Experimental implementation of Direct Torque Control of Open End Winding Induction Motor

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***Abstract*— In this paper, a modified switching algorithm for open end winding induction motor drive with less number of switching states is implemented. Open end winding induction motor requires two voltage sources operating in dual mode. With the help of two inverters, it generates 18 active voltage space vectors and three-level output voltage. The proposed algorithm is implemented to operate the induction motor drive only with two-level output voltage. Hence, the proposed algorithm is implemented only with 6 active voltage vectors and 2 null vectors. By using the proposed algorithm the induction motor drive is operated with two-level voltage and requires 8 switching states, so it provides higher switching states redundancy. The effectiveness of proposed algorithm verified experimentally with dspace DS-1104 and it is interfaced through MATLAB/simulink RTI-model.**

Keywords— Direct torque control, open end winding induction motor, two-level inverter and modified switching algorithm

I. INTRODUCTION

The most popular methods of speed control of induction motor are Field oriented control (FOC) and direct torque control (DTC). DTC became very popular due to its simple structure when compared with FOC, improved dynamic performance and direct control of flux and torque. The DTC algorithm for induction motor was first proposed by Takahashi and Noguchi in 1985 [1]. The direct torque control proposed in [1] has some drawbacks. The drawbacks of [1] are it gives high torque and flux ripples and switching frequency depends on bang-bang controllers (hysteresis). Later on, a tremendous research has been carried on DTC of induction motors to reduce its drawbacks. The switching frequency maintained as constant by using space vector modulation. In [2] SVM-DTC was implemented and it maintains constant switching frequency irrespective of rotor speed. To reduce torque and flux ripples further research has been carried on SVM-DTC [3]-[5]. The SVM-DTC requires calculation of reference voltage space vector and requires complex PI Controller. To maintain constant frequency a new DTC algorithm is developed in [6], but it requires high computational time and gives required performance for high sampling time. In [7], sensitivity analysis is applied to overcome the limitations of reference stator flux and rotor speed estimation. In [8], the authors introduced reduced loss soft switching algorithm for induction motor with the help of neuro fuzzy controllers. In this paper steady state performance was not exhibited. In [9], a new DTC algorithm is implemented for multi level inverter fed induction motors. The multi-level inverter fed induction motor drive operates with high power and voltage with lesser harmonics. In [10], model based approach based on loss optimization is implemented for induction motor drive. This requires sliding mode rotor flux observer and adaptive controller in addition to PI controller is used. This increases complexity of DTC and requires fast tracking rotor flux observer.

In [11] to improve flux and torque performance of induction motor drive type-2 fuzzy logic controller is implemented. It replaces existing PI controller with type-2 fuzzy logic controller. It provides improved dynamic performance, lesser current THD and flux distortion. It requires a complex fuzzy rule base. A new hysteresis based DTC implemented for induction motor and it is based on time taken by hysteresis controller to reach upper and lower bands [12]. In this it requires an additional torque controller and gives required performance for high sampling frequencies and it requires additional triangular carrier signals.

In [13], a simplified neuro fuzzy controller based DTC is implemented with the help of adaptive torque hysteresis controller.NFC reduces error in acceleration of motor. This method gives high dynamic performance and it needs online torque hysteresis bands adjustments. A variable hysteresis controller is used rather than fixed three level torque controller and adjustments of hysteresis bands is also difficult. In [14] DTC for induction motors is developed without using AC phase current sensors. It requires a shunt series to provide information of stator current. This algorithm is based on modified look up table and theoretical concepts are used for phase-current reconstruction.

In [15] DTC of induction motors implemented by using three two level inverters in cascaded connection and it introduces a novel switching algorithm for induction motor drive. It requires higher number of switches. From the literature, it is observed that to reduce torque and flux ripple space vector modulation technique or multi level inverter fed DTC gives better results. This paper focuses on developing the DTC algorithm for two-level inverter by reducing number of switching states of three-level inverter. To implement the proposed algorithm open end winding induction motor was

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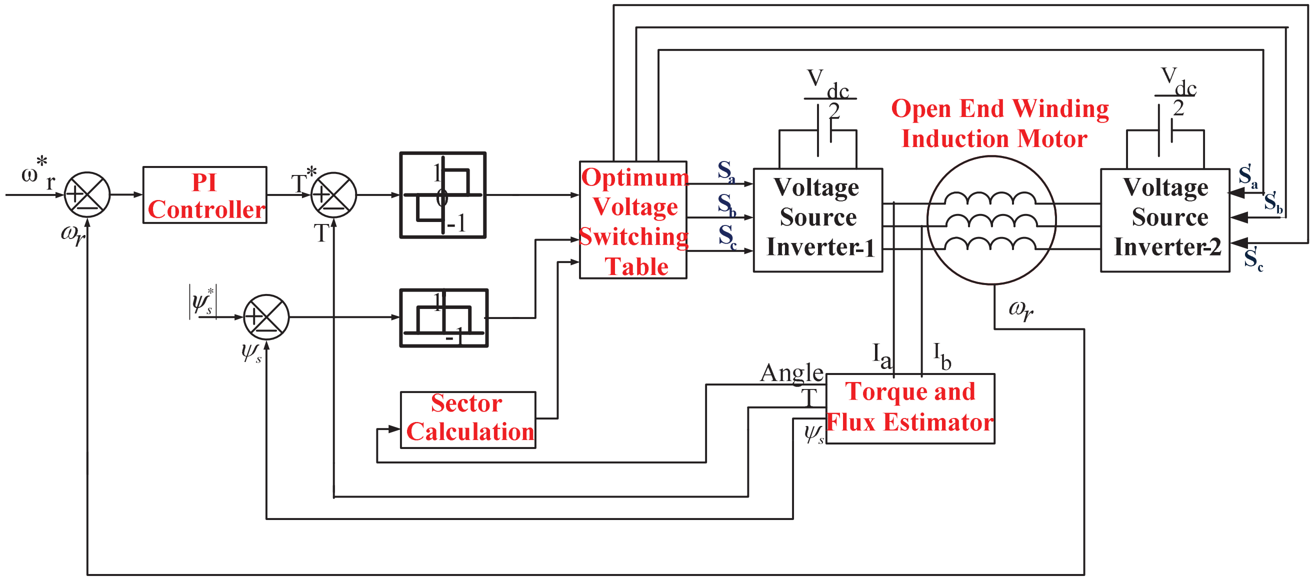


Fig. 1. Block diagram of Proposed DTC.

utilized. Open end winding induction motor requires two voltage source inverters and they should operate in dual mode [16]. In [17], direct torque control of open end winding induction motor was implemented with three-level inverter configuration. This utilizes space vector modulation to maintain constant switching frequency.

The objectives of this paper is to: Develop two-level voltage switching state algorithm for DTC of open end winding induction motor, developing voltage space vectors to obtain two-level output voltage and verification of proposed algorithm through experimentation.

II. Control Algorithm

A. Proposed DTC

The block diagram of proposed two-level DTC is as shown in Fig. 1. In the block diagram induction motor is fed with two voltage source inverters. The difference of output voltage of two inverters is used to operate the motor. In the block diagram ω_r^* is reference speed (rad/sec), ω_r is actual speed of rotor (rad/s), T^* is reference torque (N-m) obtained from speed PI controller, T is estimated torque (N-m), F_s^* is reference flux (Wb), F_s is estimated stator flux (Wb), Vdc is DC link Voltage of inverter and i_a, i_b are the stator currents.

The output voltages of inverter-1 and inverter-2 are given by (1) and (2)

$$V_{o1} = \frac{2}{3} * \frac{V_{dc}}{2} * (S_a + S_b e^{j(\frac{2\pi}{3})} + S_c e^{-j(\frac{2\pi}{3})}) \qquad (1)$$

And $$V_{o2} = \frac{2}{3} * \frac{V_{dc}}{2} * (S'_a + S'_b e^{j(\frac{2\pi}{3})} + S'_c e^{-j(\frac{2\pi}{3})}) \qquad (2)$$

The resultant output voltage of inverter (Stator voltage of induction motor) can be written as (3)

$$V_s = (V_{01} - V_{02}) \qquad (3)$$

The Switching states of two voltage source inverters to obtain two level output voltage is shown in Table I.

Fig 2, Represents arrangement of voltage space vectors to obtain two-level output voltage and it contains 6 active voltage vectors and 2 null vectors. Following is an example to realize voltage space vector. If the switching states of inverter-1 and 2 are (1,1,0) and (0,0,1) respectively. From (3), it gives magnitude of V_{dc} and phase angle of 60^0. Hence, this space vector is named as V_2.

If the switching states of inverter-1 and inverter-2 are (0,0,1) and (1,1,0) then obtained space vector is V_5.

On combining the voltage vectors V_0 to V_8 it forms like hexagon shown in Fig.2. The resultant voltage space vector is divided into six sectors. Each sector is divided with angle of 60^0. Sector-1 is from 330^0 to 30^0. Sector-2 is from 30^0 to 90^0. Sector-3 is from 90^0 to 150^0. Sector-4 is from 150^0 to 210^0. Sector-5 is from 210^0 to 270^0 and sector-6 is from 270^0 to 330^0.

Table I. Switching States of Proposed DTC.

Inverter 1			Inverter 2			Voltage Space Vectors
Sa	Sb	Sc	Sa'	Sb'	Sc'	
0	0	0	1	1	1	V_0
1	0	0	0	1	1	V_1
1	1	0	0	0	1	V_2
0	1	0	1	0	1	V_3
0	1	1	1	0	0	V_4
0	0	1	1	1	0	V_5
1	0	1	0	1	0	V_6
1	1	1	0	0	0	V_7

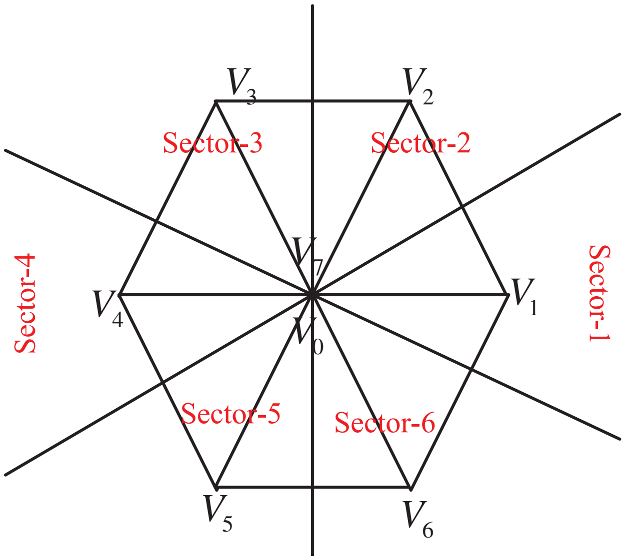


Fig. 2. Location of active voltage vectors.

B. Control Algorithm to reduce torque and flux ripple

The torque of induction motor in stationary reference frames is given by (4)

$$T = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{4}$$

On simplification (4), it can be written as

$$T = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\psi_s i_s \sin\gamma\right) \tag{5}$$

Where P is number of poles, ψ_s is stator flux linkages, i_s is stator current and γ is angle between stator flux linkage and stator current space vector. From (5) the torque of induction motor is dependent on stator flux and stator current. Therefore From (5), it is clear that lesser torque ripple can be maintained by maintaining lesser current ripple.

The dynamic changes in torque can be obtained by performing switching action to inverters 1 and 2. By performing switching action the output voltage of inverter can be controlled. The switching states of inverter are selected in such a way that they should maintain less current ripple.

The stator flux can be changed very quickly than that of rotor flux by suitable voltage vectors so the rotor flux is assumed as constant. The dynamical changes in torque can be obtained by quick change in angle between stator flux linkage and stator current.

Table II. represents application of suitable voltage vectors to increase or decrease flux and torque.

Table II. Effect of Voltage vectors on Torque and Flux

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_0
Flux	+++	++	-	---	--	+	0	0
Torque	-	++	+++	+	--	---	0	0

In Table II, +++ refers more increment, ++ increase, + indicates small increment, - indicates small decrement, -- decrease and --- large decrement. Table II gives information about effect of voltage space vectors on stator flux and angle between stator flux linkages and stator current. The voltage vectors has direct impact on stator flux, due to dynamic changes in flux it effects dynamic change of load angle and varies electromagnetic torque.

An example is illustrated to indicate impact of voltage vector by considering flux space vector in sector-1. If it is required to increase torque and flux then voltage vector V_2 is applied. If it is required to decrease flux and torque of induction motor voltage vector V_5 has to be applied. If it is required to increase torque and decrease flux then suitable voltage vector to be applied is V_3. If it is required to decrease torque and increase flux then voltage vector V_6 has to be applied.

The proposed DTC utilizes three-level torque comparator and a two-level flux comparator and information about stator flux sector. It does not depend on exact location of flux space vector, it requires in which sector the flux space vector exist. Based on outputs of torque hysteresis controller and flux hysteresis controller and flux space vector suitable voltage vector is applied. The selection of active voltage vectors based on torque and flux errors are shown in Table III and they also maintain less current ripple.

Table III. Choice of active voltage vectors in proposed DTC.

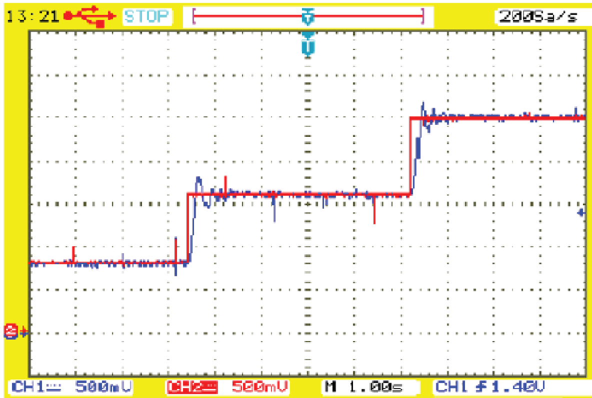
Flux Error	Torque Error	Sector 1	2	3	4	5	6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

III. Experimental Results

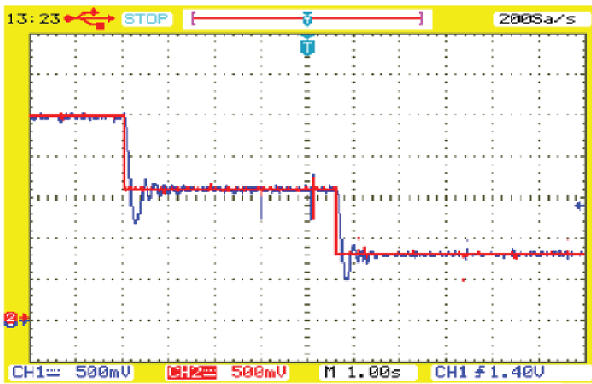
After performing mathematical analysis and modeling the required flux and torque estimators the proposed algorithm is verified experimentally. An experiment was conducted on 3-phase, 415V, 5 H.P, 1440 RPM, 6.54 A, 0.86 P.F open end winding induction motor. The rated speed of motor is 1440 RPM this is equal to 300 electrical rad/sec. The motor drive is operated at different frequencies, here the results are shown for the frequencies of 80 rad/s, 160 rad/s and 250 rad/s in forward and reverse motoring modes. The proposed DTC is verified experimentally with the help of d-space DS 1104 R&D control board.

Fig. 3 to 8 represents the experimental waveforms of proposed DTC. Fig.3 indicates the actual speed versus reference speed of motor. Fig. 3.a represents actual speed versus reference speed of induction motor drive in forward motoring mode for speed variations of 80 rad/s, 160 rad/s and

250 rad/s. Fig 3.b represents actual speed versus reference speed of motor drive for speed variations of 250 rad/s, 160 rad/s and 80 rad/s. Fig. 3.c represents the operation of motor drive in forward and reverse motoring for speeds of 80 rad/s and -80 rad/s.



(a)



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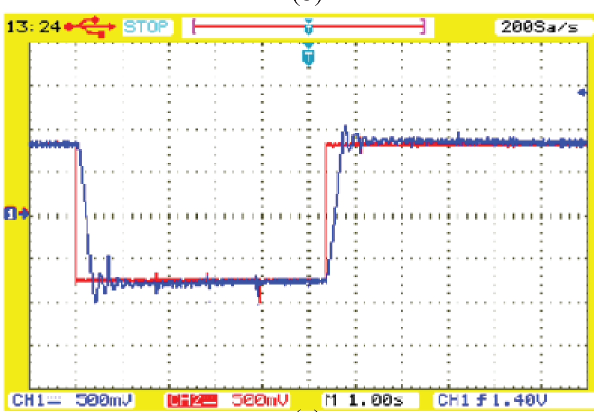
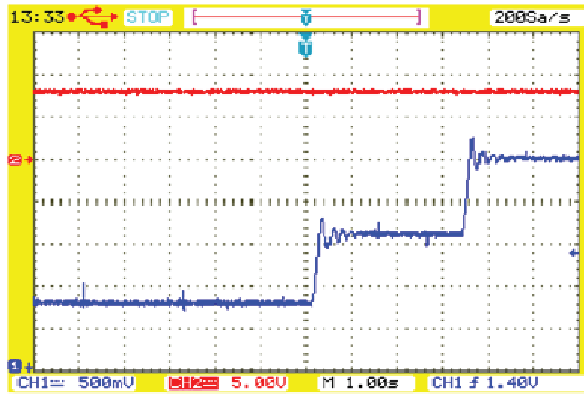


(c)

Fig. 3. Experimental Response of Proposed DTC: a) Forward motoring (Speed Increase) b) Forward Motoring (Speed Decrease) c) Variation of speed from reverse motoring to forward motoring. (Red- Reference Speed and 1 Div= 50 rad/s) (Blue- Actual Speed and 1 Div=50 rad/s).

Fig.4. represents actual speed and flux of motor drive. Fig. 4.a represents speed and flux of motor drive in forward motoring for the speed variations of 80 rad/s, 160rad/s and 250 rad/s. Fig. 4.b represents actual speed and flux of motor drive in reverse motoring for speeds variations of -80 rad/s, -160 rad/s and -250 rad/s. Fig. 4.c represents actual speed and flux of motor drive in forward and reverse motoring modes for speed variations of 80 rad/s to -80 rad/s. From Fig. 4, it is evident that the stator flux can be maintained as constant for large changes of motor speed.



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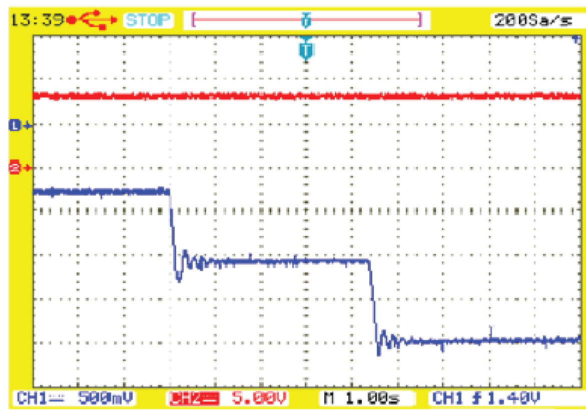

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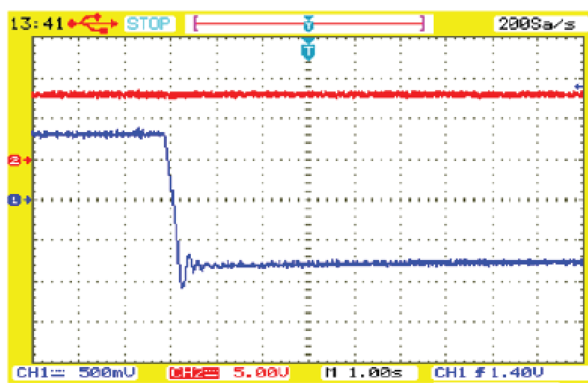
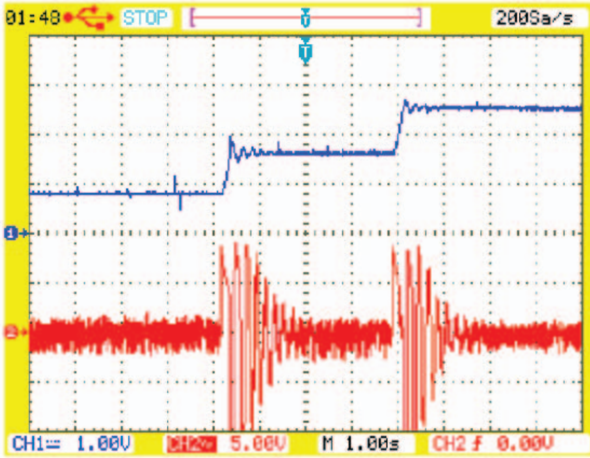
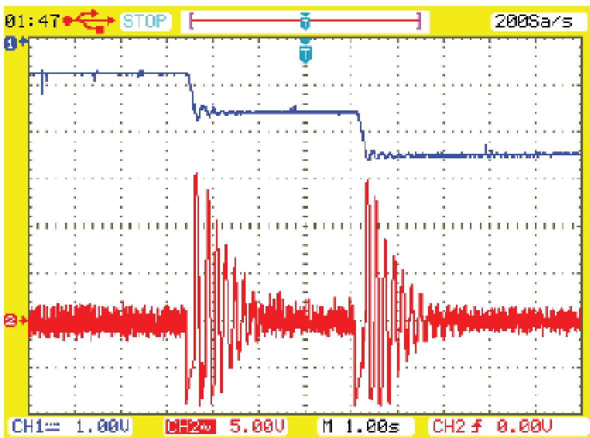


(c)

Fig. 4. Experimental Response of Proposed DTC: a) Actual speed and flux in Forward Motoring. b) Actual speed and flux in reverse Motoring. c) actual speed and flux in forward and reverse motoring. (Red- flux and 1 Div= 0.5 Wb) (Blue-Speed and 1 Div=50 rad/s).



(a)



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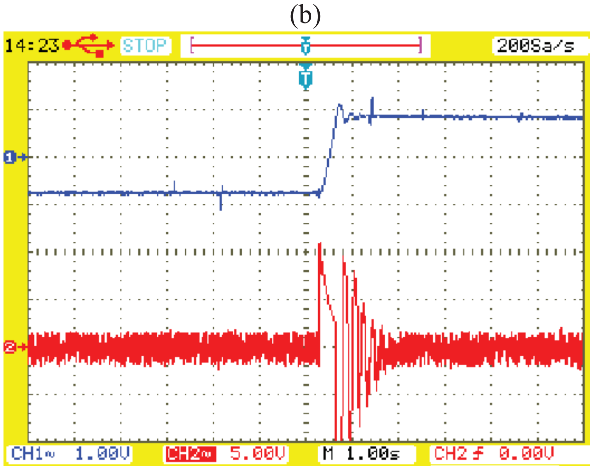
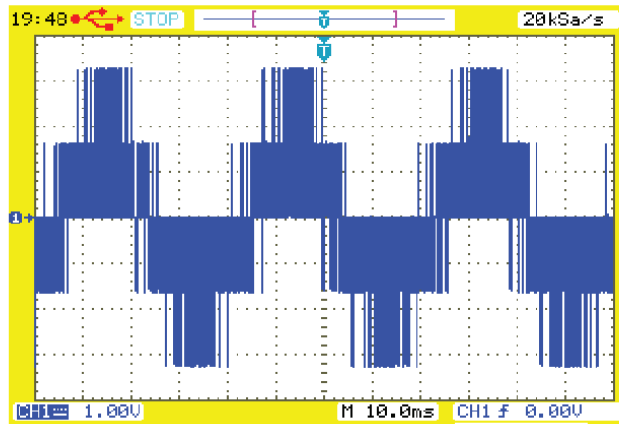


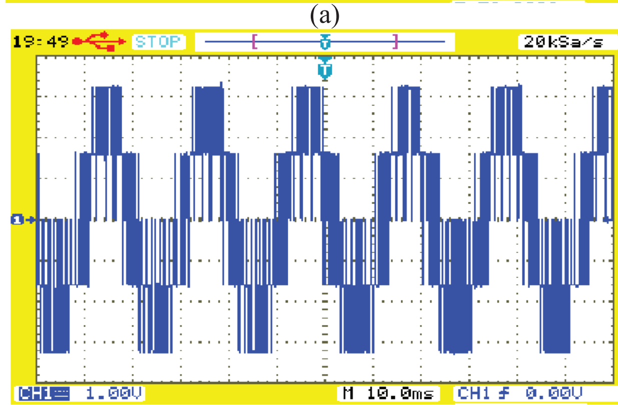
(c)

Fig. 5. Experimental Response of Proposed DTC: a) Actual speed and torque in Forward Motoring. b) Actual speed and torque in reverse Motoring. c) actual speed and torque in reverse and forward motoring. (Red- Torque and 1 Div= 5 N-m) (Blue-Speed and 1 Div=100 rad/s).

Fig. 5 represents actual speed and torque of motor drive. Fig. 5.a represents actual speed and torque of motor drive in forward motoring for the speed variations of 80 rad/s, 160 rad/s and 250 rad/s. Fig. 5.b represents actual speed and torque of motor drive in reverse motoring for the speed variations of -80 rad/s, -160 rad/s and -250 rad/s. Fig. 5.c represents reverse and forward motoring of drive for speed changes of -80 rad/s to 80 rad/s. From, Fig. 5 it is observed that the motor drive was producing high dynamic performance. The rated torque of motor is 14 N-m and from Fig. 5, the max torque ripple produced by motor is 3 N-m at 250 rad/s.



(a)



(b)

Fig. 6. Voltage of proposed DTC: a) at 160 rad/s b) 250 rad/s (1 Div=150V).

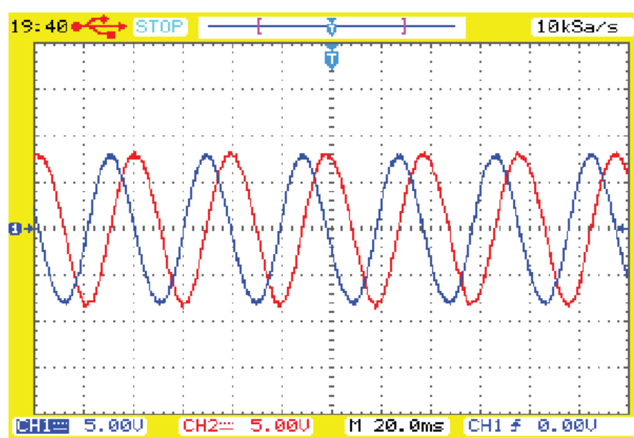


Fig. 7. d-axis and q-axis flux at 160 rad/s. (1 Div=0.5 Wb)

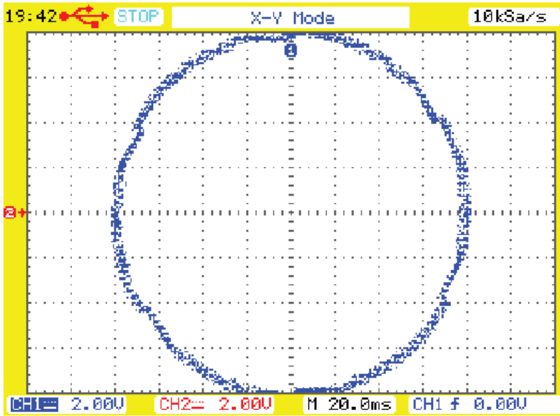


Fig.8. Flux locus of proposed DTC.

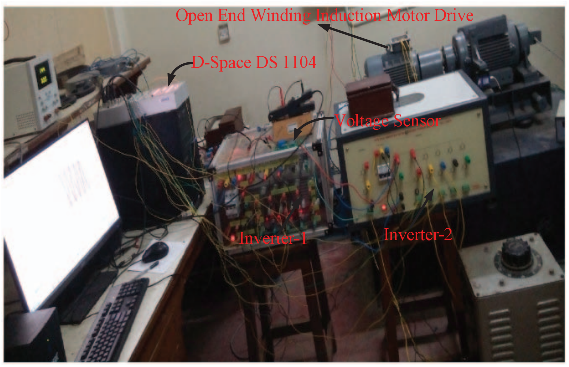


Fig.9. Experimental Setup.

Fig. 6 represents output voltage of inverter (a-Phase voltage) in forward motoring for speeds of 160 rad/s and 250 rad/s. Fig. 7 represents direct axis and quadrature axis flux of motor drive in forward motoring at a speed of 160 rad/s. Fig.8 represents flux locus of motor drive. Fig. 9 represents photograph of experimental setup.

The experimental results of proposed DTC in forward and reverse motoring fed with the two-level inverter are as shown from Fig. 3 to 8. The proposed DTC for open end winding induction motor is implemented with 6 active voltage vectors and 2 null vectors by decoupling the remaining switching states of three-level inverter. Hence, the proposed algorithm gives higher redundancy of switching states and provides simple control algorithm without losing benefits of conventional DTC.

IV. Conclusion

In this paper, a modified switching algorithm is implemented for open end winding induction motor fed with two two-level voltage source inverters. The voltage space vector diagram to obtain two-level output voltage is implemented with 8 switching states. The proposed algorithm gives high redundancy of switching states. The proposed algorithm is tested at low (80 rad/s), medium (160 rad/s) and high (250 rad/s) frequencies in forward and revere motoring. The affect of voltage vectors on torque and flux was described. The proposed DTC provides high dynamic performance and simple control algorithm to control flux and torque.

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