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Performance Improvement of Multi Level Inverter fed Vector Controlled Induction Motor Drive for Low Speed Operations

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ABSTRACT

In this paper, the analysis of space vector based multi level inverter (MLI) fed vector controlled induction motor drive for a low speed operation is presented. The performance of indirect field oriented controlled induction motor drive (IMD) is poor with two-level inverter for low speed operations (LSO). The reduction in performance and peak value of torque are mainly due to the non-linearity caused by stator voltage drop and inverter. Hence the performance factors of induction motor drive are analyzed with the multi level inverters under different operating conditions. In this approach, the steady state ripple content in the current and torque waveforms are reduced and that to ripple content of torque is reduced from 0.15 to 0.05 under steady state with five-level inverter. When there is a step change in the load torque, the momentary decrease in speed with five-level inverter is less when compared two and three-level inverters and the speed response reaches the reference value very quickly with five-level inverter during steady state and transient periods. So the overall performance of drive is improved with five-level inverter when compared to two-level and three- level inverters under low speed operations.

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1. INTRODUCTION

Recent developments in power electronics and semiconductor technology have led improvements in power electronic systems. Due to the advantages in power electronics, field oriented controlled induction motor drives are popular in industrial applications in place of DC machines. In Indirect field oriented control (FOC) the total rotor flux is aligned along the d-axis and the q-axis rotor flux is set to zero. Due to this induction motor can be controlled like a separately excited DC motor as explained in [1]. But the performance vector control under low speed operation is not satisfactory because of problems associated with unbalances, drift etc studied in [2]-[3]. The concept of the low speed operation of sensor less vector control, various strategies have been developed and studied in [4]. In all these strategies, nonlinearities introduced by inverter and parameter variations are discussed in [5]. In order to reduce these problems and to obtain better performance various observers are placed in the sensor less vector control. Due to this circuit complexity is increased and the improvement in the performance is not satisfactory and explained in [6].

The concept of the multi-level pulse width modulation (PWM) converter, various modulation strategies have been developed and studied in [7]-[8]. In all these strategies, space-vector modulation (SVM) stands out because it offers significant flexibility to optimize switching waveforms and it is well suited for implementation on a digital computer. However, regardless of its advantages, SVM for three-level inverters is still mostly unexplored. A new simplified space vector pulse width modulation (SVPWM) method for three-level inverter is proposed [10]. The performance factors of indirect vector controlled induction motor drive are proposed with two and three-level inverters at [13].

This paper presents the performance factors of induction motor drive are analyzed and compared with the multi level inverters under different operating conditions at low speed (500 rpm) operations.

2 CONVENTIONAL FOC ALGORITHM :

Though the induction motor has a very simple construction, its mathematical model is complex due to the coupling factor between a large number of variables and the non-linearities. The FOC offers a solution to circumvent the need to solve high order equations and achieve an efficient control with high dynamic. The FOC algorithm controls the components of the motor stator currents, represented by a vector, in a rotating reference frame. In the FOC algorithm, the machine torque and rotor flux linkage are regulated by controlling the stator current vector. The stator current vector is resolved into a torque producing component (i_{qs}^*) and flux producing component (i_{ds}^*) in a rotating reference frame respectively. The flux component is oriented along the rotor flux linkage vector, and the torque component is perpendicular to the flux component. This decouples the torque control from the flux control. The electromagnetic torque expression for an induction motor is given as

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \tag{1}$$

To achieve decoupling control, the entire rotor flux is aligned along d-axis and hence the q-axis flux component will become zero. With this, the torque expression can be modified as given in (2).

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs}\right) \tag{2}$$

Hence, the total rotor flux can be given as in (3).

$$\psi_r = \psi_{dr} = L_m i_{ds} \tag{3}$$

From (3), it can be observed that the rotor flux is directly proportional to i_{ds}^* and is maintained constant. Hence, the torque linearly depends on i_{qs}^*, and provides a torque response as fast as the i_{qs}^* response. Then, the slip frequency can be evaluated from (4) and added to the rotor speed to generate unit vectors.

$$\omega_{sl} = \frac{L_m R_r}{L_r \Psi_r} i_{qs}^* \tag{4}$$

3 SVPWM BASED MULTI LEVEL INVERTERS (EXISTING METHODS):

3.1 Two-level Inverter

The three-phase, two-level VSI has a simple structure and generates a low-frequency output voltage with controllable amplitude and frequency by programming high-frequency gating pulses. For a 3-phase, two-level VSI, there are eight possible voltage vectors, which can be represented as shown in Figure 1. Among these voltage vectors, V_1 to V_6 vectors are known as active voltage vectors or active states and the remaining two vectors are known as zero states or zero voltage vectors.

$$V_k = \frac{2}{3} V_{dc} e^{j(k-1)\frac{\pi}{3}} \quad \text{where } k = 1,2,\ldots,6 \tag{5}$$

and V_{dc} is dc link voltage.

The active voltage vectors can be represented as given in (5).

The reference voltage space vector or sample, which is as shown in Figure 1 represents the corresponding to the desired value of the fundamental components for the output phase voltages. In the space vector approach this can be constructed in an average sense. V_{ref} is sampled at equal intervals of time, T_s referred to as sampling time period.

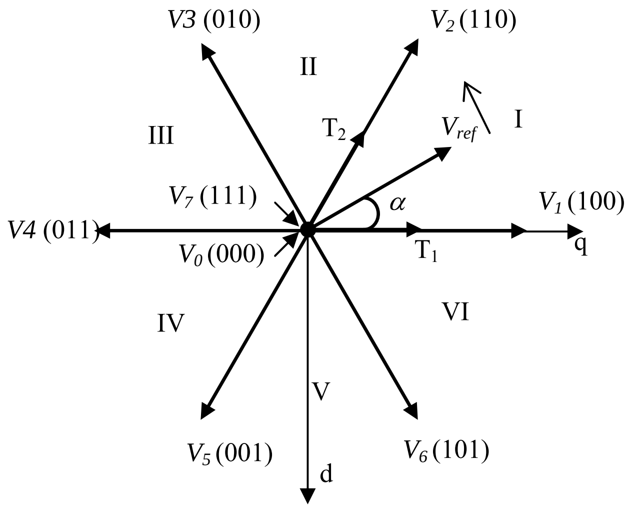

Figure 1. Possible voltage space vectors for VSI

Different voltage vectors that can be produced by the inverter are applied over different time durations with in a sampling time period such that the average vector produced over the sampling time period is equal to the sampled value of the V_{ref}, both in terms of magnitude and angle. It has been established that the vectors to be used to generate any sample are the zero voltage vectors and the two active voltage vectors forming the boundary of the sector in which the sample lies. As all six sectors are symmetrical, the discussion is limited to the first sector only. For the required reference voltage vector, the active and zero voltage vectors times can be calculated as in (6), (7) and (8).

$$T_1 = \frac{2\sqrt{3}}{\pi} M_i \sin(60^o - \alpha) T_s \quad (6)$$

$$T_2 = \frac{2\sqrt{3}}{\pi} M_i \sin(\alpha) T_s \quad (7)$$

$$T_z = T_s - T_1 - T_2 \quad (8)$$

where M_i is the modulation index and defined as in [11]. In the SVPWM algorithm, the total zero voltage vector time is equally divided between V_0 and V_7 and distributed symmetrically at the start and end of the each sampling time period. Thus, SVPWM uses 0127-7210 in sector-I, 0327-7230 in sector-II and so on.

3.2 Three-Level Inverter

The space vector diagram three-level inverter is shown in Figure 2 and all these voltage space vectors can be grouped into four groups based on their magnitude namely, zero vector, small vectors, medium vectors and large vectors. The zero voltage vector has two redundant states and small voltage vectors have one redundant state. In conventional space vector PWM (CSVPWM) generation, the reference voltage vector is sampled at regular time intervals and also the reference voltage vector is approximated by time averaging the nearest three voltage vectors. Unlike two level inverters, in the case of three level inverters, the zero vector is no longer common for all the regions. Figure 2 shows the representation of the space voltage vectors for output voltage and the space vector diagram of all switching states, where the P, O, N represent terminal voltage respectively, that is Vdc/2, 0, -Vdc/2. According to the magnitude of the voltage vectors, we divide them into four groups; zero voltage vector (V0), small voltage vectors (V1,V4, V7, V10, V13, V16), middle voltage vectors (V3, V6, V9, V12, V15, V18) and large voltage vector (V2, V5, V8, V11, V14, V17). The zero voltage vector (ZVV) has three switching states, small voltage vector (SVV) has two switching states, the middle voltage vector (MVV) and large voltage vector (LVV) have only one switching state and as explained in [11].

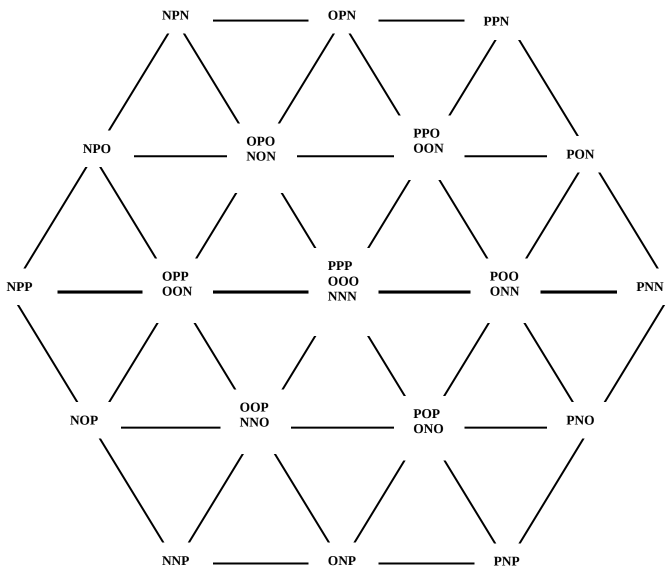

Figure 2. Space vectors of a three level inverter

The switching states of different sections of three-level inverter are shown in Table 1 and Table 2 which shows the switching times of voltage vector in sector-I where $K = \frac{2}{\sqrt{3}}V$

Table 1. Switching states of three-level inverter

Switching symbols	**Switching conditions**				**Output voltage**
	S_{11}	S_{12}	S_{13}	S_{14}	
P	ON	ON	OFF	OFF	+ Vdc/2
O	OFF	ON	ON	OFF	0
N	OFF	OFF	ON	ON	-Vdc/2

Table 2. Switching times of three-level inverter

Region	**Ta**	**Tb**	**Tc**
1	2KTs Sin(60- α)	Ts [1-2K Sin(α +60)]	2KTs Sin(60- α)
2	2Ts [1-K Sin(α +60)]	2KTs Sin α	Ts [2K Sin(60- α)+1]
3	Ts [1-2K Sin α]	Ts [2K Sin(α +60)-1]	Ts [2KSin(α -60)+1]
4	Ts [2K Sin α -1]	2KTs Sin(60- α)	2Ts [1-K Sin(α +60)]

3.3 Five–Level Inverter

In a five-level inverter, Each leg of the inverter can have five possible switching states, P1, P2, O, N1 or N2. When the top four witches Sx1, Sx2, Sx3 and Sx4 (x = a, b, c) are turned on, switching state is P2. When the switches Sx2, Sx3, Sx4 and Sx5 are turned on switching state is P1. When the switches Sx3, Sx4, Sx5 and Sx6 are turned on, the switching state is O. when the switches Sx4, Sx5, Sx6 and Sx7 are turned on, the switching state is N1. When the switches Sx5, Sx6, Sx7 and Sx8 are turned on, the switching state is N2. Figure 3 shows the space vector diagram for five-level inverter.

Table 3. Switching states and terminal voltage of five-level inverter

States	S_{X1}	S_{X2}	S_{X3}	S_{X4}	S_{X5}	S_{X6}	S_{X7}	S_{X8}	V_{X0}
P2	1	1	1	1	0	0	0	0	2E
P1	0	1	1	1	1	0	0	0	E
0	0	0	1	1	1	1	0	0	0
N1	0	0	0	1	1	1	1	0	-E
N2	0	0	0	0	1	1	1	1	-2E

The output voltage space vector is identified by combination of switching states P2, P1, O, N1 or N2 of the three legs. For example, in the case of P2ON1, the output terminals a, b and c have the potentials 2E, 0, and −E respectively. Since five kinds of switching states exist in each leg, three-level inverter has 5^3 = 125 switching states. The output voltage vector can take only 61 discrete positions in the diagram because some switches states are redundant and create the same space vector. In Figure 4, it is also indicated an arbitrary reference vector V* to be generated by the inverter and studied in [12].

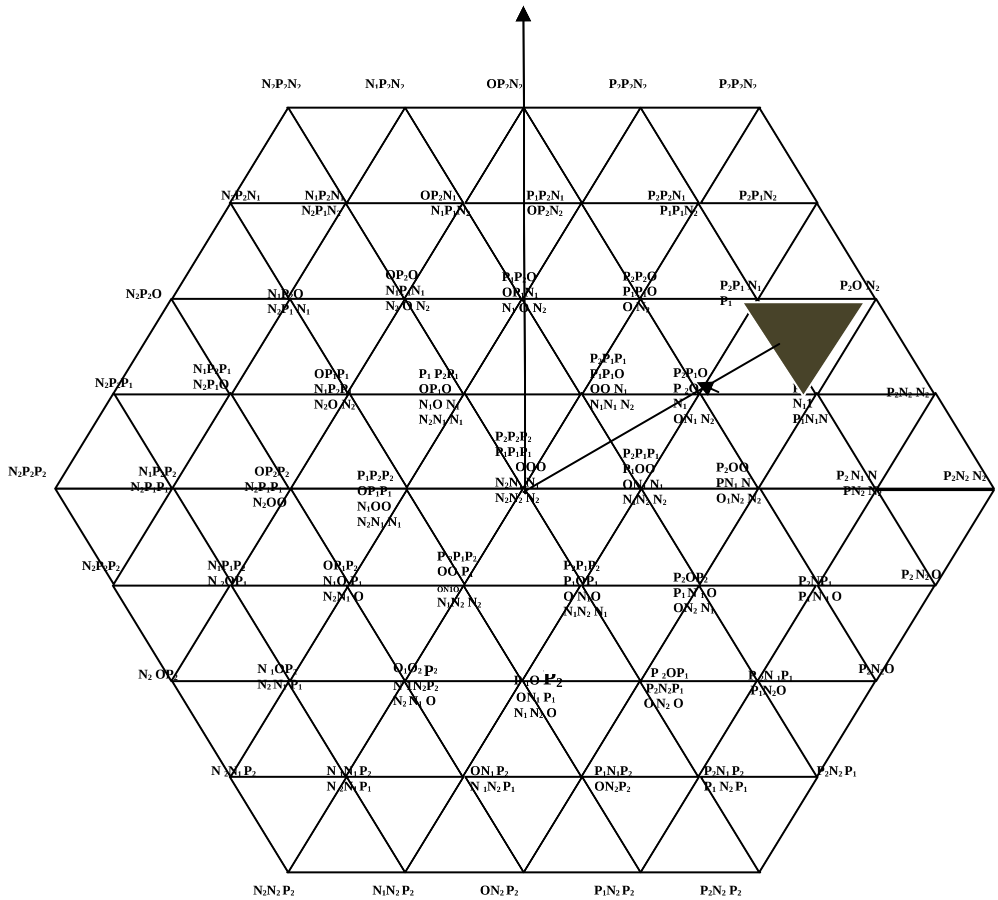

Figure 3. Space Vector diagram of Five-level inverter

In Multilevel inverters the reference voltage vector can be reproduced in the average sense by switching amongst the inverter states situated at the vertices, which are in closest proximity to it. The duty cycles (ON time for each state) will be found by equating volt-seconds of reference voltage with nearest 3 states.

$$m = d_1 V_1 + d_2 V_2 + d_3 V_3 \quad (9)$$

Where d1, d2 and d3 are duty cycles of voltage vectors (states) (V1, V2 and V3) in inverter space vector diagram nearer to the reference vector and m is the voltage reference vector. The values of m_1 and m_2

for reference vector in each region can be calculated with Equation (9). The duty cycles of vertices of reference voltage will be m_1, m_2 and $[1-(m_1+m_2)]$. For example, with reference to m_3 (reference vector in region 2), the reference vector can be synthesized by switching vectors V_1, V_2 and V_3. It shall be important to note that duty cycle for switching state V_1 shall be length of the vector joining V_3 and V_1, whereas, m_1 is the projection of reference vector m_3 from origin. As such, the corrected duty cycle for switching state V_1 in present case would be (m_1-0.25). The length of vector joining V_3 and V_2 is m_2. As such, corrected duty cycles for switching states V_1, V_2 and V_3 would be (m_1-0.25), m_2 and (0.75-m_1-m_2) respectively. The values of m_1 and m_2 are useful in identifying the region where reference vector is located, which is the major problem in multilevel inverters. The conditions for identifying reference vector location in each region and the corrected duty cycles for each of the level of inverter are shown in Table-3. Once the region is identified, the appropriate switching sequence of a region can be identified. The ON time period for each state can be calculated with duty cycles as in (10), (11) and (12).

$$T_{ON} \text{ for state1} = Ts \times m_1 \quad (10)$$

$$T_{ON} \text{ for state2} = Ts \times m_2 \quad (11)$$

$$T_{ON} \text{ for state3} = Ts \times [1-(m_1+m_2)] \quad (12)$$

4 MULTI LEVEL INVERTER FED IFO BASED INDUCTION MOTOR DRIVE (PROPOSED METHOD):

In the vector controlled induction motor drive, the multi level inverter is supposed to drive the induction motor so that the slip frequency can be changed according to the particular requirement. Assuming the rotor speed is measured, and then the slip speed is derived in the feed-forward manner. For decoupling control, it is desirable that the rotor flux is aligned onto the d-axis of the synchronously rotating reference frame, then $\psi_{qr} = 0$ and $\psi_{dr} = \psi_r = L_m i_{ds}$. The block diagram of proposed vector controlled induction motor drive is as shown in Fig. 4. This shows how the rotor flux linkage position can be obtained by integrating the sum of rotor speed and actual speed. In the vector control scheme, to regulate ψ_r and rotor speed to desired values are the two objectives. Apparently the stator voltages that are required to generate the desired rotor flux linkage and rotor speed are not directly related to these variables. So the alternative way is to regulate the rotor flux linkage and rotor speed through PI controllers and the outputs of these two controllers give out the reference values for the q- and d-axis stator currents in synchronous reference frame. Then the actual q- and d-axis stator currents are regulated to these two reference currents to get the stator voltages. Then these two-phase voltages are converted into three-phase voltages and given to the SVPWM block, which generates the gating pulses to the Multi Level Inverter.

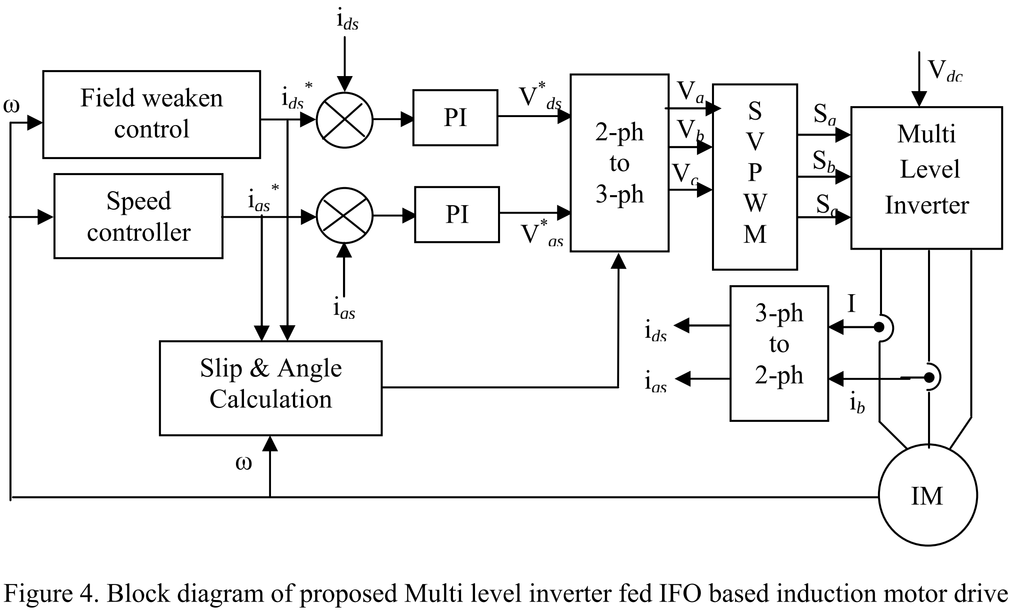

Figure 4. Block diagram of proposed Multi level inverter fed IFO based induction motor drive

5 SIMULATION RESULTS AND DISCUSSIONS

To validate the proposed methods, numerical simulation studies have been carried out by using Matlab-Simulink. For the simulation studies the switching frequency is taken as 5 KHz. The parameters of the induction motor used in this paper are shown below

Three-phase, 400 V, 10 hp, 1480 rpm induction motor

Stator resistance Rs = 0.7384 Ω

Stator inductance Ls= 0.127145 H

Rotor resistance Rr = 0.7402 Ω

Rotor inductance Lr= 0.127145 H

Mutual inductance Lm= 0.1241 H

Moment of inertia J= 0.1 Kg-m2

The simulation results of proposed methods are shown from Figure 5 – Figure 9

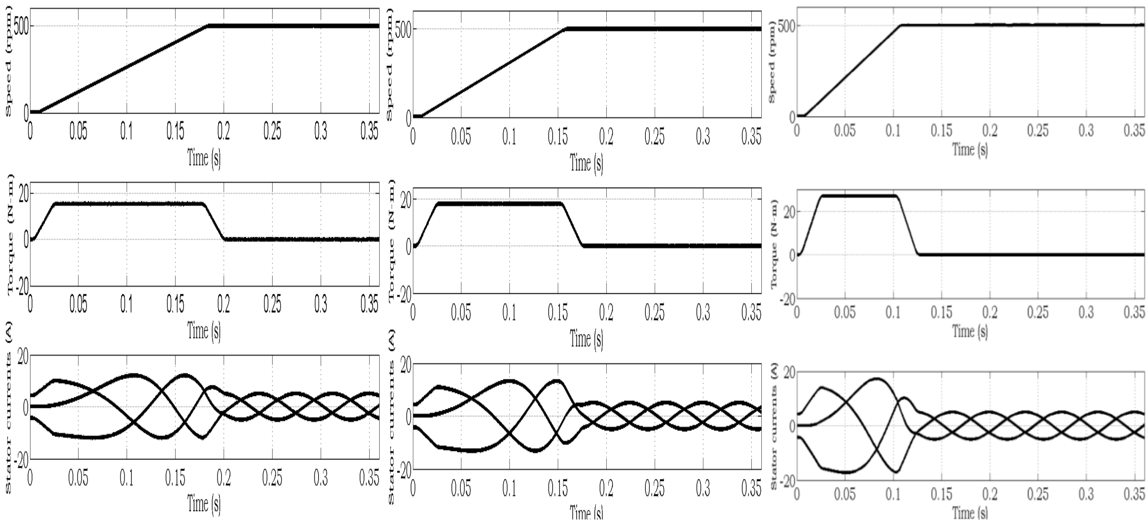

Figure 5. Starting transients of Two-level, Three-level and Five-Level inverter fed vector controlled induction motor drive respectively

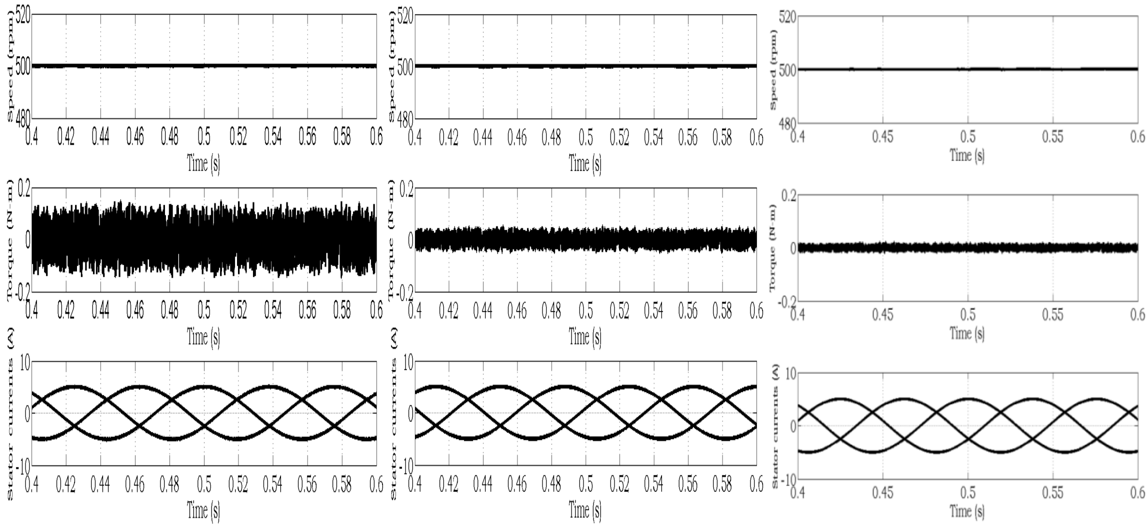

Figure 6. Steady state performance of Two-level, Three-level and Five-Level inverter fed vector controlled induction motor drive respectively

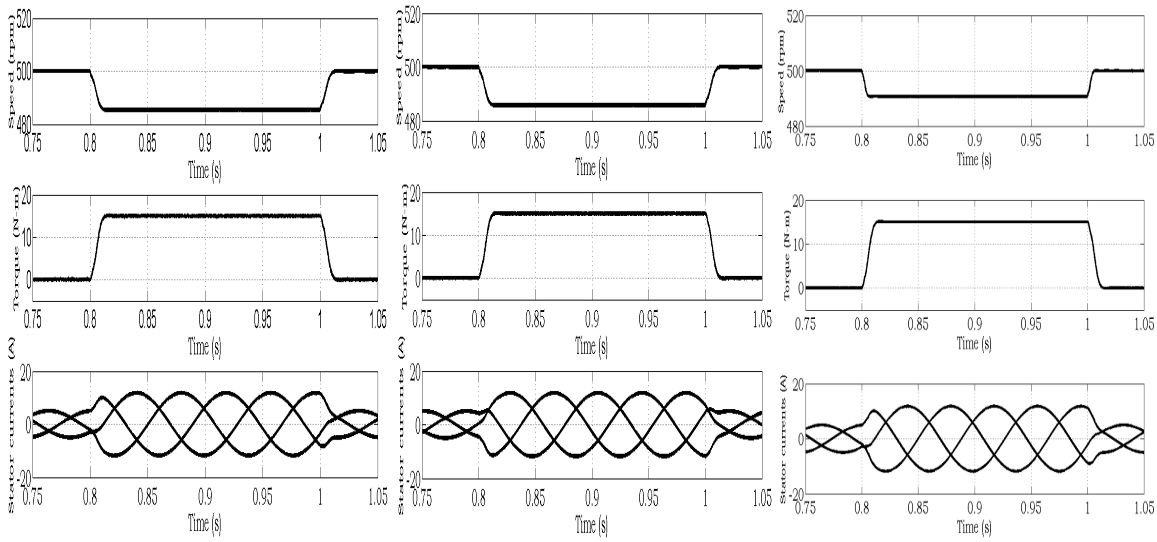

Figure 7. Performance during step change in load torque with Two-level, Three-level and Five- Level inverter fed vector controlled induction motor drive respectively

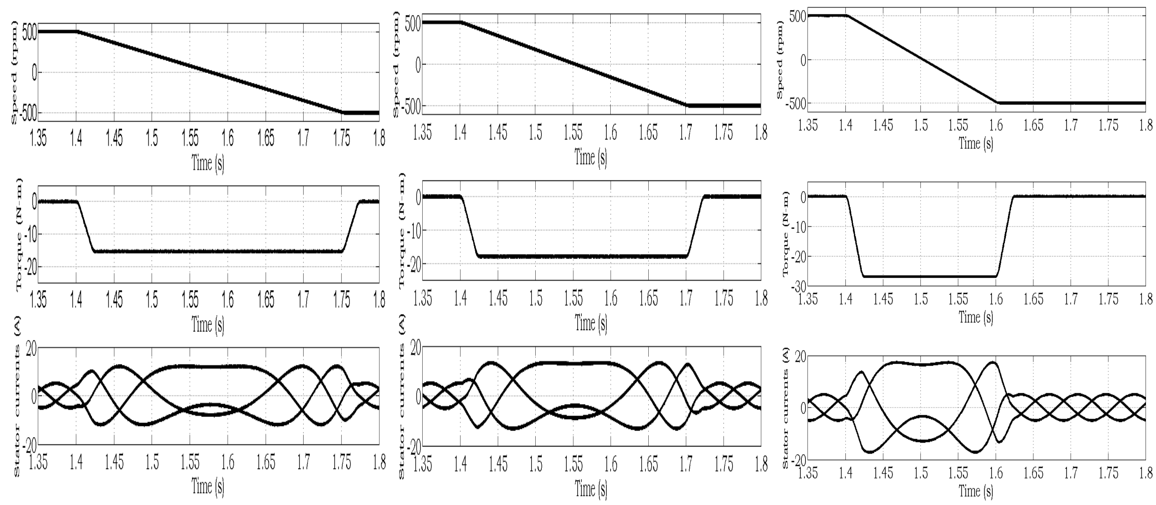

Figure 8. Performance during speed reversal operation (Speed is changed from (+500 rpm to -500 rpm) of Two-level, Three-level and Five- Level inverter fed vector controlled induction motor drive respectively

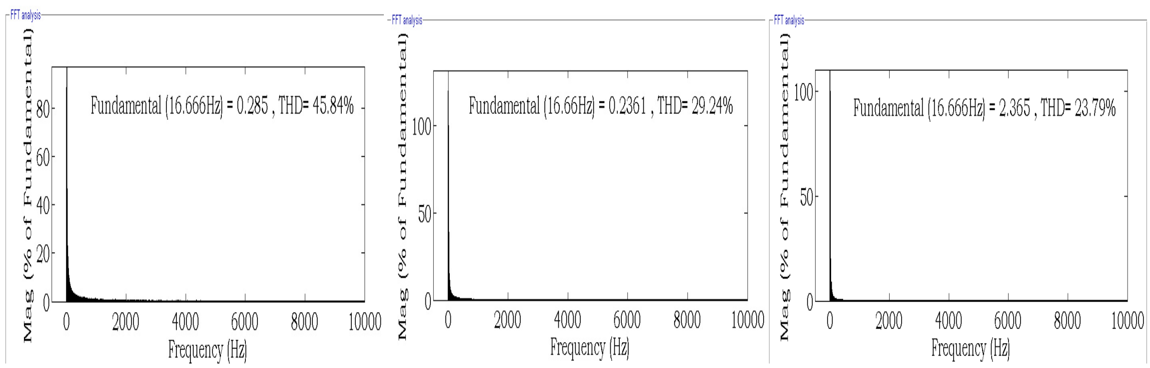

Figure 9. Harmonic spectra of line current of Two-level, Three-level and Five-Level inverter fed vector controlled induction motor drive respectively

From the simulation results, the following observations are made. The starting transients are upto 0.18 secs, 0.16 secs and 0.12 secs in with two-level, three level and five-level inverters respectively. From the steady state performance factors, It is observed that the torque ripple is drastically reduced from 0.15 to 0.05 with five-level inverter. The response during change in load torque command (the load torque of 15 N-m is applied at 0.8 sec and removed at 1 sec) and the momentary decrease in speed with five-level inverter is less when compared with two-level and three-level inverters. The speed reversal response (from +500 rpm to -500 rpm) is also better with five-level inverter. Finally the performance of five-level inverter fed drive provides better performance based on harmonic spectra of line current (low THD) when compared to the two-level and three-level inverters.

6 CONCLUSION

The indirect vector controlled induction motor drive performance with multi level inverters under low speed operations is presented. It is observed that the performance of the drive is improved with the five-level inverter when compared to two and three-level inverters. The steady state ripple content in the current and torque waveforms are reduced and that to ripple content of torque is reduced from 0.15 to 0.05 under steady state with five-level inverter. When there is a step change in the load torque, the momentary decrease in speed with five-level inverter is less when compared two and three-level inverters. The speed response reaches the reference value very quickly with five-level inverter during steady state and transient periods. So the overall performance of drive is improved with five-level inverter when compared to other inverters under low speed operations.

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