calculation of the conventional control system. Vargas et al. (2008) introduced a Predictive Torque Control for MC including a strategy to control the input power factor. The proposed method considers all valid voltage vectors generated by a MC, including rotating vectors that are neglected by most control strategies. Gambôa et al. (2007) presented a predictive optimal control applied to field oriented controlled employing a MC. The optimal controller minimizes output current, thus allowing the establishment of field oriented control and input current errors using a cost functional with adequate weights.

Lee and Blaabjerg (2008) presented a method for sensorless control of MC using a power flowing to the motor. The proposed control algorithm is based on controlling the instantaneous real and imaginary powers into the induction motor. To improve low speed sensorless performance, the nonlinearities of a MC such as commutation delays, turn-on and turn-off times of switching devices and ON state switching device voltage drop are modeled using a PQ power transformation and compensated using a reference power control scheme.

ABNORMAL INPUT/OUTPUT VOLTAGES

Several performance and reliability issues of the MC have been investigated. The influence of input line voltage disturbances on both the load side performance and the input current is significant and undesirable. Since the MC is a direct frequency conversion device, the disturbances at the AC utility grid (line) side are immediately reflected to the load side. Line voltage source or impedance unbalances can result in unwanted input/output harmonic currents. The operation of MC fed induction motor drives under various abnormal conditions such as unbalanced power supply, balanced non-sinusoidal power supply, input voltage sags and short time blackout of power supply has been analyzed (Kumar and Bansal, 2008). Kang et al. (2002) proposed a technique to eliminate the input current distortion due to the input voltage unbalance.

Mei and Huang (2006) analyzed the output voltage distortion of MC under different conditions. The output voltage error caused by multistep commutation delay can be cancelled inherently by using three step commutation. Two compensation methods are proposed to improve the output waveform quality for different causes which uses the output current direction.

HARMONIC AND SWITCHING LOSSES

Knowledge of the extra harmonic loss is of particular importance for an integrated drive application where the motor cooling must be designed to remove the semiconductor device power loss in addition to the motor power loss. Where the extra harmonic loss is significant, appropriate derating must be applied for continuous operation. Wheeler et al. (2008) quantified the extra harmonic losses in an induction motor that are associated with the use of a MC topology as a motor drive. These extra losses are compared to the harmonic losses associated with an inverter based motor drive. The results show that the extra harmonic loss and consequently the overall drive efficiency is affected by the choice of modulation technique. Kang et al. (2002) analyzed method for evaluating power device losses of MC that consist of switching and conduction losses of IGBTs and diodes which is dependent on the modulation scheme.

HARDWARE DEVELOPMENT

The MC is still unpopular in industrial applications since it is not suitable for use with standard induction motors because the maximum voltage transfer ratio between the input and output can only be as high as 86%. Potential practical implementations of the converter have therefore focused on applications where there is control over the design of the motor as well, and where space and weight are at a premium, such as in integrated motor drives, aerospace and marine or naval applications. Podlesak et al. (2004) described the design, construction and testing of a three-phase to three-phase MC induction motor drive in electric vehicle applications. Imayavaramban et al. (2007) presented a method of avoiding regeneration using

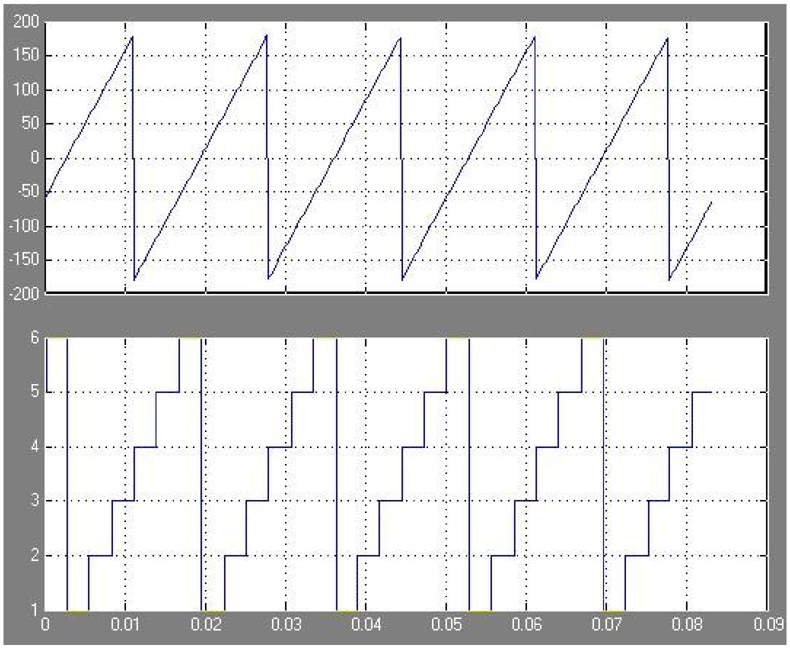


Figure 5. Result for sector identification.

the Power Comparison and Input Voltage Reference method. The avoidance of regeneration is important in many aerospace applications such as aircraft actuation and refueling systems. Wheeler et al. (2005) explored the viability of using direct power converter technology to realize integrated motor drives, at power levels significantly higher than is possible with traditional approaches, fitting within the same space envelope as an equivalent motor. The integrated motor design was targeted at pump and fan applications where the need to install motor drives in a separate location is often an impediment to the replacement of fixed speed motors. Wang et al. (2004) proposed an adaptive modulation rate regulation method to enhance the voltage transfer ratio. The proposed method can be used to the loads non sensitive to the quality of the voltage, such as fan and water pump. Thomas and Doncker (2008) derived a novel Angle-Modulation strategy and alter a carrier based PWM modulation algorithm to control the output phases of the MC converter independently which is in this case in unsymmetric control of a two phase inductive melting furnaces. Ahmed et al. (2011) developed a mathematical model for SVM direct controlled matrix converter. The mathematical expressions relating the input and output of the three phase matrix converter are implemented by using MATLAB/SIMULINK. The processing took 56 s for the passive RL load and 45 s for the induction machine load. It was loaded by three phase induction motor (3 hp, 200 V, 60 Hz star connected) for 0.5 and 0.866 transfer ratio. Figure 5 shows the sector identification and reference angle generation. The angle is generated from the reference output frequency by integrating it. Based on the angle, the sector can be identified. The input and output line voltage with loaded passive load is shown in Figures 6 and 7 for transfer ratio of 0.5 and 0.866. For the induction machine loaded the simulation result is shown in Figures 8 and 9. Figures 10 and 11 are the input current for the passive load and induction motor load respectively. The input currents are mostly sinusoidal for the induction motor load.

CONCLUSION

After few decades of research effort several modulation and control methods have been developed for the MC, allowing the generation of sinusoidal input and output currents, operating with unity power factor using standard processors. The most important practical implementation problem in the MC circuit, the commutation problem between two controlled bidirectional switches which has been solved with the development of highly intelligent multistep commutation strategies. The solution to this problem has been made possible by using powerful digital devices that are now readily available in the market.

Another important drawback that has been present in all evaluations of MC was the lack of a suitably packaged bidirectional switch and the large number of power semiconductors. This limitation has recently been overcome with the introduction of power modules which include the complete power circuit of the MC. However, research work has shown that the MC is not a "pure silicon converter" and that passive elements in form of

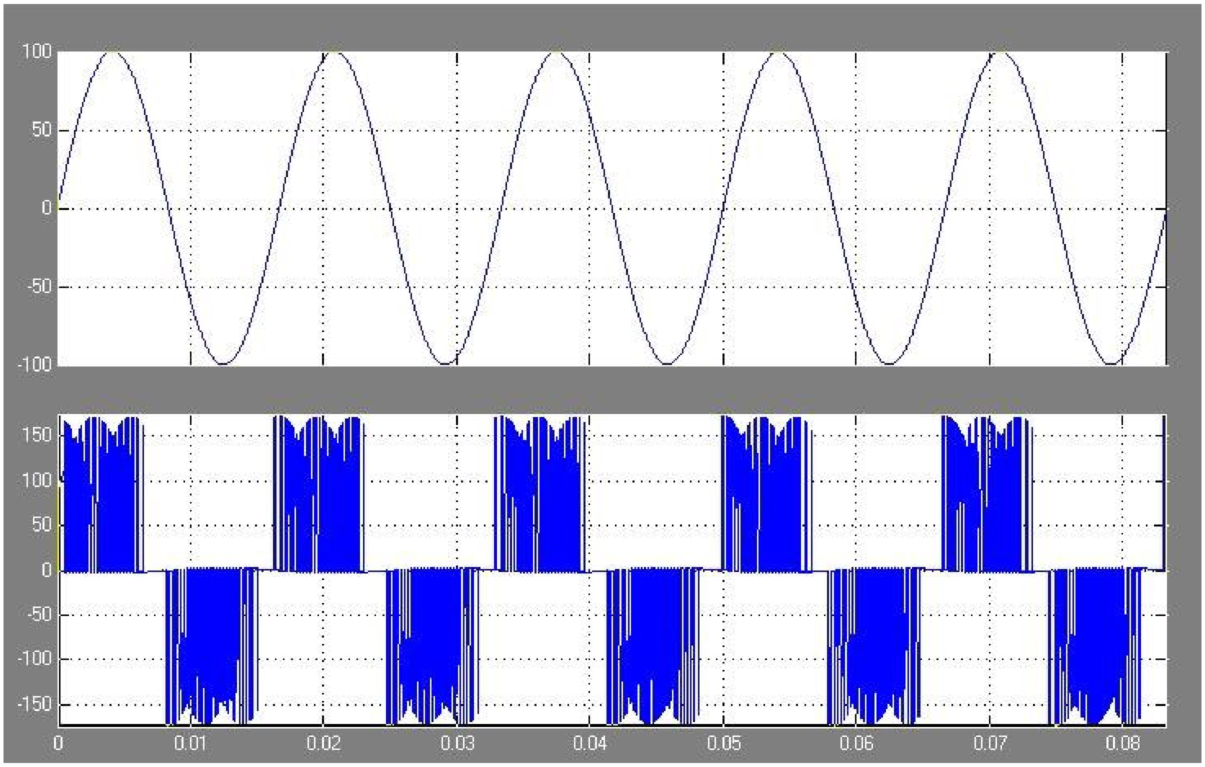


Figure 6. Input and output voltage with passive load for q = 0.5; R = 135.95 Ω, L = 168.15 mH, V_{im} = 100 V, f_o = 60 Hz, f_s = 2 kHz.

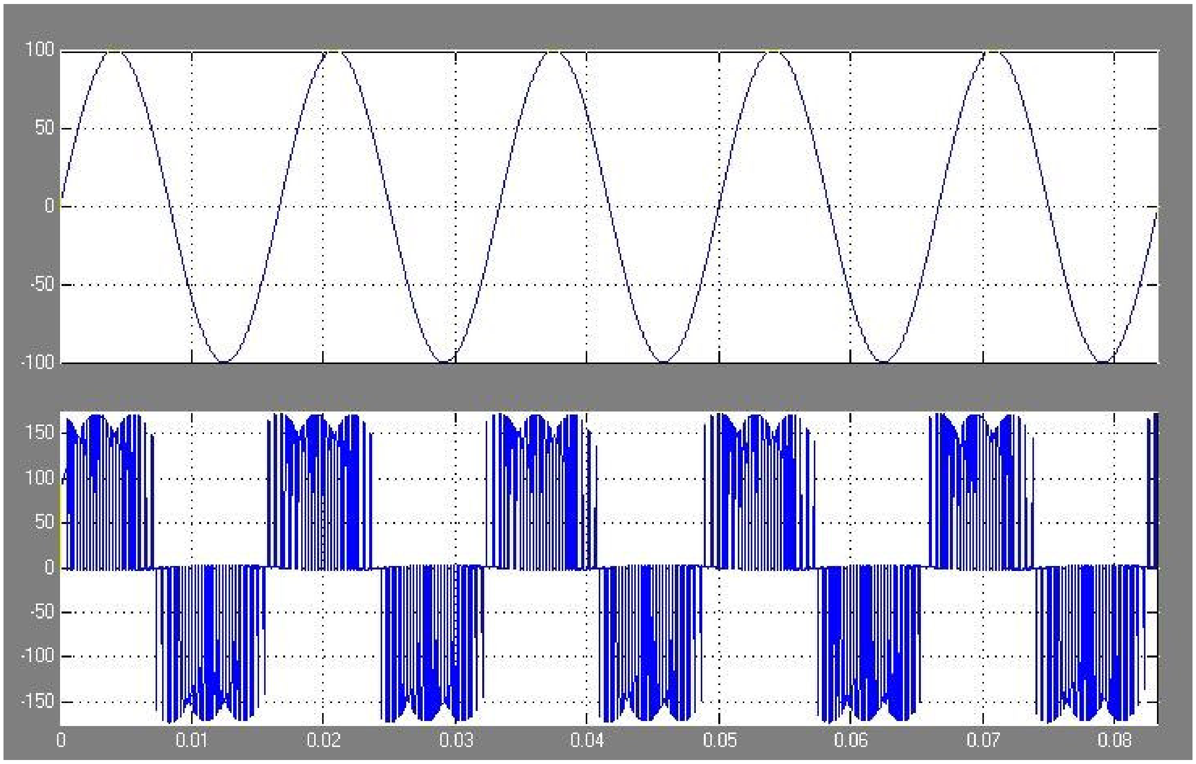


Figure 7. Input and output voltage with passive load for q = 0.866; R = 135.95 Ω, L = 168.15 mH, V_{im} = 100 V, f_o = 60 Hz, f_s = 2 kHz.

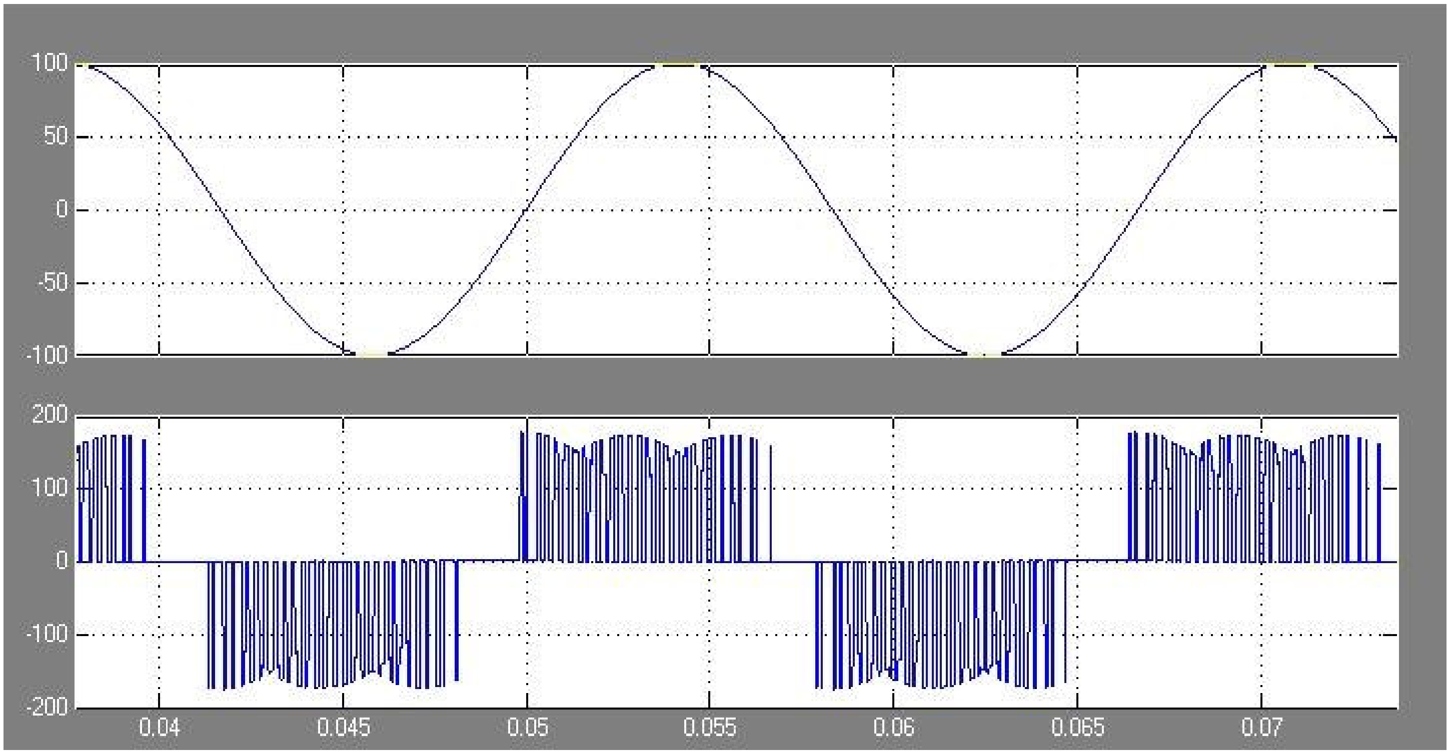


Figure 8. Input and output voltage with loaded induction motor for q = 0.5; 3hp, R_s = 0.277Ω, R_r = 0.183 Ω, N_r = 1766.9 rpm, L_m = 0.0538 H, L_r = 0.05606 H, L_s = 0.0533 H, f_o = 60 Hz, f_s = 2 kHz.

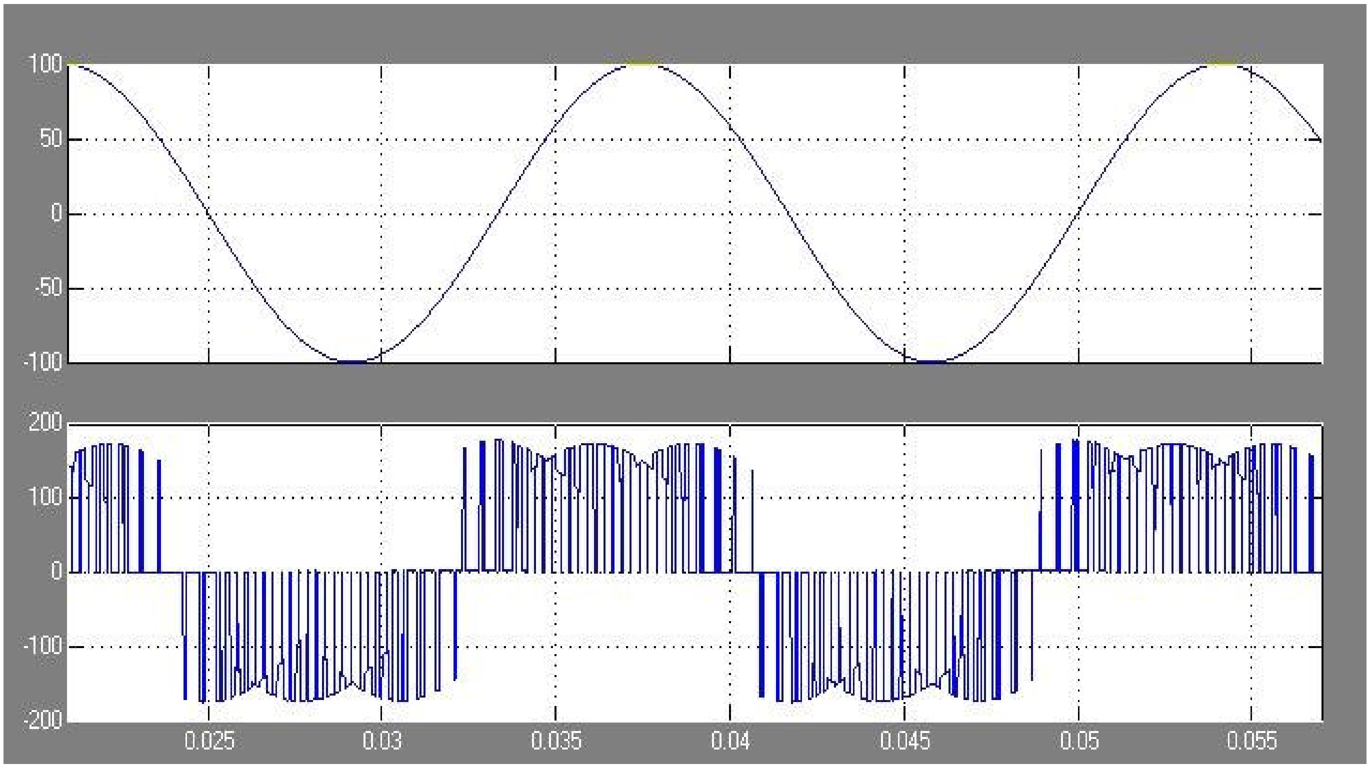
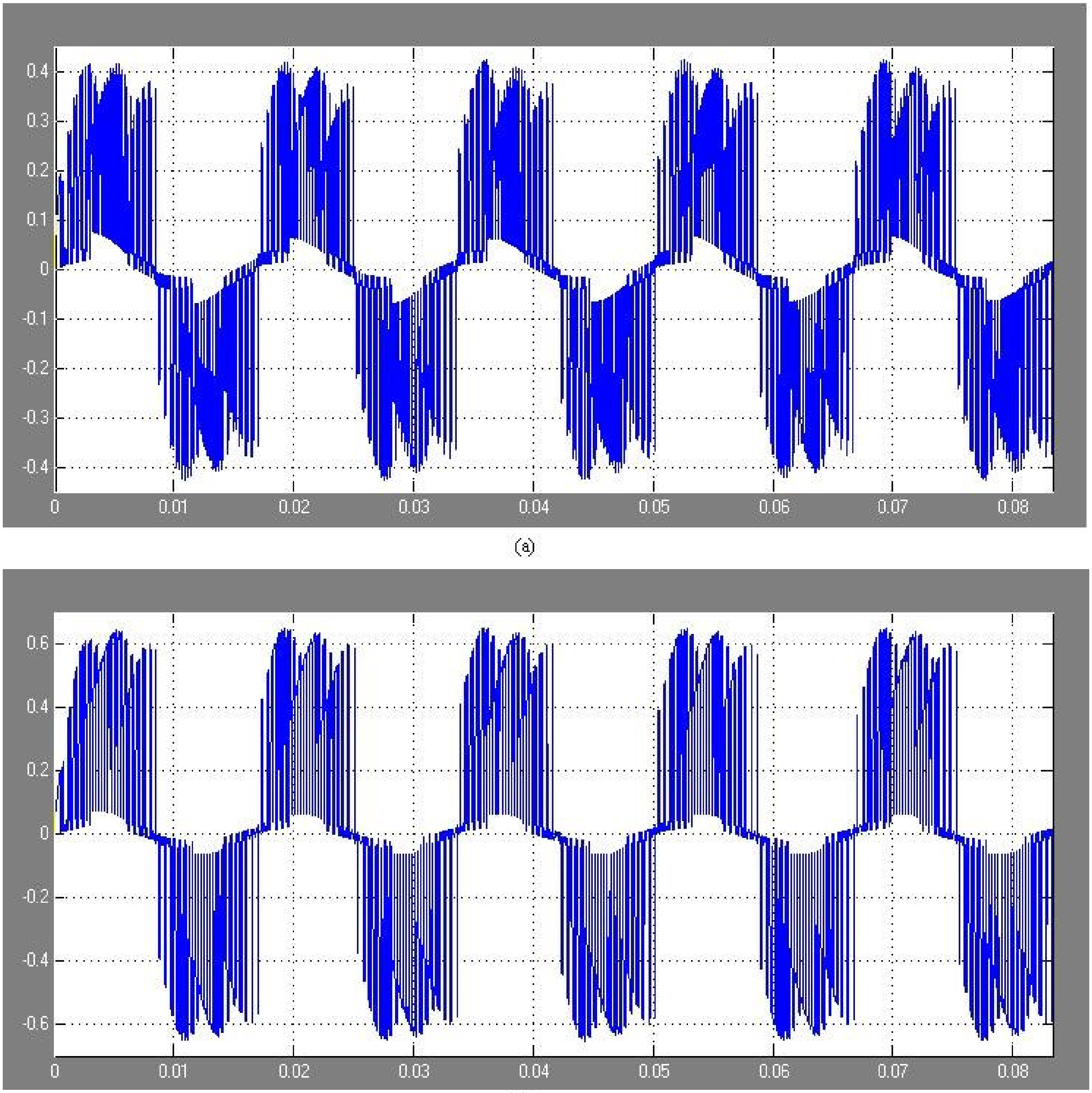


Figure 9. Input and output voltage with loaded induction motor for q = 0.866; 3 hp, R_s = 0.277 Ω, R_r = 0.183 Ω, N_r = 1766.9 rpm, L_m = 0.0538 H, L_r = 0.05606 H, L_s = 0.0533 H, f_o = 60 Hz, f_s = 2 kHz.



(a)

(b)

Figure 10. Input current with passive load; R = 135.95 Ω, L = 168.15 mH, V_{im} = 100 V, f_o = 60 Hz, f_s = 2 kHz (a) q = 0.5, (b) q = 0.866.

input filters are needed. More work must be done in order to optimize the size of these filters.

The real challenge for the MC is to be accepted in the market. In order to achieve this goal the MC must overcome the VSI-AFE solution in terms of costs, size and reliability.

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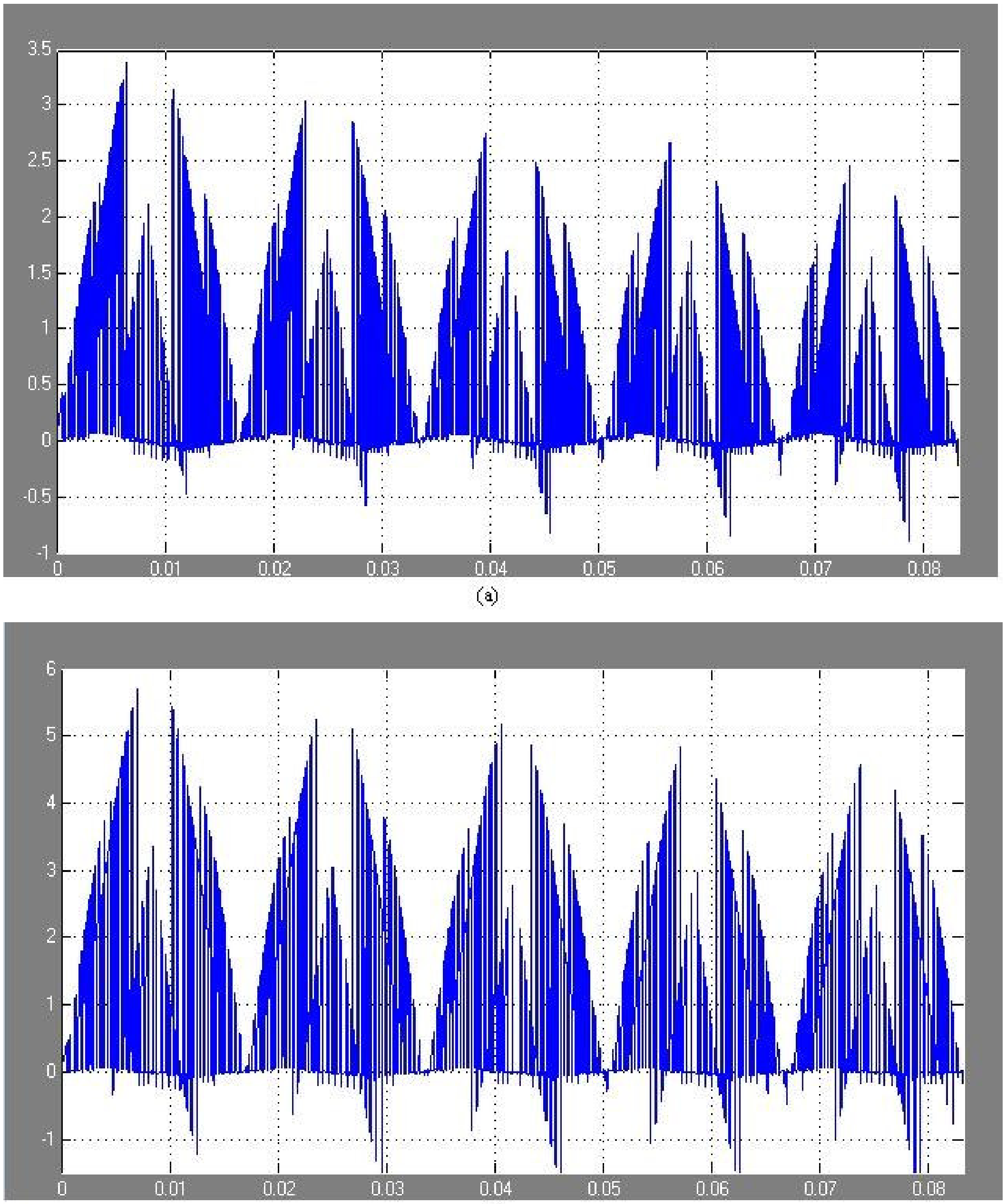

(b)

Figure 11. Input current with loaded induction motor for q = 0.866; 3 hp, $R_s = 0.277\ \Omega$, $R_r = 0.183\ \Omega$, N_r = 1766.9rpm, $L_m = 0.0538$ H, $L_r = 0.05606$ H, $L_s = 0.0533$ H, f_o= 60 Hz, f_s = 2 kHz.

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