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Enhanced DTC induction motor drives- THD reduction multilevel inverter fed drives control

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ABSTRACT

Direct Torque Control (DTC) is a control method that controls speed and torque of Induction Motor (IM) directly, accurately and independently without pulse encoder feedback from the motor shaft. However, in Fast Fourier Transform (FFT) analysis of Total Harmonic Distortion (THD) for motor drive, DTC control with a conventional inverter leads to higher THD. Therefore, the main challenge of this study is to reduce the THD in three-phase line current DTC IM drive while maintaining the drive's speed and torque performance. A Multilevel Inverter (MLI) based DTC IM drive system is proposed in this study with the aim to reduce THD in three-phase line current while remaining the good speed and torque response of DTC IM drive system. The proposed MLI are realized by three-level neutral point clamped (NPC) MLI fed DTC of IM. In proposed MLI, pulse width modulation (PWM) is a control strategy used to control the switching at appropriate conducting angles. Proposed MLI based THD reduction DTC IM drive has several advantages over conventional inverter, which enable the operation with multiple switches instead of one switch that generates higher output voltage with low distortion, has ability to operate under low switching frequency, and it allowed the system to work with renewable energy to convert DC voltage into AC voltage. In order to verify the effectiveness of proposed MLI in THD reduction in DTC IM drive, simulation is conducted with MATLAB Simulink to investigate the performance and THD of IM drive system under different operating speed. The results show the THD of the three-phase line current has been decreased with the implementation of proposed MLI based THD reduction DTC IM drive as compared with the conventional DTC IM drive.

Key words : Direct torque control; Total harmonic distortion; Multilevel inverter; Induction motor; Fast fourier transform.

1. INTRODUCTION

Induction motor (IM) is an alternating current (AC) motor that has been widely used in industry as variable speed drives to replace DC motor due to several advantages over direct current (DC) motor includes greater efficiency, simple and robust construction, cheaper in price, and absence of brushes that require less maintenance [1][2]. IM has dynamic and nonlinear characteristics which require advanced control techniques including field-oriented control (FOC) and direct torque control (DTC) for high performance variable speed drive applications [3]. Both of the advanced control techniques have similarities in providing better torque response in transient and steady-state conditions with direct control of torque and flux separately [4]. However, DTC has gained more attention in research over FOC due to several advantages of DTC such as structure with ease control, fast torque response, robustness against the change of rotor parameters, reduce the computational cost, and less dependency on motor parameter [5]–[10].

Multilevel Inverter (MLI) is an inverter that used series of semiconductors for generating higher output voltage with better harmonic spectrum and achieves higher voltage with the stepped waveform in the maximum available device rating which has recently increased interest in both research studies and industry applications [11][12]. Due to the high efficiency, low electromagnetic interference (EMI), and low switching losses, MLI is suitable in motor drive applications with high power rating [13][14]. MLI is categorized into three different types, which are neutral point clamped (NPC), flying capacitors (FC), and lastly, cascaded H-bridge inverter (CHB) [15][16]. By compare MLI with the conventional two-level inverter, MLI with high switching frequency PWM has several advantages over conventional two-level inverter. MLI operates with multiple switches instead of one switch, it generates higher output voltage with low distortion, has ability to operate under low switching frequency, and MLI can worked with renewable energy to convert DC voltage into AC voltage [15][17]. The topology of MLI is shown in Figure 1, which divided into two types namely common DC sources (NPC and FC) and separated DC sources (CHB). NPC MLI is mainly composed of two conventional two-level voltage source inverter (VSI) that connected together with one over other with some modification. This NPC MLI is widely accepted in the industry due to its high voltage capability with maximum efficiency in optimum operation. FC MLI required lots of capacitors in this topology which bring about capacitor balancing problem. In this FC MLI, the load is either connected to anode or cathode bar through flying capacitor with opposite polarity to obtain zero level voltage. CHB MLI are formed from two or more single-phase H-bridge inverters with back to back series connection. Three different voltage level, $+V_{dc}$, 0, and $-V_{dc}$ can be generated with a single H-bridge inverter. The CHB MLI is able to produce output with 2N+1 levels with the series connection of N single H-bridge [18][17].

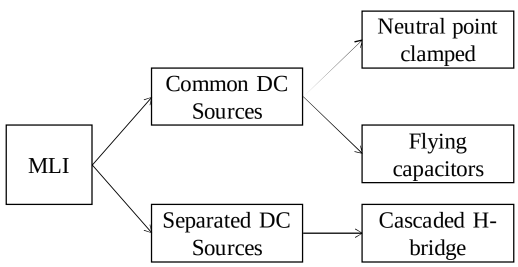


Figure 1: Topologies of MLI

A three-phase DTC IM drive with and without MLI is presented in this paper to minimize the THD of the motor drive at different operating speeds. MATLAB Simulink is used to stimulate and study THD of DTC IM drive with conventional inverter and three-level MLI at low (300 rpm), medium (850 rpm) and high speed (1400 rpm). The results are compared between conventional inverter with the proposed three-level MLI under the same conditions. This paper has been divided into four sections. In section II, the mathematical model of IM is discussed. Section III explains the proposed MLI based THD reduction DTC IM drive. Lastly. section IV discusses the simulation result of the proposed MLI based THD reduction DTC IM drives obtained from Simulink.

2. MATHEMATICAL MODEL OF INDUCTION MOTOR

The dynamic behavior of an IM can be described from time-varying voltage equation and torque equation [1]. With the elimination of time-varying inductance, the complexity of the equation can be reduced. The time-varying inductance in voltage equation of IM that caused by electric circuit in relative motion can be eliminate by relocated the rotor and stator variables to reference frame, which remains stationary or rotating at angular velocity [19][20].

IM with synchronous rotating reference frame is used in this paper due to the variable including current, voltage or flux linkage is stationary and fixed in constant magnitude in the synchronous frame. The mathematical equations of an IM are quizzes by dq0 equivalent circuit of IM as shown in figure 2 [21]. Three-phase stator voltage equation of an IM under equilibrium situation derived as:

$$V_a = \sqrt{2}V_{rms}\sin(\omega t) \tag{1}$$

$$V_b = \sqrt{2}V_{rms}\sin(\omega t - 2\pi/3) \tag{2}$$

$$V_c = \sqrt{2}V_{rms}\sin(\omega t + 2\pi/3) \tag{3}$$

The flux linkage of the rotor and stator in stator reference frame can be derived as below:

$$\lambda_{qs} = L_{ls}i_{qs} + L_m i_{qr} \tag{4}$$

$$\lambda_{ds} = L_{ls}i_{ds} + L_m i_{dr} \tag{5}$$

$$\lambda_{qr} = L_{lr}i_{qr} + L_m i_{qs} \tag{6}$$

$$\lambda_{dr} = L_{lr} + L_m i_{ds} \tag{7}$$

From equation (4), (5), (6) and (7), the voltage equation of rotor and stator at dq axis of an IM is given by:

$$V_{qr} = r_r i_{qr} - \omega_r\lambda_{dr} + d\lambda_{qr}/dt \tag{8}$$

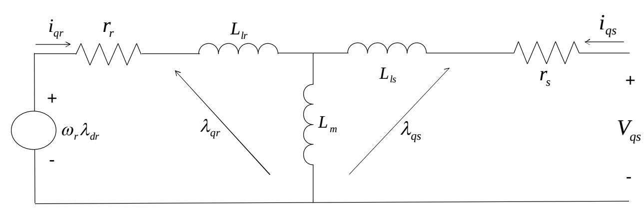
$$V_{dr} = r_r i_{dr} + \omega_r\lambda_{qr} + d\lambda_{qr}/dt \tag{9}$$

$$V_{ds} = r_s i_{ds} + d\lambda_{qs}/dt \tag{10}$$

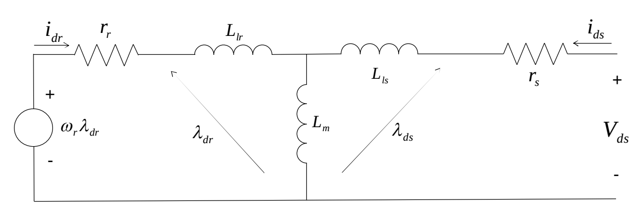
$$V_{qs} = r_s i_{qs} + d\lambda_{qs}/dt \tag{11}$$

Therefore, the torque of IM can be expressed as:

$$T_e = 3/2(P/2)(\lambda_{qr}i_{dr} - \lambda_{dr}i_{qr}) \tag{12}$$



(a) Q-equivalent circuit



(b) D-equivalent circuit

Figure 2: Equivalent circuit diagram of IM in dq0 frame

3. PROPOSED MLI BASED THD REDUCTION DTC IM DRIVES

In this paper, MLI is applied in DTC IM drive to reduce THD of the drive system. The simplified block diagram of the proposed MLI based THD reduction DTC IM drive is shown in Figure 3. DTC of IM with space vector pulse width modulation (SVPWM) technique is proposed to implement in this study due to the advantages of the SVPWM in low current distortion and low torque ripple compared to hysteresis controller [22][23]. For the conventional DTC IM, the working principle of the system is to use the flux error and torque error that generated from the difference between the reference flux and reference torque with estimated flux and estimated torque respectively. In the proposed SVPWM control technique, it used eight sorts of different switch modes (two zero voltage vector and six non-zero voltage vector) of VSI to attains high control performance and control the stator flux to approach the reference flux circle. Simulink model of DTC IM drive with the conventional two-level inverter and Simulink model of the proposed MLI based THD reduction DTC IM drive are shown in Figure 4 and Figure 5 respectively. The specification of IM used in both Simulink model is shown in Table 1.

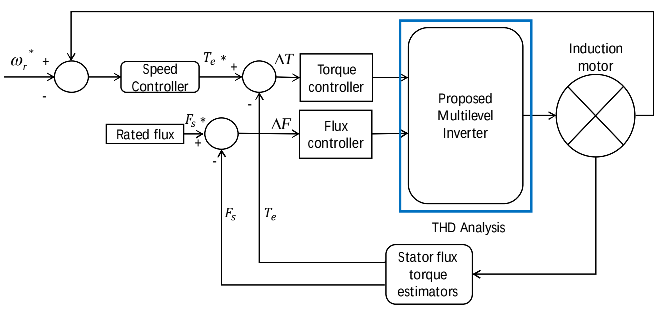


Figure 3: Block diagram of proposed MLI based THD reduction DTC IM drive

THD is a method used to compute harmonic order present in current or voltage waveform. Furthermore, output current or voltage quality and sinusoidal wave quality also can analyse by using THD [24]. THD is prescribe as the ratio of root mean square (rms) value of harmonic component to the rms value of the fundamental component [13][25].

$$THD_I\,\% = \sqrt{\sum_{n=2}^{\infty}\left(I_{oh,rms}\right)^2} \,/\, I_{or,rms} \tag{13}$$

$$THD = I_h / I_{sr} \tag{14}$$

Equation (14) represents the current THD, where,

I_h is the rms value of harmonic component of rotor current,

I_{sr} is the rms value of fundamental component of current supply.

The importance of reducing harmonic distortion is for appropriate execution of system [13][26]. Fourier analysis is the basic operation of frequency-domain method. Frequency-domain method offers quick outcome at minimum calculation therefore real-time implementation in digital signal processing (DSP) can be done. Harmonic distortion detection can classify into three types, namely fast fourier transform (FFT), discrete fourier transform (DFT), and recursive discrete fourier transform (RDFT) [13][27]. FFT technique of frequency domain is used in this study for computation of fundamental components of voltage and current.

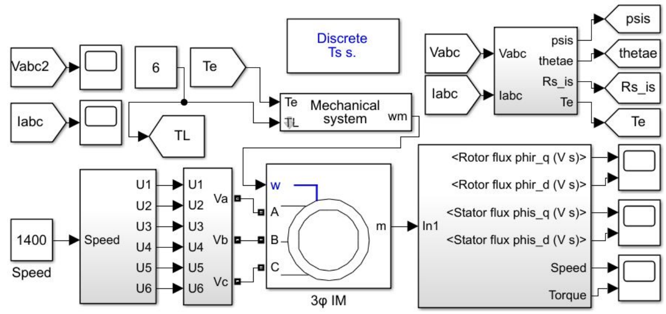


Figure 4: Conventional DTC IM drive with conventional inverter

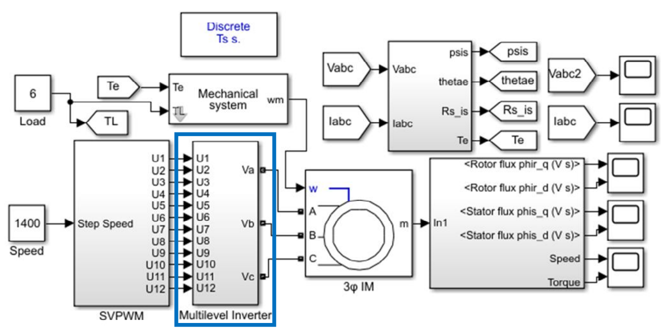


Figure 5: Proposed MLI based THD reduction DTC IM drive

Table 1: IM specification

Specification of IM	Parameters
Mechanic power	5.4 HP, 4 KW
Rated voltage	400 V
Rated frequency	50 Hz
Rotor speed	1430 rpm
Number of poles	4
IM parameters and type of frame	
Reference frame	Stationary
Stator resistance	1.405 Ω
Rotor resistance	1.395 Ω
Stator inductance	5839 mH
Rotor inductance	5839 mH

4. RESULT AND DISCUSSION

To verify the effectiveness of the proposed MLI based THD reduction DTC IM drive, the corresponding result of THD, speed response, and load torque response for the proposed MLI based THD reduction DTC IM drive is observed at low speed (300 rpm), medium speed (850 rpm) and high rotating speed (1400 rpm) with constant load torque of 6Nm. In each different speed testing, the resulting THD of proposed MLI based THD reduction DTC IM drive obtained is compared with the conventional DTC IM drive. Figure 6 shows the speed and load torque of proposed MLI based THD reduction DTC IM drive, and figure 7, 8 and 9 show the FFT result of current, I_a, I_b, and I_c respectively when the speed of IM is 300rpm.

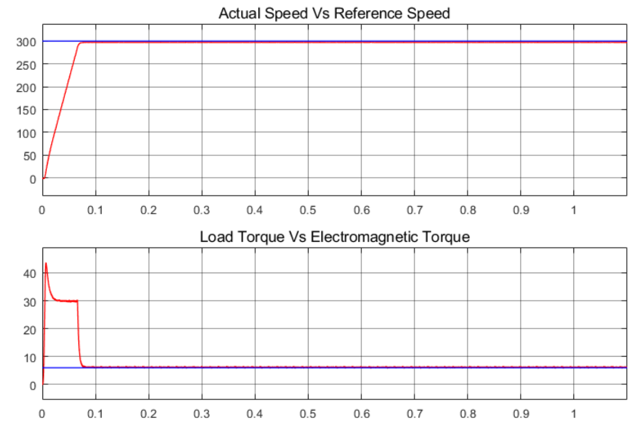
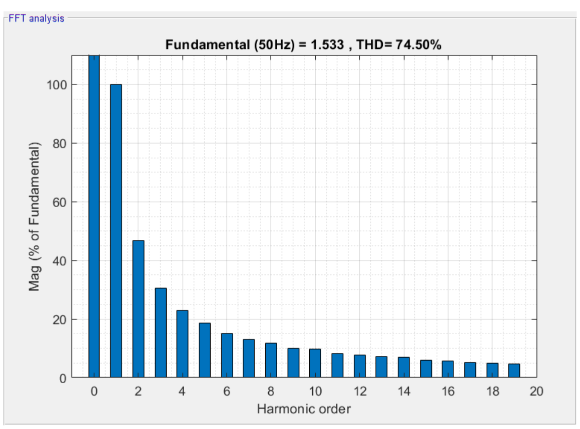


Figure 6: Speed and load torque response of proposed MLI based THD reduction DTC IM drive for low speed (300rpm)



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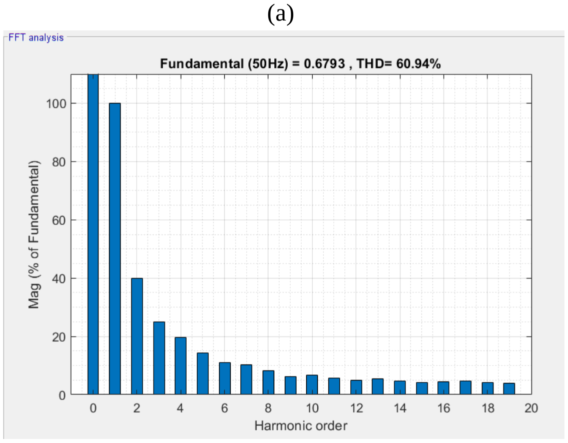

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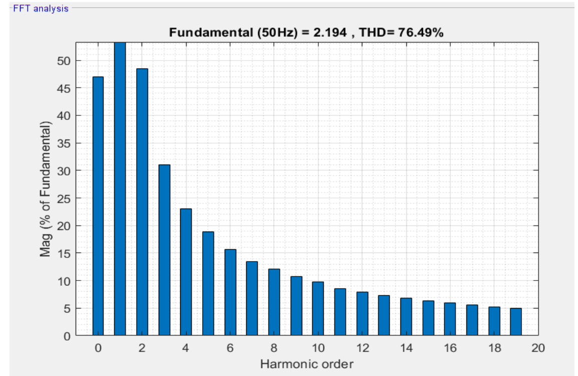
Figure 7: FFT result of current, I_a when low speed (300rpm). (a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive



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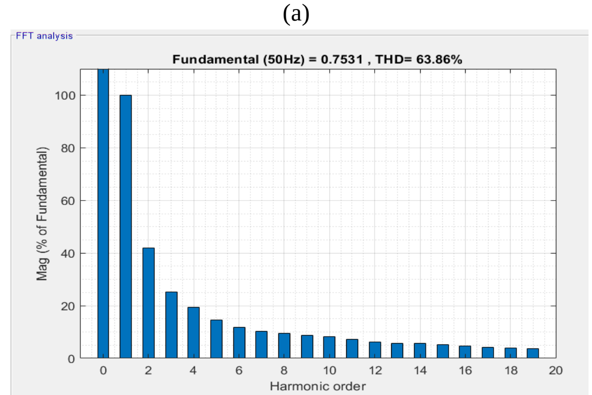

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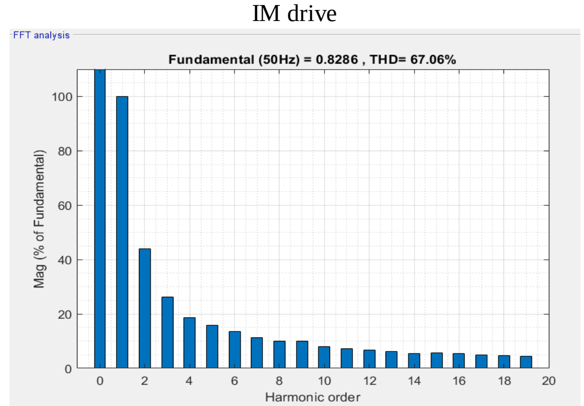
Figure 8: FFT result of current, I_b when low speed (300rpm). (a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive



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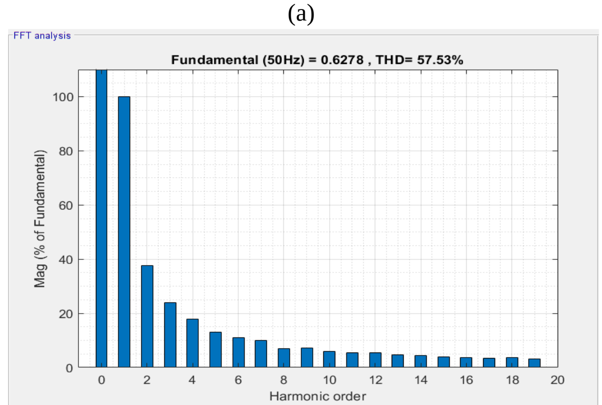


(b)

Figure 9: FFT result of current, I_c when low speed (300rpm). (a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive

Figure 10 shows the speed and load torque of proposed MLI based THD reduction DTC IM drive, while figure 11, 12 and 13 shows the FFT result of current, I_a , I_b , and I_c respectively when speed of IM is 850rpm.

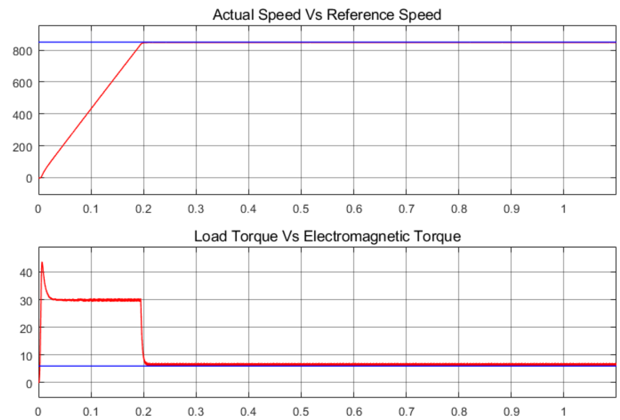
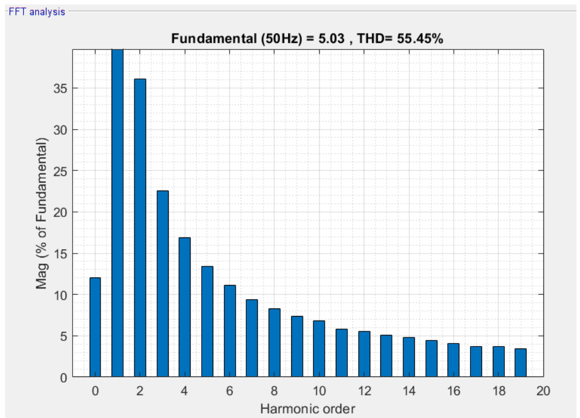


Figure 10: Speed and load torque of proposed MLI based THD reduction DTC IM drive for medium speed (850rpm)



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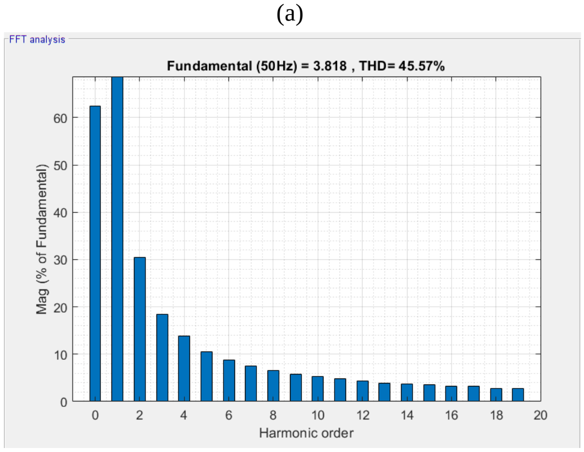

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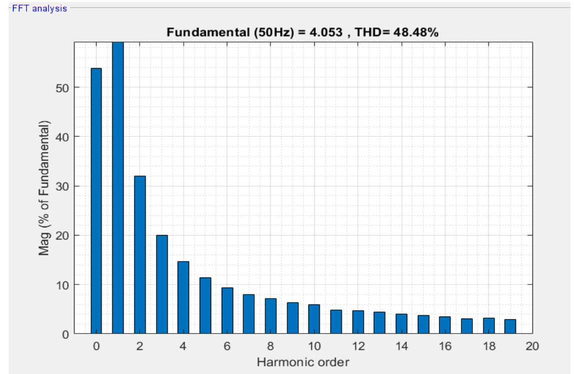
Figure 11: FFT result of current, I_a when medium speed (850rpm). (a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive



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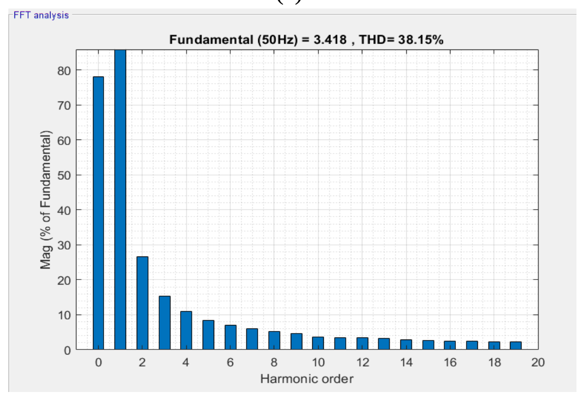

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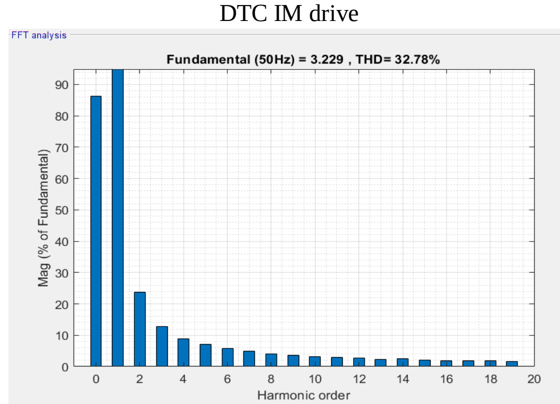
Figure 12: FFT result of current, I_b when medium speed (850rpm). (a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive



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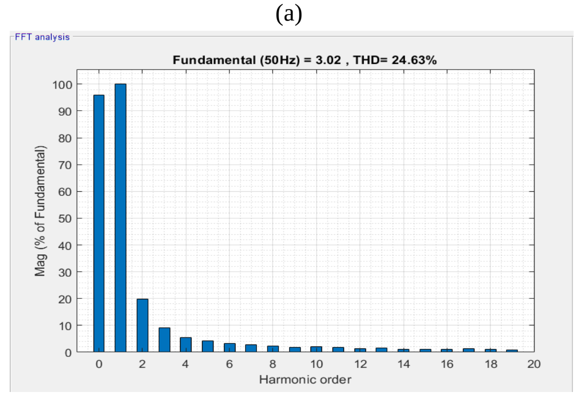


(b)

Figure 13: FFT result of current, I_c when medium speed (850rpm). (a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive

And lastly, figure 14 shows the speed and load torque of proposed MLI based THD reduction DTC IM drive, and figure 15, 16 and 17 shows the FFT result of current, I_a, I_b, and I_c respectively when speed of IM is 1400rpm.

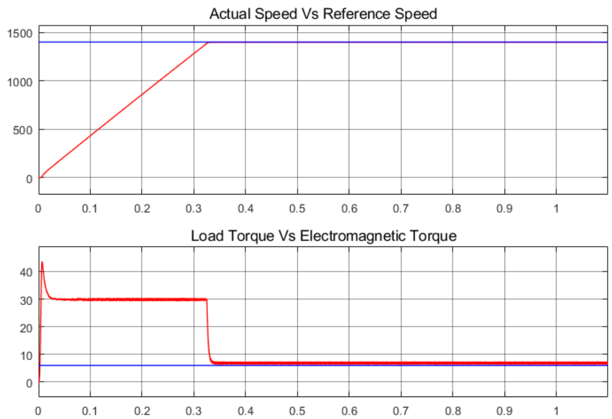
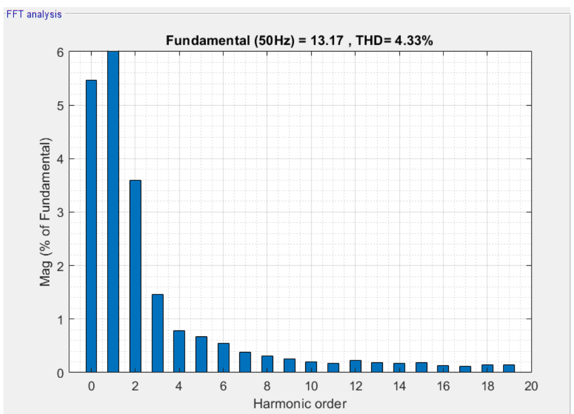


Figure 14: Speed and load torque of proposed MLI based THD reduction DTC IM drive for high speed (1400rpm)



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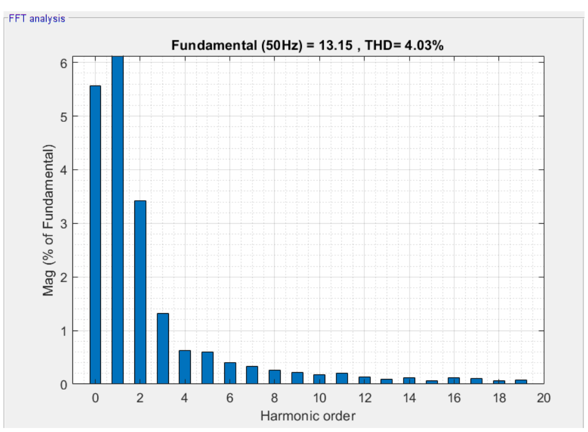
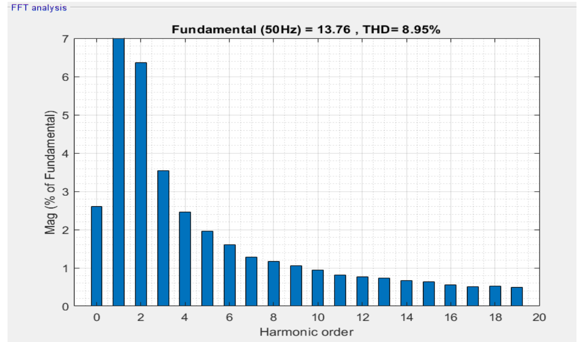


(b)

Figure 15: FFT result of current, I_a when high speed (1400rpm).

(a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive



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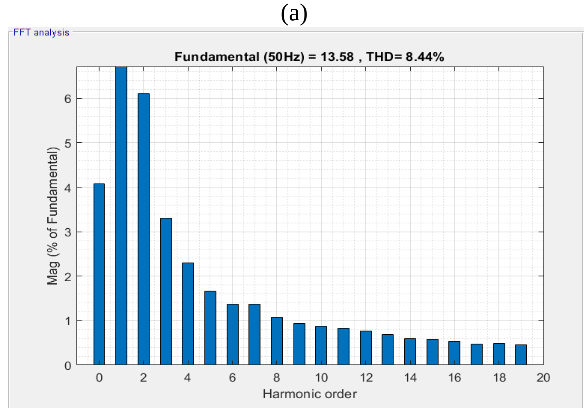
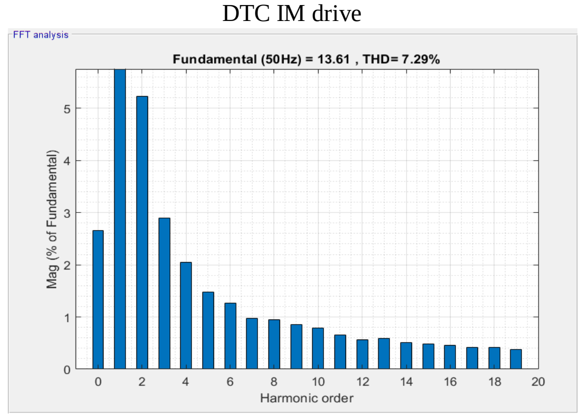


(b)

Figure 16: FFT result of current, I_b when high speed (1400rpm).

(a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive



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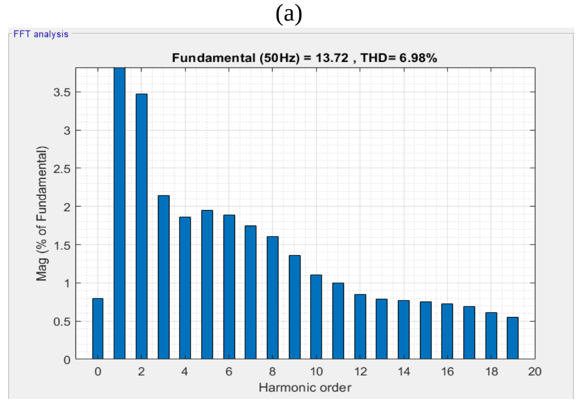

(b)

Figure 17: FFT result of current, I_c when high speed (1400rpm).

(a) Conventional inverter (b) Proposed MLI based THD reduction DTC IM drive

The THD for proposed MLI based THD reduction DTC IM drive and DTC IM drive with a conventional inverter at low speed, medium speed and high rotating speed of IM with constant load torque 6Nm are summarised in table 2. It is observed that THD of the IM drive is considerably reduced with the proposed MLI based THD reduction DTC IM drive as compared with DTC IM drive with the conventional inverter. Besides that, when simulation are conducted with low speed to high rotating speed of IM, it also can be observed that THD of the IM drive reduced from low speed to high speed condition and when IM operates at rated condition (1400 rpm), the THD of IM drive is minimum. In addition, the speed and torque performances of IM is not affected with the proposed MLI based THD reduction DTC IM drive as shown in figure 6, figure 10 and figure 14 for low speed, medium speed and high rotating speed of IM respectively.

Table 2: THD of DTC IM drives with and without MLI corresponding to different speed

THD (%)						
Current	I_a		I_b		I_c	
Speed (rpm)	Convent-ional	Proposed MLI	Convent-ional	Proposed MLI	Convent-ional	Proposed MLI
300	74.50	60.94	76.49	63.86	67.06	57.53
850	55.45	45.57	48.48	38.15	32.78	24.63
1400	4.33	4.03	8.95	8.44	7.29	6.98

5. CONCLUSION

In conclusion, proposed three-level MLI are realized in MATLAB Simulink with PWM as the control strategy that control the switching of MLI in IM drive. With the proposed MLI based THD reduction DTC IM drive is applied in this study, the simulation result shows that the appropriate operation of the MLI results in reducing the THD of the motor drive system. The simulation result of conventional inverter based DTC IM drive shows the robustness and simplicity of the drive system, but there are high switching loss and torque ripples while for the proposed MLI based THD reduction DTC IM drive will reduce the switching losses and torque ripples, but increase the drive system complexity. From this study, with the proposed MLI based THD reduction DTC IM drive, THD of the DTC IM drive can be reduced approximately at an average 11.91% for low speed operation, 9.45% for medium speed operation and 0.37% for high speed operation.

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