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TORQUE RIPPLE MINIMIZATION OF A THREE PHASE MATRIX CONVERTER FED BLDC MOTOR

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Abstract: The Matrix Converter (MC) is capable of synthesizing variable magnitude and frequency output voltage while maintaining desired input power factor and it eliminates the need for DC link capacitors. This has led to the broad classification of matrix converters as indirect matrix converter (IMC) on the presence of a DC link and Direct MC(DMC) based on the absence of a DC link. In this paper, a three phase IMC is used to drive the three phase BLDC motor, which consists of a Current Source Rectifier (CSR) and a Voltage Source Inverter(VSI) connected via a fictitious DC link. Space-vector modulation is used to generate the gate pulses for the CSR and the gate pulses for the VSI are generated based on the rotor position of the BLDC rotor. The PI speed controller is used hereto improve the speed response of the motor and a PI current controller is used to minimize the torque ripples. The IMC fed BLDC motor is simulated using Matlab software package and the results of open loop and closed loop systems are compared and validated.

Keywords: Indirect matrix converter (IMC), Permanent magnet Brushless DC Motor, PI Controller, Current source rectifier(CSR), Voltage source inverter(VSI), Space Vector PWM(SVPWM).

I. INTRODUCTION

Permanent magnet brushless DC (BLDC) motor is increasingly used in automotive, industrial, and household products because of its high efficiency, high torque and lower maintenance [1,2]. A BLDC motor is designed to develop the trapezoidal back EMF with square wave currents to generate the constant torque. Three hall position sensors are used to determine the position of the rotor, each are displaced by 120 electrical degree[3-6]. Since 180° magnetic arc rotor is used here, the two phase conduction mode is preferred.

BLDC motors are traditionally driven by Pulse Width Modulated Voltage Source Inverters (PWM-VSI). However it has certain disadvantages like need of additional filter elements at input and output side, the poor quality of output waveforms and harmonics. The harmonics mainly depends on stability of DC link voltage. Compared with these conventional converters, matrix converters has the most desirable features of sinusoidal input current, regeneration capability, generation of load voltage with arbitrary amplitude and frequency[9,10].Fig.1. shows the general block diagram of matrix converter fed BLDC motor.

In this paper, a BLDC motor is fed by a three-phase indirect matrix converter (IMC)and the IMC is constructed from 18 back-to-back IGBT switches which drives the BLDC motor .The IMC is considered as a CSR and a VSI connected via a fictitious DC link. The switching algorithm for CSR is based on space-vector modulation (SVM) [11].SVM allows direct control of input current and hence the harmonic contentsare reduced. The inverter gate signals are generated by decoding the halleffect signals of the BLDC motor and the three-phase output of the converter are given to the stator windings of BLDC motor.

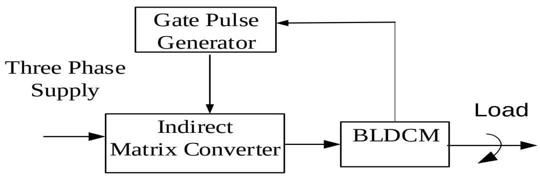

Fig.1. Block Diagram of Matrix Converter Fed BLDC Motor

In this paper, a control strategy using a PI speed and current control unit is proposed, designed and compared with the open loop system. The proposed control system guarantees the BLDC motor driven at the set speed, over the entire operating range and reduced torque ripples, while maintaining the three phase source side requirements like sinusoidal current, improved displacement factor etc.IMC fed BLDC motor drive is implemented in Matlab/ Simulink and simulation results were presented.

Next to the introduction part, the rest of the paper is organized as follows. Section II deals with the Matrix converter types and its switching strategy.Section III presents fundamentals and switching of BLDC motor.Section IV describes the MC fed BLDCM in open loop. Section V outlines the PI speed and current control scheme as used in the Matrix converter and the results and discussions are presented. Comparative analysis between open loop and closed loop system is discussed in Section VI.Finally conclusions are summarizedand presented in section VII.

II. Matrix Converter (MC)

Matrix Converter has an array of $m \times n$ bidirectional switches directly connect a “m” input phases to “n” output phases with variable magnitude and frequency output

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voltage.Matrix converters have the capability ofpower regeneration and suppression of input current harmonics, hence they areidentified as optimum drives for applications ranging from cranes, elevators and centrifugal pumps, to air-conditioning fans and feed-water pumps.Basic topologies of MC are direct matrix converter(DMC), indirect matrix converter(IMC) and sparse matrix converter.

A. Direct Matrix Converter(DMC)

The basic configuration of three phase to three phase direct matrix converter was introduced by Venturini in 1980 [13]. It consists of nine bidirectional switches that connect each output phase to each input phase which is capable of conducting currents and blocking voltages of both polarities, depending on control signal [15].

B. Indirect Matrix Converter

An IMC topology without a DC link capacitor was suggested by ziogas in 1986 [16]and analyzed in detail by Kim et al in 1998 [17].The IMC features a two stage power conversion with a unipolar current source input stage with six bidirectional switches(CSR) and a voltage source converter output stage(VSI)which is shown in Fig.2[14].

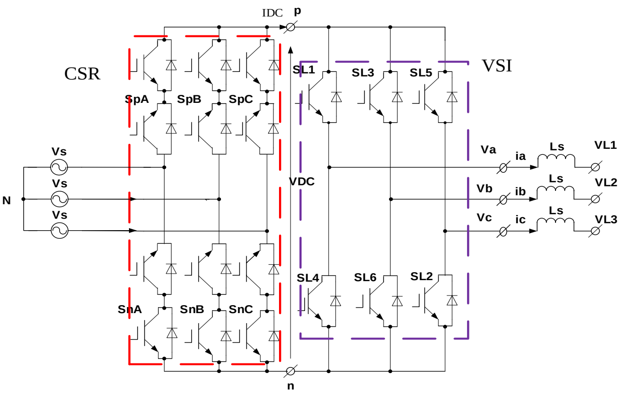

Fig.2. Indirect Matrix Converter

The DC side voltage should be positive for all time to ensure proper operation of this converter. The main objective of the CSR is to maintain pure sinusoidal input current waveforms as well as maintain positive voltage on the DC side. Assuming a stiff voltage source as the input and stiff current sink as the output, the DC side voltage is essentially decided by the switching functions of the rectifier and the input voltage and the DC side current is determined by the combination of output switching functions and output current.

Space Vector Modulation for IMC

The MC modulation methods are developed by Venturini and Alesina in 1980 which is referred to as the "direct modulation method ".A different types of modulation was introduced by Rodriguez in 1983 based on "fictitious DC link".The SVM was applied for MC by Huber and Boroyevich in 1989 [15].The SVM for IMC was developed by Huber in 1995 [11].In the SVM, the rectification stage is considered as the standalone CSR.Due to the inductive nature of the load, the input current i_p is assumed constant for each switching period. Hence the load of the rectifier is assumed to be constant DC current sink with the current $i_p = I_{DC}$. At any instant, the input lines should never be short circuited which results,

$$S_{kA} + S_{kB} + S_{kC} = 1, \qquad k \in \{p, n\} \tag{1}$$

Where S_{kA}, S_{kB} and S_{kC} are the switching function of bidirectional switches. The rectifier should not only generate the DC link voltage but also has to maintain the sinusoidal and balanced input current with controllable displacement angle with respect to the input voltage.

In SVM, the input current is transformed into six distinctive input space vectors as shown in Fig.3. The magnitude of these current vectors depends on the instantaneous value of the current i_p. The switching combination for the CSR is shown in Table 1.

Each current vector shows the connection of input phases with the DC link. The current vector I_3 represents that the input phase B is connected with the p terminal and the input phase A is connected with the n terminal of the DC link. The switches $S_{pB}$and $S_{nA}$are ON at this instant. To maintain the displacement factor, the input currents have to be synchronized with the input voltages.

TABLE 1
SWITCHING COMBINATION FOR THE CSR

Switching State						**Output voltages**			**Input currents**		
S_{pA}	S_{pB}	S_{pC}	S_{nA}	S_{nB}	S_{nC}	V_{pz}	V_{nz}	V_{pn}	i_A	i_B	i_C
1	0	0	0	0	1	V_A	V_C	V_{AC}	i_p	0	$-i_p$
0	1	0	0	0	1	V_B	V_C	V_{BC}	0	i_p	$-i_p$
0	1	0	1	0	0	V_B	V_A	V_{BA}	$-i_p$	i_p	0
0	0	1	1	0	0	V_C	V_A	V_{CA}	$-i_p$	0	i_p
0	0	1	0	1	0	V_C	V_B	V_{CB}	0	$-i_p$	i_p
1	0	0	0	1	0	V_A	V_B	V_{AB}	i_p	$-i_p$	0
1	0	0	1	0	0	V_A	V_A	0	0	0	0
0	1	0	0	1	0	V_B	V_B	0	0	0	0
0	0	1	0	0	1	V_C	V_C	0	0	0	0

The reference input current space vector is expressed as

$$\vec{i_i} = I_i e^{j(\omega_i t - \varphi_i)} = I_i \angle \theta_i \tag{2}$$

The reference current vector is synthesized into three vectors: I_α, I_β and I_0

$$\vec{i_i} = d_\alpha I_\alpha + d_\beta I_\beta \tag{3}$$

d_α and d_β are the duty cycles of I_α and I_β within one switching period respectively.

$$d_\alpha = m_R \sin\left(\frac{\pi}{3} - \theta_i\right) \tag{4}$$

$$d_\beta = m_R \sin\theta_i \tag{5}$$

$$0 \le m_R \le 1$$

Where, $m_R = \frac{I_i}{i_p}$ is the modulation index of the rectifier.

The duty cycle of the zero vector I_0 is calculated using

$$d_0 = 1 - d_\alpha - d_\beta \tag{6}$$

Average DC link voltage V_{pn} generated by the CSR is

$$V_{pn} = \frac{3}{2} V_i m_R \cos\varphi_i \tag{7}$$

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Rotor Position	Forward Rotation						Switches
	Hall Sensor Output			Output Phase			
	H1	H2	H3	A	b	C	
0 - 60°	1	0	0	1	0	-1	S_{L1} , S_{L2}
60 - 120°	1	0	1	1	-1	0	S_{L1} , S_{L6}
120 -180°	0	0	1	0	-1	1	S_{L5} , S_{L6}
180 -240°	0	1	1	-1	0	1	S_{L5} , S_{L4}
240 -300°	0	1	0	-1	1	0	S_{L3} , S_{L4}
300 -360°	1	1	0	0	1	-1	S_{L3} , S_{L2}

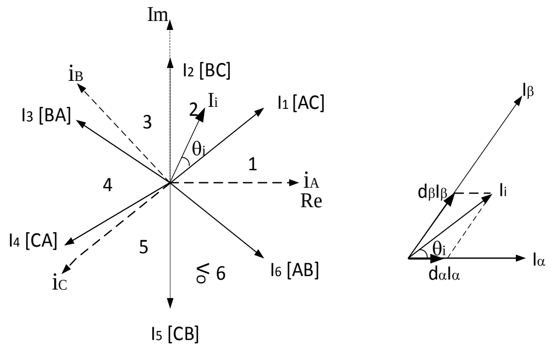

Fig. 3 Input Current vector and reference vector

III. OPERATION OF BLDC MOTOR

In conventional DC motor, mechanical commutation is achieved using brushes which results in friction, noise, sparks and these drawbacks can be overcome by BLDC motors (BLDCM). The BLDC motor has a permanent magnet in rotor and thewindings are wound in the stator [1]. The motor is supplied by three phase rectangular currentblocks of 120° duration, in which ideal motional EMF istrapezoidal. In each phase, the flat top of the back EMF is in phase with the conduction period of the phase current to generate the maximum torque. The machine needs rotor positioninformationfor every 60° electrical and these signals provide the correct commutation information to the logic circuit. Due to this, the BLDC motor rotates continuously.

A SWITCHING STRATEGY

In the 120º mode operation of inverter, two switches are turned ON at a time. Table 2 shows the switching sequence formulation based on the rotor position [18]. The switching sequence can be explained as follows. In Table 2, "1" represents positive excitation, "-1" represents negative excitation and "0" represents no current flows through the winding. For the rotor position (0º-60º), conducting devicesS_{L1} andS_{L2} are turned ON so that winding C and A gets energized with positive voltage applied to A phase and negative voltage applied to C phase.

TABLE 2
SWITCHING SEQUENCE FOR VSI

For the rotor position 60º-120º, winding B(negative voltage) and A(positive voltage) gets energized with conducting devices S_{L1} andS_{L6} . This process continues for a full electrical cycle and various switches conduct for various positions. Motor parameters used in this paper is shown in Table.3.

TABLE 3
BLDC MOTOR PARAMETERS

Motor parameters	Values
Stator phase Resistance (Ω)	3.07
Stator phase Inductance (mH)	6.75
pole pairs	2
Torque constant (Nm/A)	0.49
Inertia (kgm^2)	0.00018
Friction Factor	0.005

IV. OPEN LOOP SYSTEM

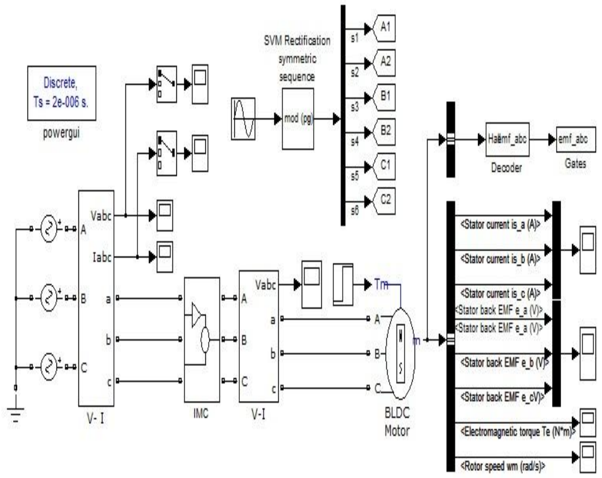
Fig.4. Simulation Diagram of Open loop MC

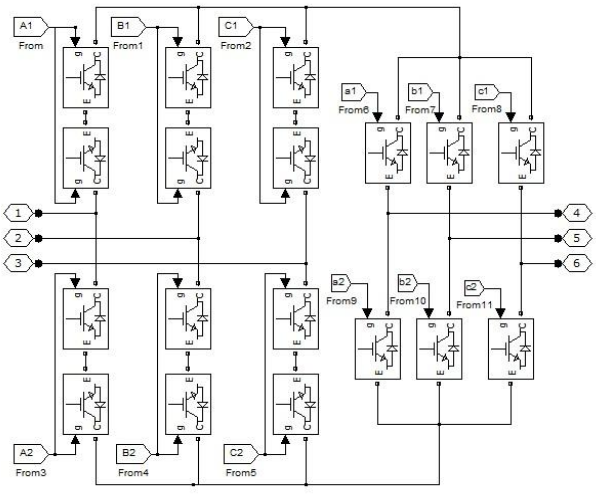
Fig. 4(b).Inside view of Indirect Matrix Converter

Space-vector modulation(SVM)is used to generate the gate pulses for CSR. The inverter gate signals are produced by decoding the Hall effect signals of the BLDC motor and the three-phase output of the converter are applied to the stator windings of BLDC motor. Fig. 4(a) Shows the Matlab / Simulink model of MC fed BLDC motor drive in openloop and Fig. 4(b) shows the inside view of IMC.

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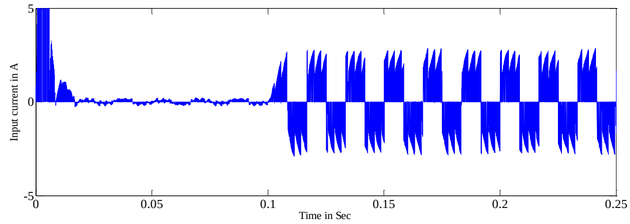
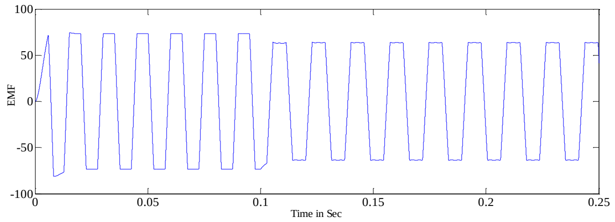
A. Simulation Results and discussions

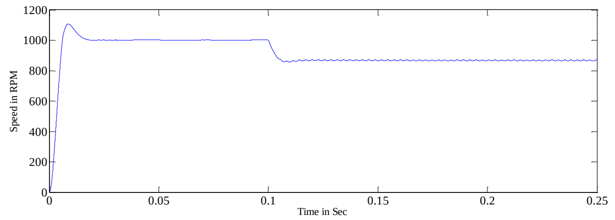
The motor is initially started with the no load. The speed of the motor reaches 1000rpm at 0.01sec. The load torque of 3Nm is applied to the machine's shaft at t = 0.1 s and shown in Fig.5(c).At this point the speed of the motor reduces from 1000rpm to 800 rpm which is shown in Fig.5(d) and the magnitude of trapezoidal back EMF also reduceswith speed is shown in Fig.5(b).The stator current increases from no load current to 2.5 A and shown in Fig.5(a).



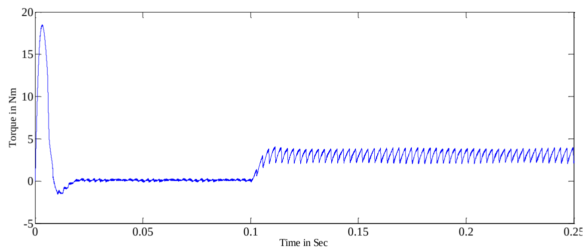
(a)



(b)



(c)



(d)

Fig.5. Simulated Waveforms of open loop a) Stator current b) EMF c)speed d) torque

V. CLOSED LOOP CONTROL AND SIMULATION RESULTS

There could be two control loops functioning simultaneously: Inner torque control loop and outer speed control loop. The inner current loop synchronises the inverter gate signals with the electromotive forces. The outer loop controls the speed of the BLDC motor.

In the speed controller, proportional and integral (PI) control action is presented to achieve better speed response and PI current control loop reduces the torque ripple of the BLDC motor. The actual speed is measured and it is compared with the reference speed in the outer speed loop and the error is given to the PI speed Controller. Hall sensors are used for measuring the actual speed of the motor.This controller generates the reference torque. In BLDC motor, the reference torque is proportional to stator current and the current reference $(I_{Ref})$is obtained from the speed controller.

$$I_{Ref} = T_{ref} / K_t \qquad (8)$$

Where K_t - Torque constant

The PWM current controller is used to reduce the torque ripples and the torque reference is decomposed into stator current references and the phase currents of the motor are sensed and compared with the respective phase current references. These current errors are given to PI controller in each phase.

The current controller's output is the reference voltage signal to interact with the PWM carrier signal to generate the gate pulses with variable duty cycle for the devices in the corresponding phase leg of the inverter.In order to achieve optimum solutions for K_p and$K_i$gains, manualtuning method is used according to the system characteristics.In this paper, the K_p and$K_i$values of speed controller are 0.137 and 1 and for the current controller are 40 and 3 respectively.Fig.6 shows the block diagram of closed loop system.The simulated diagram of closed loop system is shown in Fig.7. The motor is started at no load with reference speed of 1000 rpm at 0.01sec. At 0.05 sec, the reference speed of the motor is increased to 1100 rpm which is shown in Fig.8(b).The motor develops rated torque to bring the motor to the new operating point. The load of 3Nm is applied at 0.1s which is shown in Fig.8(c). At this point the motor draws the required higher current from the supply to meet the requirement of the load torque.

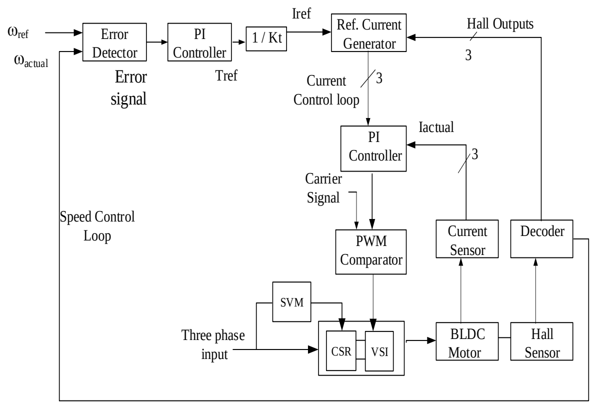


Fig.6. Block Diagram of Closed loop Control

Fig.8(a) shows the input current waveformwhich has reduced harmonic content.In the closed loop system, due to the presence of the current controller, regeneration takes place. Due to that, the current is negative eventhough the emf is positive.

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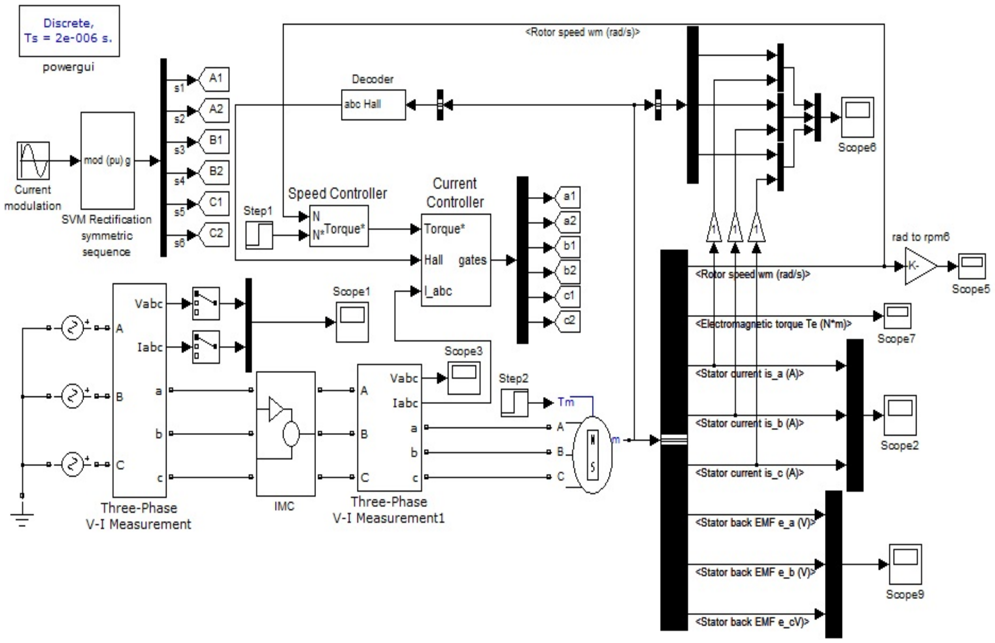
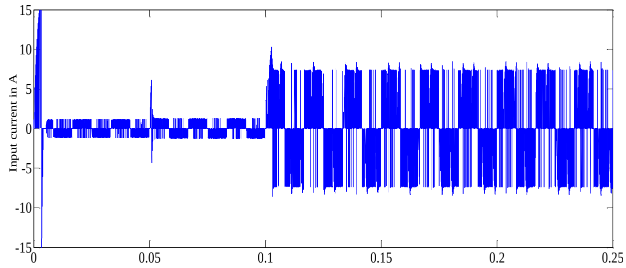
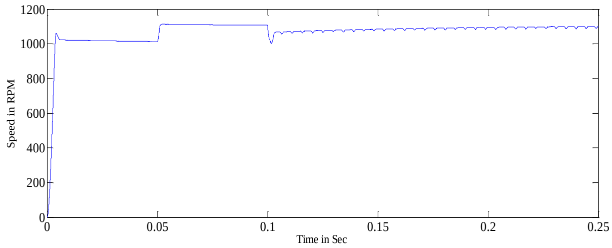


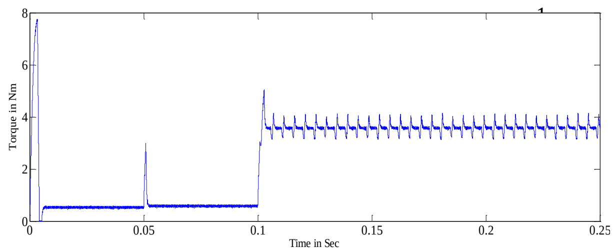
Fig.7.simulated diagram of closed loop system



(a)



(b)

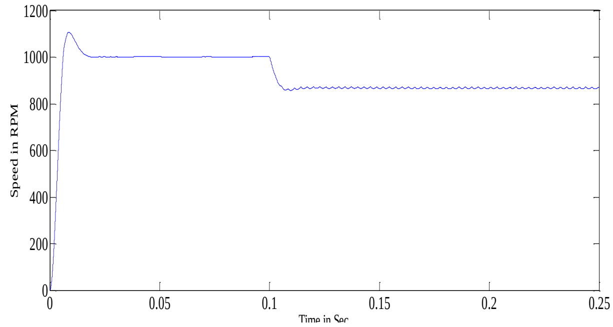


(c)

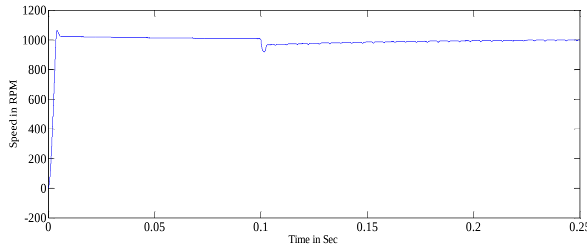
Fig.8. closed loop simulated waveforms a) Input current b) speed c) torque

VI. COMPARATIVE ANALYSIS

A. *SpeedAnalysis*



(a)



(b)

Fig.9. speed response of (a) open loop (b) closed loop control system

Fig.9 (a) & (b) shows the speed curve of open loop and closed loop control system respectively. In the closed loop system, the speed of 1000rpm is maintained as constant after the load of 3Nm whereas in the openloop, the speed is reduced from 1000rpm to 800rpm.

B. *Torque Analysis*

Figure 10 (a) & (b) shows the load torque of open loop and closed loop respectively. The torque in open loop lies in the range between 2-4 Nm. In the closed loop control, PI current controller reduces the torque ripples and the torque lies in the range between 3.32-3.85 Nm. For the load torque of 3 Nm, the torque is 2 Nm in open loop

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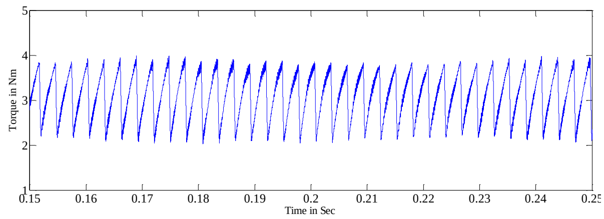
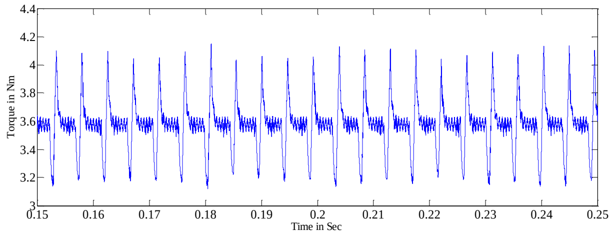
Vol. 3, Issue 2, February 2015

system whereas 0.5 Nm in the closed loop system.Comparison of speed and torque between open loop and closed loop system is shown in Table 4.



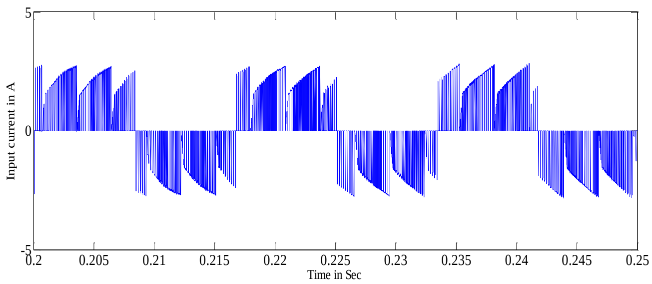
(a)



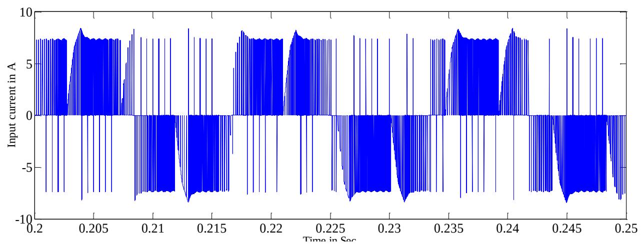
(b)

C. Input Current Analysis

Figure 4.11 (a) & (b) shows the input current of open loop and closed loop control system respectively.



(a)



(b)

Fig. 11. Input current in (a) Open loop system, (b) Closed loop control system

In the open loop system, the current is positive when the emf is positive and the current is negative when the emf is negative and produces the unidirectional torque. When the load torque is 3Nm, the speed of the motor is 800rpm and the input current is 2.8 A.

In the closed loop system, due to the presence of the current controller, regeneration takes place. Due to that, the current is negative eventhough the emf is positive. When the load torque is 3Nm, the speed of the motor is 1000 rpm and the input current is 6.2 A.

TABLE 4
COMPARISON BETWEEN OPEN LOOP AND CLOSED LOOP SYSTEM

	OPEN LOOP		CLOSED LOOP	
	No load	3Nm load	No load	3Nm Load
Speed (RPM)	1000	800	1000	1000
Torque (Nm)	0.2	2	0.26-0.36	0.5

VII. CONCLUSION

In this project, torque ripple minimization of IMC fed BLDC motor and proper switching of the IMC has been presented and simulated using MATLAB/SIMULINK. SVM technique is used to reduce the harmonic contents and it maintains sinusoidal input current. It can be concluded that the closed loop drive with PI controller offers reduced torque ripple to modulate the matrix converter for driving BLDC motors with reduced supply harmonics when compared with the openloop system.

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