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Reduction of Torque & Flux Ripple of 3-Φ Asynchronous Machine Using Multi-Level Inverter

M. V. G. Vara Prasad[1], R. S. Ravi Sankar[2], Dr. K. Alice Mary[3]

PG Student [P&ID], Dept. of EEE, Vignan's IIT, Duvvada, Visakhapatnam, India [1]

Associate professor, Dept. of EEE, Vignan's IIT, Duvvada, Visakhapatnam, India [2]

Principal in Vignan's IIT, Duvvada, Visakhapatnam, India [3]

ABSTRACT: This paper proposes a approach in direct torque control (DTC) i.e. the applied voltage is a function of rotor speed and describes a new switching state algorithm which gives an optimum flux & torque ripple at steady state condition & fast dynamic torque response [1]. This approach is applied to two-level and three-level inverters. Simulation results for proposed two level DTC and proposed three level DTC techniques for various speed conditions (very low, low, rated, and high speeds) are compared. The proposed two level and three level inverters fed three phase asynchronous machine using Micro Controller in open loop is implemented through hardware realization.

Keywords: Direct Torque Control, Multilevel Inverter, Induction Motor, Switching State Algorithm.

I.INTRODUCTION

The difference between conventional Direct Torque Control (conventional DTC) and proposed Direct Torque Control (proposed DTC) i.e. a model of three level Neutral Point Clamped (NPC) inverters (cascaded two level inverters). The control strategy optimizes the current ripple (Flux and Torque ripple) in steady state condition and fast dynamic torque response in transient state. The proposed model type inverters are used because they are provided high safety voltages with less harmonic components compare to two level structures [7]. As the number of levels is increasing the implementation of space vector modulation technique (SVPWM) becomes difficult, because the design of flux and torque controller for three level inverter is difficult [3].

So a proposed switching state algorithm is used to trigger the switching devices. And simulation results are observed for both proposed two and three level DTC techniques for various speed conditions (very low <25% of rated speed, low 25% to 50% of rated speed, rated, and high >50 % of rated speeds). And it is observed those torque and stator flux ripples are lesser for proposed three level DTC. With available results of both proposed two and three level DTC laid a path for open loop hardware for both two and three level inverter using Micro Controller is enhanced

II. MODELING OF INDUCTION MOTOR

The modeling of Induction Motor in stationary reference frame using Stanley model is as follows [13],

$$\left.\begin{aligned}\psi_{qs} &= L_s i_{qs} + L_m i_{qr}\\ \psi_{ds} &= L_s i_{ds} + L_m i_{dr}\\ \psi_{qr} &= L_r i_{qr} + L_m i_{qs}\\ \psi_{dr} &= L_r i_{dr} + L_m i_{ds}\end{aligned}\right\} \quad (1)$$

$$\left.\psi_{qm} = L_m (i_{qs} + i_{qr})\right\} \quad (2)$$

$$\psi_{dm} = L_m(i_{ds} + i_{dr})$$

From equation (1) and (2) we get

$$\left.\begin{aligned} v_{ds} &= R_s i_{ds} + p\psi_{ds} \\ v_{qs} &= R_s i_{qs} + p\psi_{qs} \\ v_{dr} &= R_r i_{dr} + \omega_r \psi_{qr} + p\psi_{dr} \\ v_{qr} &= R_r i_{qr} - \omega_r \psi_{dr} + p\psi_{qr} \end{aligned}\right\} \qquad (3)$$

Since the rotor windings are short circuited, the rotor voltages are zero. Therefore

$$\left.\begin{aligned} R_r i_{dr} + \omega_r \psi_{qr} + p\psi_{dr} &= 0 \\ R_r i_{qr} - \omega_r \psi_{dr} + p\psi_{qr} &= 0 \end{aligned}\right\} \qquad (4)$$

From equation (4), we have

$$\left.\begin{aligned} i_{dr} &= \frac{-p\psi_{dr} - \omega_r \psi_{qr}}{R_r} \\ i_{qr} &= \frac{-p\psi_{qr} - \omega_r \psi_{dr}}{R_r} \end{aligned}\right\} \qquad (5)$$

By solving the equations (1), (2), (3), (4) and (5) we get the following equations

$$\psi_{ds} = \int (v_{ds} - R_s i_{ds})dt \qquad (6)$$

$$\psi_{qs} = \int (v_{qs} - R_s i_{qs})dt \qquad (7)$$

$$\psi_{dr} = \frac{-L_r \omega_r \psi_{qr} + L_m i_{ds} R_r}{R_r + SL_r} \qquad (8)$$

$$\psi_{qr} = \frac{L_r \omega_r \psi_{dr} + L_m i_{qs} R_r}{R_r + SL_r} \qquad (9)$$

$$i_{ds} = \frac{v_{ds}}{R_s + sL_s} - [\frac{\psi_{dr} s L_m}{L_r(R_s + sL_s)}] \qquad (10)$$

$$i_{qs} = \frac{v_{qs}}{R_s + sL_s} - [\frac{\psi_{qr} s L_m}{L_r(R_s + sL_s)}] \qquad (11)$$

The electromagnetic torque of the induction motor in stator reference frame is given by

$$T_e = \frac{3}{2}\frac{p}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \qquad (12)$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}(i_{qs}\psi_{dr} - i_{ds}\psi_{qr}) \tag{13}$$

The electro-mechanical equation of the induction motor drive is given by

$$T_e - T_L = \frac{2}{p} J \frac{d\omega_r}{dt} \tag{14}$$

This model is used when stator variables are required to be actual i.e. the same as in the actual machine stator and rotor variables can be fictitious. This reduces the number of competitions and thus lends themselves to real time control applications in high performance variable speed drives requiring the computation of stator currents, flux linkages and electromagnetic torque.

III. CONTROL METHOD

Two stator currents i_a and i_b are sensed. stator voltage and currents as d-q vectors in the stationary reference frame are computed and the stator flux and electric torque are calculated and compared with their reference values using the hysteresis comparators as shown in figure 2 and then the output of this comparator are fed to the look up table of switching information to select an appropriate inverter voltage vector which is applied based on the position of the stator flux and the required changes in magnitude of stator flux and torque, thus the selected voltage vector will be applied to asynchrous motor. For two level inverter there are six equally spaced voltages having the same magnitude and zero voltage vectors as shown in table 1. And for three level inverter there are eighteen equally spaced voltages having the same magnitude and zero voltage vectors for certain speed operation of asynchronous drive is as shown in table 2 and optimum switching is shown in table 3. Hence each sector in two level inverter is of 60^0 and similarly for three level inverter it is 30^0

The control method proposed is as shown below

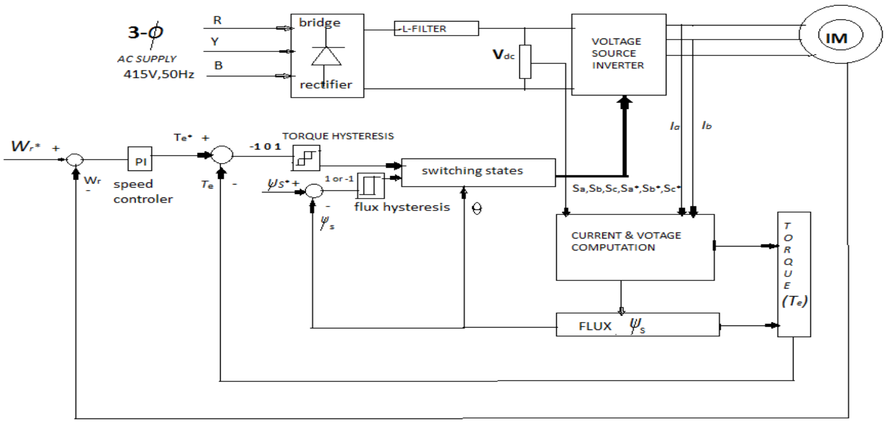

Figure 1: The control approach of three level inverter

In DTC torque and flux are controlled independently by selecting the optimum voltage space vector for entire switching period and the error signal is given to the hysteresis band, for small errors the motor torque may exceed the upper/lower torque limit [10]. The slip frequency can be controlled by introducing zero vectors. Switching frequency always varies according to the width of hysteresis band. Three level inverter is proposed in this paper as the harmonics are lesser compared to the two level inverter.

Table 1: Switching table for two level inverter [4], [8]

Hysteresis Controller		Sector Selection θ_c (k)					
Ψ	τ	Sector Θc (1)	Sector Θc (2)	Sector Θc (3)	Sector Θc (4)	Sector Θc (5)	Sector Θc (6)
1	1	U_2 110	U_3 010	U_4 011	U_5 001	U_6 101	U_1 100
	0	U_7 111	U_8 000	U_7 111	U_8 000	U_7 111	U_8 000
	-1	U_6 101	U_1 100	U_2 110	U_3 010	U_4 011	U_5 001
-1	1	U_3 010	U_4 011	U_5 001	U_6 101	U_1 100	U_2 110
	0	U_8 000	U_7 111	U_8 000	U_7 111	U_8 000	U_7 111
	-1	U_5 001	U_6 101	U_1 100	U_2 110	U_3 010	U_4 011

Table 2: Switching table for three level inverter

Hysteresis Controller		Sector Selection Θc(k)											
Ψ	τ	Θ1	Θ2	Θ3	Θ4	Θ5	Θ6	Θ7	Θ8	Θ9	Θ10	Θ11	Θ12
1	1	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U7	U8
	0	U0	U0	U0	U0	U0	U0	U0	U0	U0	U0	U0	U0
	-1	U17	U18	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16
-1	1	U11	U12	U13	U14	U15	U16	U17	U18	U7	U8	U9	U10
	0	U0	U0	U0	U0	U0	U0	U0	U0	U0	U0	U0	U0
	-1	U15	U16	U17	U18	U7	U8	U9	U10	U11	U12	U13	U14

Where,
U_0 - 000000000000, U_1 - 110001101010, U_2 - 111000101010, U_3 - 011100101010, U_4 - 001110101010,
U_5 - 000111101010, U_6 -100011101010, U_7 - 110001110001, U_8 - 110001111000, U_9 - 111000111000,
U_{10} - 011100111000, U_{11} - 011100011100, U_{12} -011100001110, U_{13} - 001110001110, U_{14} - 000111001110,
U_{15} - 000111000111, U_{16} - 000111100011, U_{17} - 100011100011, U_{18} - 110001100011

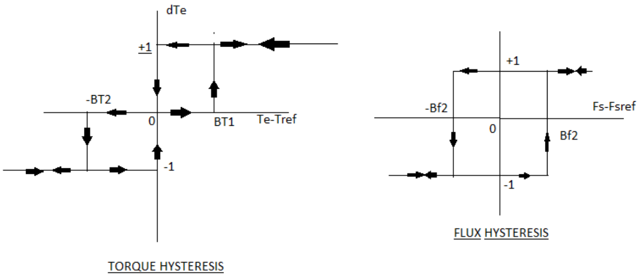

Figure 2: Torque and Flux Hysteresis

IV. OPERATION OF INDUCTION MOTOR AT VARIOUS SPEEDS FOR THREE LEVEL INVERTER

The choice of voltage vector between $V_{1'}$ to $V_{6'}$ vectors and null vector V0 is selected for very low speed operation. The voltage vector is divided in 12 sectors in α-β plane as shown in figure 3. The selection of voltage vectors depends on the flux error, torque error and also sector number. For example, the selection of $V_{1'}$, $V_{2'}$& $V_{6'}$ voltage vectors increases the stator flux magnitude for any position of Ψs in sector 1 similarly $V_{3'}$, $V_{4'}$& $V_{5'}$ voltage vectors decreases the stator flux magnitude. Positive torque errors are compensated by selecting $V_{2'}$ and V_3' voltage vectors in sector 1 and negative torque errors are compensated by selecting V_5' and V_6' in the same sector.

Table 3: For different speed operations the choice of voltage vectors in optimization of torque and flux ripple

	Very Low Speed	Low Speed	High Speed
Range	<25% of rated speed	25% - 50% of rated speed	> 50% of rated speed
Choice of Voltage vector	V_1' to V_6' & V_0 (null vector)	V_1 to V_6 & V_0 (null vector)	V_7 to V_{18} & V_0 (null vector)
Increase in Magnitude Of Stator Flux	V_1', V_2' & V_6'	V_1 , V_2 & V_6	V_7 , V_8 & V_9
Decrease in Magnitude Of Stator Flux	V_3', V_4' & V_5'	V_3, V_4 & V_5	V_{11}, V_{12} & V_{15}
Compensation Of Positive Torque Error (anti-clock wise)	V_2' & V_3'	V_2 & V_3	V_9, V_{10} & V_{11}
Compensation Of Negative Torque Error (clock wise)	V_5' & V_6'	V_5 & V_6	V_{15}, V_{16} & V_{17}

The choice of voltage vector between V_1 to V_6 vectors and null vector V_0 is selected for low speed operation. The voltage vector is divided in 12 sectors in α-β plane as shown in figure 5. The selection of voltage vectors depends on the flux error, torque error and also sector number. For example, the selection of V_1, V_2& V_6 voltage vectors increases the stator flux magnitude for any position of Ψs in sector 1 similarly V_3, V_4& V_5 voltage vectors decreases the stator flux magnitude. Positive torque errors are compensated by selecting V_2 and V_3 voltage vectors in sector 1 and negative torque errors are compensated by selecting V_5 and V_6 in the same sector.

The choice of voltage vector between V_7 to V_{18} vectors and null vector V_0 is selected for high speed operation. The voltage vector is divided in 12 sectors in α-β plane as shown in figure 5. The selection of voltage vectors depends on the flux error, torque error and also sector number. For example, the selection of V_7, V_8& V_9 voltage vectors increases the stator flux magnitude for any position of Ψs in sector 1 similarly V_{11}, V_{12} & V_{15} voltage vectors decreases the stator flux magnitude. Positive torque errors are compensated by selecting V_9, V_{10} and V_{11} voltage vectors in sector 1 and negative torque errors are compensated by selecting V_{15}, V_{16}& V_{17} in the same sector.

V. OPERATION OF VOLTAGE VECTORS TO OPTIMIZE TORQUE AND FLUX RIPPLE

As the flux and torque ripples are function of current ripple and in order to optimize the torque and flux ripples of 3-Φ asynchronous machine is based on reduction of torque ripple [10].

$$\psi_r = (L_r/L_m)\psi_s - \left(L_s L_r - L_m^2/L_m\right) i_s \qquad (15)$$

$$d\psi_r/dt = (L_r/L_m)\,d\psi_s/dt - \sigma\, di_s/dt \qquad (16)$$

$$di_s/dt = \left[AV_s - jB\psi_{rs}\omega_r\right] \qquad (17)$$

Where $A = L_r / \sigma L_m \quad B = 1/\sigma$

From equation (17) $[AV_{sr}]$ is the applied voltage and $[jB\psi_{rs}\omega_r]$ is the back emf of the stator winding.

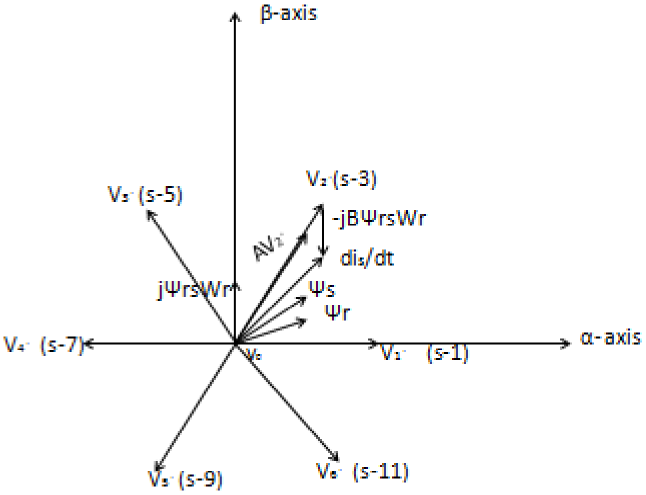

Fig 3: An incremental change in stator current at very low speed. (<25 % of rated speed) by increasing flux & torque w.r.t. sector-1 (s-1) (V_1' to V_6' & V_0)

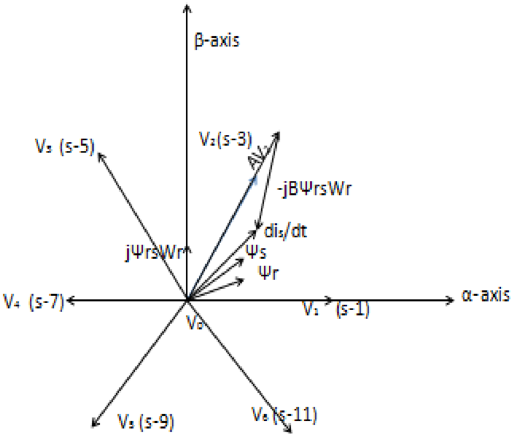

Fig 4: An incremental change in stator current at low speed. (25 to 50 % of rated speed) by increasing flux & torque w.r.t. sector-1 (s-1) (V_1 to V_6 with v_0

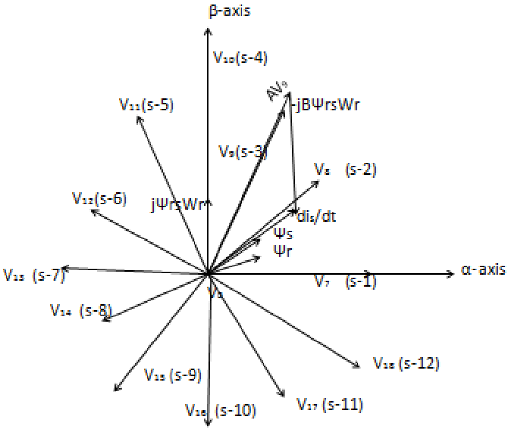

Fig 5: An incremental change in stator current at high speed. (> 50 % of rated speed) by increasing flux & torque w.r.t. sector-1 (s-1) (V_7 to V_{18} with v_0)

From fig (3), (4)& (5) shows how the current ripple is varying for very low, low and high speeds and the incremental change in current ripple for various speeds. For suppose the stator flux vector is 1 and for very low speed the choose of voltage vector V_2', the flux and torque values are increased then current ripple will decreased. For suppose the stator flux vector is 1 and for low speeds the choose of voltage vector V_2, the flux and torque values are increased then current ripple will decreased. For supposed the stator flux vector is 1 and for high speeds the choose of voltage V_9, the flux and torque values are increased then the current ripple will decreased.

VI. SIMULINK BLOCK

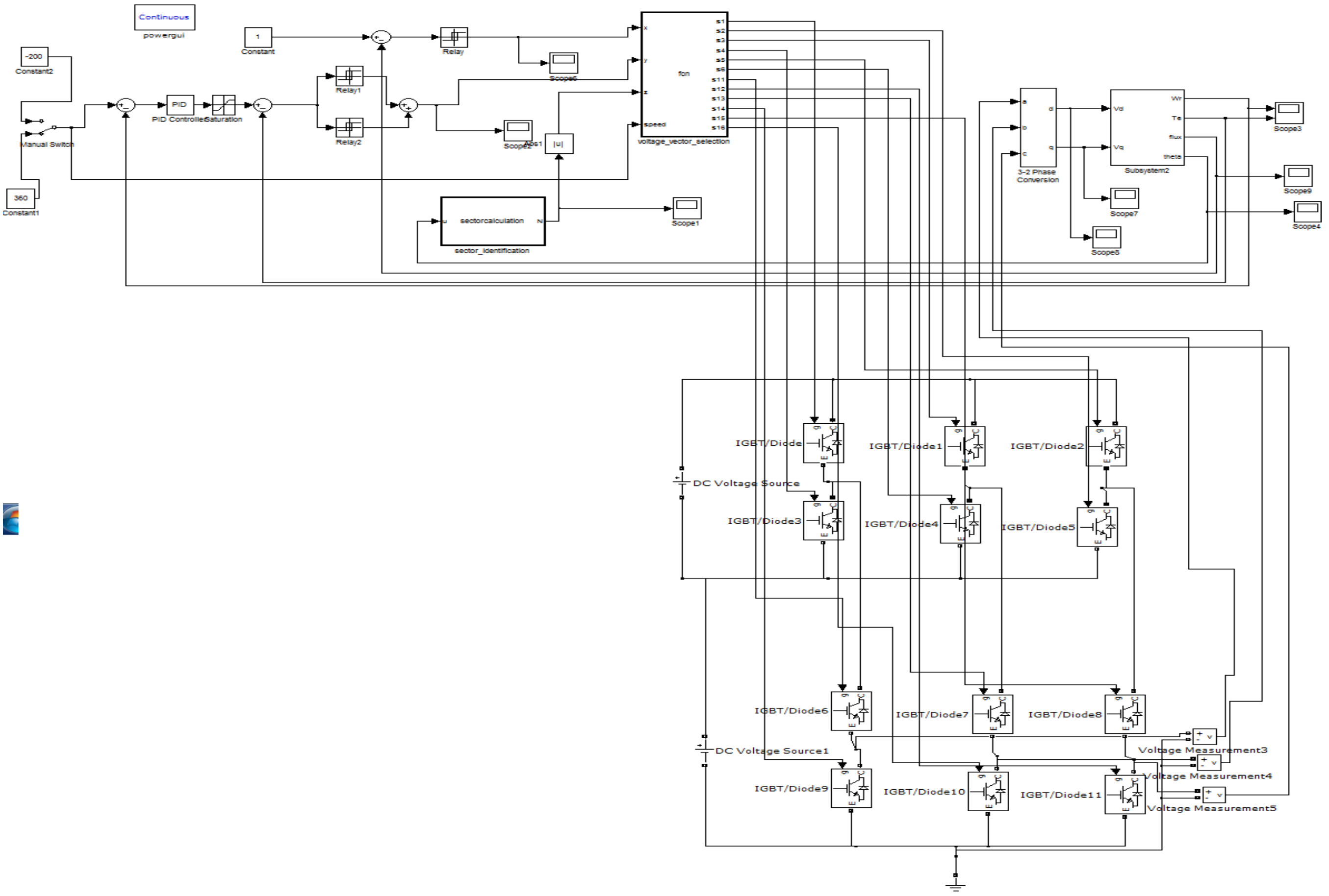

Fig 6 : Simulation block diagram of proposed Three level inverter

VII. PROPOSED THREE LEVEL MULTI LEVEL INVERTER

The proposed three level inverter which is shown below is cascaded two level inverter configuration, this scheme does not experience the neutral point fluctuations, which even has less number of switching devices as compared to conventional one. The power supplies are required for proposed topology is less when compared to conventional one [9], [12].

Advantages of multi level inverters are [6], [5]:

(i) High voltage
(ii)High power with less harmonics in output with optimum switching frequency.
(iii)The required voltage rating of the devices is lower and equal to half of the dc link voltage.

Table 4: Switching States of a phase U, Where X= U,V or W

Switching States	S_{1X}	S_{2X}	S_{3X}	S_{4X}	V_{XO}
	ON	ON	OFF	OFF	Vdc
	OFF	ON	ON	OFF	$\frac{Vdc}{2}$
	OFF	OFF	ON	ON	0

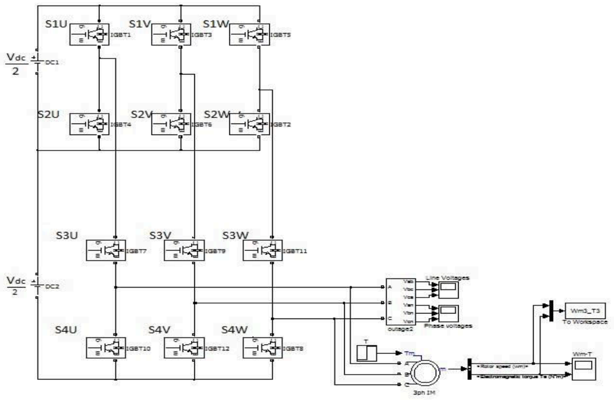

Fig 7.Three level inverter using cascading two 2- level inverter.

Table 5: Switching States of a Three Level Inverter

Voltage Vectors	Switching state of	Switching state of
V_1	S_{1U} S_{2V},S_{2W}	S_{3U},S_{3V},S_{3W}
V_2	S_{1U},S_{1V},S_{2W}	S_{3U},S_{3V},S_{3W}
V_3	S_{2U},S_{1V},S_{2W}	S_{3U},S_{3V},S_{3W}
V_4	S_{2U},S_{1V},S_{1W}	S_{3U},S_{3V},S_{3W}
V_5	S_{2U},S_{2V},S_{1W}	S_{3U},S_{3V},S_{3W}
V_6	S_{1U},S_{2V},S_{1W}	S_{3U},S_{3V},S_{3W}
V_7	S_{1U},S_{2V},S_{2W}	S_{3U},S_{4V},S_{4W}
V_8	S_{1U},S_{2V},S_{2W}	S_{3U},S_{3V},S_{4W}
V_9	S_{1U},S_{1V},S_{2W}	S_{3U},S_{3V},S_{4W}
V_{10}	S_{2U},S_{1V},S_{2W}	S_{3U},S_{3V},S_{4W}
V_{11}	S_{2U} S_{1V},S_{2W}	S_{4U},S_{3V},S_{4W}
V_{12}	S_{2U},S_{1V},S_{2W}	S_{4U},S_{3V},S_{3W}
V_{13}	S_{2U},S_{1V},S_{1W}	S_{4U},S_{3V},S_{3W}
V_{14}	S_{2U},S_{2V},S_{1W}	S_{4U},S_{3V},S_{3W}
V_{15}	S_{2U},S_{2V},S_{1W}	S_{4U},S_{4V},S_{3W}
V_{16}	S_{2U},S_{2V},S_{1W}	S_{3U},S_{4V},S_{3W}
V_{17}	S_{1U},S_{2V},S_{2W}	S_{3U},S_{4V},S_{3W}
V_{18}	S_{1U},S_{2V},S_{2W}	S_{3U},S_{4V},S_{3W}

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VIII. SIMULATION RESULTS

The entire developed model is analyzed and simulation results are carried out for 3-Φ asynchronous machine for both two and three level inverters at different operating speeds and the results are compared for both two and three level inverters in SIMULINK/MATLAB.

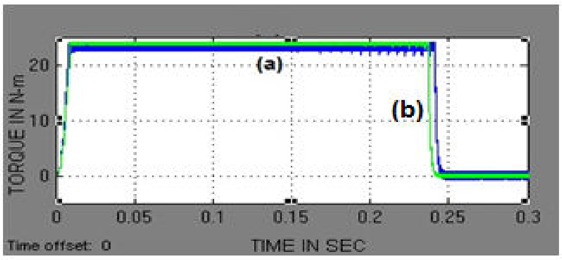

Fig 8 : Torque ripples with Proposed (a) two level and (b) three level DTC at above rated speed condition

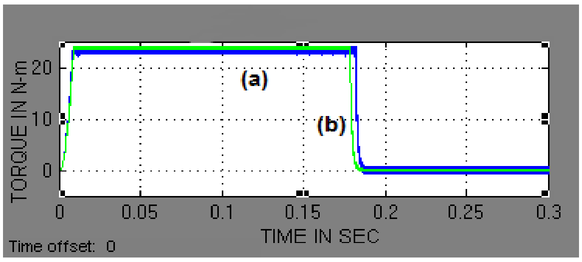

Fig 9 : Torque ripples with Proposed (a) two level and (b) three level DTC at rated speed condition

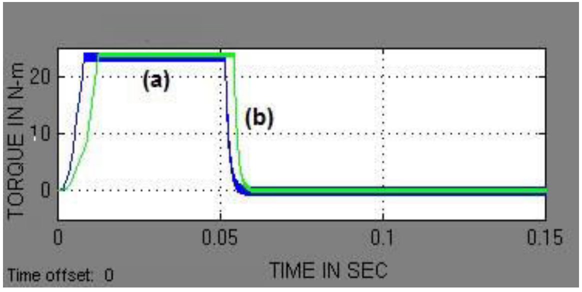

Fig 10 : Torque ripples with Proposed (a) two level and (b) three level DTC at low speed condition

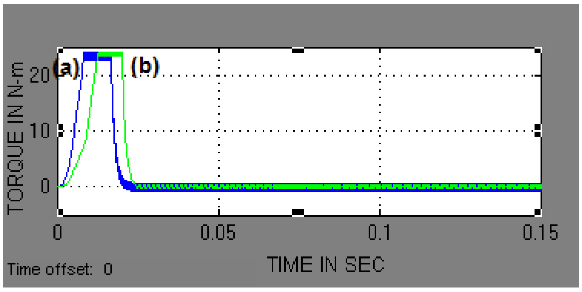

Fig 11 : Torque ripples with Proposed (a) two level and (b) three level DTC at very low speed condition

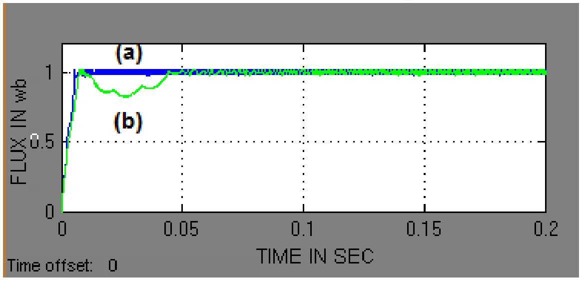

Fig 12 : Stator flux ripples with Proposed (a) two level and (b) three level DTC at above rated speed condition

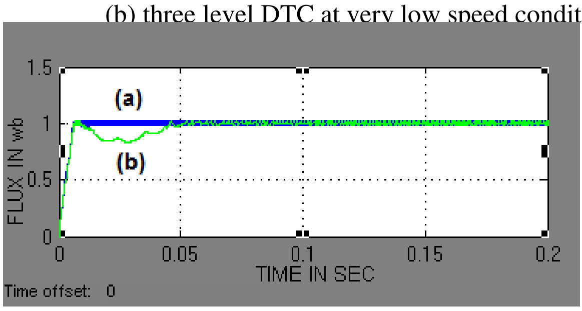

Fig 13 : Stator flux ripples with Proposed (a) two level and (b) three level DTC at rated speed condition.

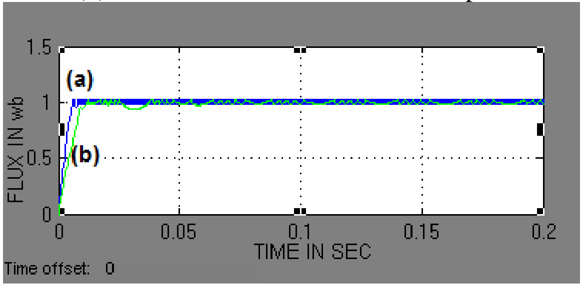

Fig 14 : Stator flux ripples with Proposed (a) two level and (b) three level DTC at low speed condition

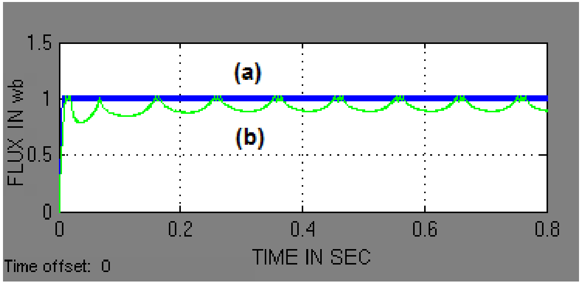

Fig 15 : Stator flux ripples with Proposed (a) two level and (b) three level DTC at very low speed condition

Table 6: Machine Parameters for simulation [2]

Parameter	Value
Rated Power (kw)	2.2
Rated Voltage (v)	220
Rated speed (rad/sec)	150
Rated Torque (n-m)	12
Stator Resistance (Ω)	2.23
Rotor Resistances (Ω)	1.55
Stator Inductance (H)	0.21
Rotor Inductance (H)	0.21
Mutual Inductance (H)	0.1988
Inertia (kg-m2)	0.055
No of pole pairs	2

IX. EXPERIMENTAL SETUP

Fig 16 : Experimental setup for Two level Inverter

Hardware Results for Two Level Inverter

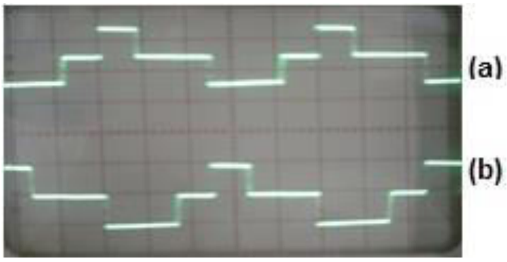

Fig 17 : Phase Voltages (a) V_u, (b) V_v

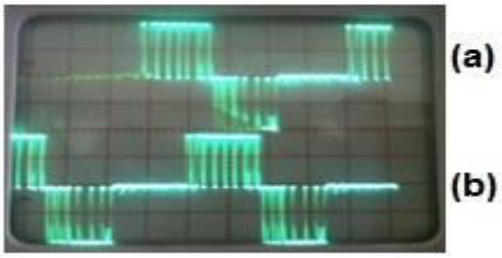

Fig 18 : Line Voltages (a) V_{uv}, (b) V_{vw}

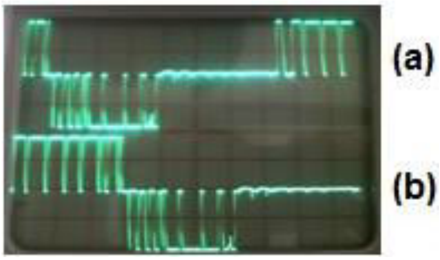

Fig 19 : Line Voltages (a) V_{vw}, (b) V_{wu}

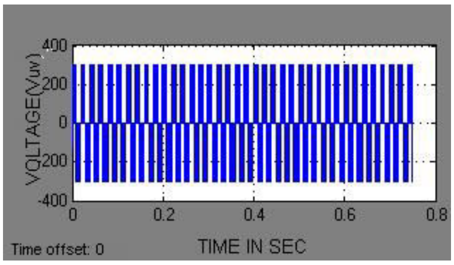

Fig 20 : Line voltage (V_{uv})

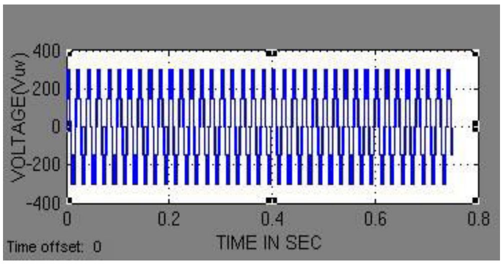

Fig 21 : Phase Voltages (V_u)

Fig 22 : Experimental setup for Three level Inverter

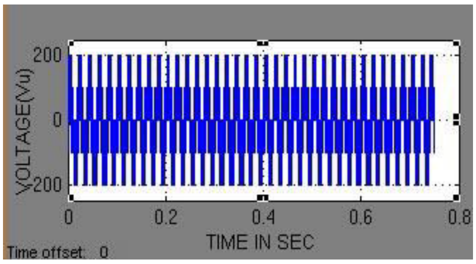

Fig 23 : Line to line voltage (V_{uv})

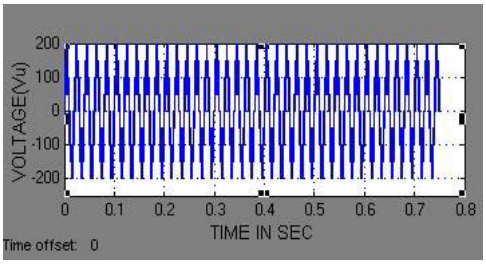

Fig 24 : Phase Voltages of the phase (V_u)

Table 7 : Hardware Specifications

Name of the Components	Type
Diodes	IN4007
Transformers (230v/12v)	TRAN-2P2S
Voltage Regulator	7805, 7812
Microcontroller	AT89C51
Crystal Oscillator	11.0592 MHZ
Optocouplers	MCT2E
Igbt	FGA25N120
Resistors	10KΩ, 470Ω, 2.2KΩ, 330Ω
Capacitors	0.1MF ,470MF, 10MF, 33PF, 100NF
Induction Motor	415V, 50HZ, 0.35KW, 1350RPM, 0.58A

X. CONCLUSION

In this paper, the torque and flux ripple minimization for proposed two level DTC and proposed three level DTC of 3-Ø Induction Motor drive, using an efficient switching algorithm is discussed and it is justified that torque and flux ripples are low for three level inverter. A hardware implementation of two and three level inverter in open loop using micro controller, and results of torque and flux errors for both two level and three level inverters for different speeds are calculated and observed that for wide range of speeds, torque and flux ripples are drastically reduced by using three level inverter.

Table 8: Percentage of torque and flux ripples for two and three level inverter at various speeds

Speed in rpm		Torque ripple (%)		Flux ripple(%)	
		Two level	Three level	Two level	Three level
High speed	1910	12.5	3.75	4.7	4.1
Rated speed	1440	9.58	2.26	4.8	3.92
Low speed	360	8.33	2.91	4.4	3.92
Very low speed	120	7.91	2.33	4.1	3.92

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BIOGRAPHY

1. M. V. G. Vara Prasad received B.Tech (EEE) degree, First class with distinction from JNTU, Kakinada in April 2011. At present he is pursuing his M.Tech (Power & Industrial Drives) at Vignan's Institute of Information Technology, Duvvada, Affiliated to JNTU, Kakinada, A.P, India.

2. Sri. R. S. Ravi Sankar received his AMIE (EEE) in the year 2002. He received M.Tech degree(Electrical power engineering), First class with distinction from JNTU, Hyderabad in 2004.He is having teaching experience of last 8 years. At present, he is working as Associate Professor in Vignan's Institute of Information Technology, Duvvada, Affiliated to JNTU, Kakinada, A.P, India.

3. Dr. K. Alice Mary received B.E (Electrical Power) degree in December 1981 from Mysore University. She received master's degree M.E (power apparatus & electric drives) in1989 from IIT, Roorkee, UP. She received Ph.D from IIT Kharagpur, WB in 1998. She is in teaching profession for last 31 years. She has published 40 Research Papers and presently guiding 5 Ph.D. Scholars. She received best paper award at national system conference Tiruvanantapuram in 1996 for her research work. She is a recipient of "Mahila Jyothi Award(National award) for her overall educational excellence by Integrated Council for Socio-Economic progress, New Delhi, 2002 and "Mother Teresa Excellence Award"(National award) in 2002 by Front for Nations Progress, Bangalore and Shastra award and.Vijeta award for academic excellence and authoring 5 Technical books. She is also recipient of best teachers award by JNTUK, Kakinada in 2010 and by Vignan's IIT, visakhapatnam in 2013. Her research interests include control systems and power electronics control of electrical machine drives. At present she is working as Principal of Vignan's IIT, Duvvada, Visakhapatnam, AP, India.