



Performance Analysis of DTC, FOC and their combination applied to Multiple Induction Motor Drives with FLI

Aadam I. Harnekar¹, Anmol A. Welpulwar², Akshay Ekbote³, Madhavi Nerkar⁴

UG Student, Department of Electrical Engineering, DVVP COE, Pune University Ahmednagar, Maharashtra, India^{1,2,3}

Professor, Department of Electrical Engineering, DVVP COE, Pune University Ahmednagar, Maharashtra, India⁴

ABSTRACT: Various industrial processes require multiple induction motors that are to be operated at variable speeds and torques. In order to achieve the same different controllers are required for each motor which adds to the cost of the overall industrial process. The recent methods available to control the induction motor are VFD, FOC, and DTC. This paper presents a modified design to control multiple induction motors with a single controller using FLI for two induction motors. The performance characteristics of FOC and DTC applied to individual motor are evaluated in MATLAB. Also, the combination of FOC and DTC is designed and applied to two induction motors with variable speed torque requirements. All the three controller results are compared and its analysis is presented.

KEYWORDS: VFD- Variable Frequency Drive, FOC- Field Oriented Control, DTC- Direct Torque Control, FLI- Five Leg Inverter.

I. INTRODUCTION

Vector Control and Direct Torque Controls are becoming a choice for high performance induction motor drive system in industrial applications. Most of the research and studies focused on the vector control or direct torque control with a single three-phase motor and a single-three leg inverter drive system. There are many industrial manufacturing processes that require high performance control of a multi motor operation under different loads and speeds requirement. The multi motor operations under this condition encourage research on the multi motor drive system by using a single inverter. The research offers advantage of allowing independent control of the motors with cost reduction and space minimization. The independent control of two inductions can be realized by using Four Leg Inverter, Five Leg Inverter (FLI) or Nine Switched Inverter. This drive system offers cost reduction by reducing the numbers of power electronics switches devices, using only one DC bus supply, one DSP and less space. ^[3]

Many researches on the two motor control operation have discussed on the development of the inverter, motors connection, PWM strategy and performance analysis of the inverter. All of the system used vector control method for both motors. This paper focused on the development of combined vector control and DTC methods with a single FLI system to operate two three phase induction motors independently. One of the important components in independent control of two AC motor drive systems is the inverter control. Either in Four Leg Inverter, Five Leg Inverter Vector Control and Direct Torque Controls are becoming a (FLI) or Nine Switched Inverter, the PWM methods are used to control the switching gates to produce an appropriate output voltage to the motor. In the FLI topology, there are numerous PWM techniques such as Dual Voltage Modulation (DVM), Modulation Bock Method (MBM), Inversion Table Method (IVM), Double Zero Sequence Method (DZS) and Two Arm Modulation (TAM). The DZS is one of the best methods which enables an arbitrary distribution of the DC link voltage between the two motors and maintain to operate in constant switching frequency mode. DZS offer less complexity and easy to implement using standard DSP. This method is able to solve the drawback of previous PWM such as restriction of 50% of the DC bus voltage for one motor, asymmetrical switching frequency, underutilizing of the switching state, sideband harmonics, high magnitude THD generation and their complexity issue. ^[2]

The vector control or DTC offers better dynamic performance of induction motor drives. The vector control imitates the principle of separately excited DC motor. Independent control of both magnetic field and torque is

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 12, December 2017

achieved. The vector control concept implies that the current components supplied to the machine should be split into a flux component and a torque component. The flux component of the current is oriented in phase with the rotor flux vector, and the torque component is oriented in quadrature. This system applied the indirect field oriented control (IFOC) which only required correct alignment of rotating reference frame with rotor flux frame. The flux orientation can be achieved by imposing a slip frequency derived from rotor dynamic equation. Thus, it offers more easy implementation and cost saving compared to the direct field oriented control method (DFOC). Direct Torque Control-Space Vector Modulation (DTCSVM) method offers constant switching frequency and lower flux and torque ripple, reliable start up and low speed operation compared to the conventional method. Apart from these advantages, the DTC-SVM is chosen because it is able to work with the vector control to feed signal into the modulation of the FLI. Many research have been conducted to improve the DTC-SVM schemes introduced such as closed loop flux control, closed loop torque control and closed loop for flux and torque control. DTC scheme with closed loop and flux control selected for this analysis because it offers better flux and torque components control. This paper proposes a combined vector control and DTC methods for independent control of two induction motors fed by a single FLI.^[1]

II.SYSTEM MODEL

A. Five Leg Inverter (FLI) Configuration

The typical connection of the five leg voltage source inverter for two three-phase induction motors is shown in Figure 1. Each of the leg consists of two switches with a total number of ten switches altogether. Inverter legs A and B are connected to M1 meanwhile D and E legs are connected to M2. In the FLI topology, one leg is used as the common leg. This common leg is shared to the both motors. In this case, leg C is chosen as the common leg. All the legs are connected to the three-phase supply termination of the motors denoted as a1,b1,c1 and a2,b2,c2 to represent M1 and M2 termination respectively.

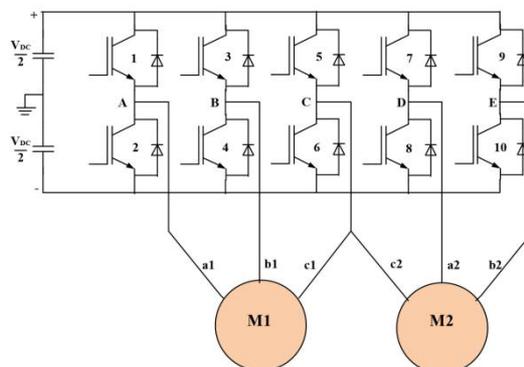


Figure 1: Connection between five leg inverter and motors

B. Double Zero Sequence (DZS) Injection Method Configuration

This simulation focused on the space vector PWM techniques applied using the DZS methods. These methods are the best solution to the FLI issues nowadays. Even though this method faced the natural constraints of the FLI which requires the total voltage of the machines must not exceed the DC bus voltage, it is able to utilize any portion of the DC bus voltage to be allocated to any of the two machines. The space vector DZS block diagram is shown in Figure 2. This method utilizes the standard three-phase space vector modulator to generate modulation signals for the FLI.

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 12, December 2017

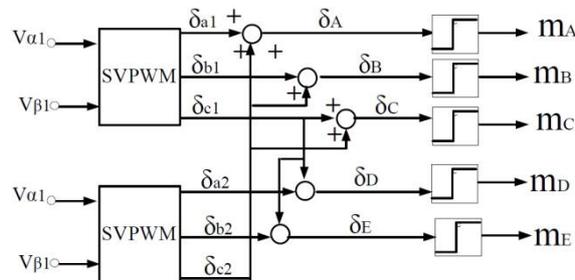


Figure 2 : Double Zero Sequence Injection Method block diagram.

Based on the principle, the first set of fundamental voltages in stationary frame is synthesized in the three-phase leg space vector modulator. This process is repeated for set 2. The output of the modulator is δ , which can be considered as the duty cycle for each three leg. The output signals of set 1 and set 2 are then summed in an appropriate manner to reduce the number of modulation signals from six to five as presented in the block diagram configuration. The summed results of output set 1 and set 2 generate modulated signal for all the five legs of the inverter as equation below:

$$\delta_A = \delta_{a1} + \delta_{c2}$$

$$\delta_B = \delta_{b1} + \delta_{c2}$$

$$\delta_C = \delta_{c1} + \delta_{c2}$$

$$\delta_D = \delta_{a2} + \delta_{c1}$$

$$\delta_E = \delta_{b2} + \delta_{c1}$$

Finally, the modulation signals of the FLI which are noted as mA, mB, mC, mD and mE respectively are compared to the carrier signal to generate output voltage of the FLI. The FLI then gives the input to the induction motors as per the switching states and angles of the IGBT, which in turn produces input voltages across the line terminals of the motor. This leads to a precise control of the speed and torque of the two induction motors.

C. Three phase Induction motor model

The MATLAB/Simulink model of three-phase induction motor is developed based on the following equations in synchronous reference frame^[1].

Stator voltage equation:

$$V_{ds} = R_s \bar{I}_{ds} + \frac{d\bar{\varphi}_{ds}}{dt} - \omega_s \bar{\varphi}_{qs}$$

$$V_{qs} = R_s \bar{I}_{qs} + \frac{d\bar{\varphi}_{qs}}{dt} - \omega_s \bar{\varphi}_{ds}$$

Rotor voltage equation:

$$\bar{V}_{dr} = 0 = R_r \bar{I}_{qr} + \frac{d\bar{\varphi}_{dr}}{dt} - (\omega_s - \omega_r) \bar{\varphi}_{qr}$$

$$\bar{V}_{qr} = 0 = R_r \bar{I}_{qr} + \frac{d\bar{\varphi}_{qr}}{dt} - (\omega_s - \omega_r) \bar{\varphi}_{dr}$$

Stator flux equation:

$$\bar{\varphi}_{ds} = L_s \bar{I}_{ds} + L_m \bar{I}_{dr}$$

$$\bar{\varphi}_{qs} = L_s \bar{I}_{qs} + L_m \bar{I}_{qr}$$

Rotor flux equation:

$$\bar{\varphi}_{dr} = L_m \bar{I}_{ds} + L_r \bar{I}_{dr}$$

$$\bar{\varphi}_{qr} = L_m \bar{I}_{qs} + L_r \bar{I}_{qr}$$

Torque equation:

$$T_e = \frac{3P}{2} (\bar{\varphi}_{ds} \bar{I}_{qs} - \bar{\varphi}_{qs} \bar{I}_{ds})$$

$$T_e - T_L = J \frac{d\omega_r}{dt}$$

III. FOC AND DTC CONFIGURATION IN FLI SYSTEM

The block diagram of two induction motors applying FOC and DTC schemes in a FLI system is illustrated in Figure 3. The FOC scheme is applied to control motor M1 while the DTC scheme is applied to the motor M2. Both of the schemes are used to control the variable speed demand for forward and reverse direction. In a single three-phase motor with single inverter application, this method is proven to be able to control the motor torque and flux effectively in order to force the motor to accurately track the command regardless of the machine and load variation or disturbance.

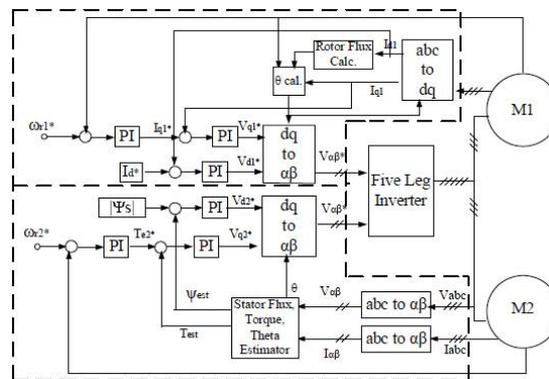


Figure 3: Two induction motor drive in FLI system diagram

With reference to Figure 3 the indirect FOC block diagram is applied to M1. In this system, the rotating coordinate reference frame having direct axis is aligned with the rotor flux vector that rotate at the stator frequency. This results in a decoupling of the variable so that the flux and torque can be separately controlled by the direct axis stator current, i_d and the quadrature axis stator current, i_q component. Based on the rotor voltage quadrature axis equation of induction motor, the rotor flux linkage can be estimated using this formula;

$$\hat{\psi}_r = \frac{L_m I_{ds}}{1 + \tau_r s}$$

Where, τ_r is the rotor time constant

The slip frequency is obtained from the rotor voltage direct axis equation:

$$\omega_{sl} = \frac{L_m R_r I_{qs}}{\hat{\psi}_r L_r}$$

The rotor flux position, for coordinate transform is generated from the integration of root speed and slip frequency.

$$\Theta_e = \int \omega_r + \omega_{sl}$$

The reference torque current, i_q^* is generated from the error of speed demand, ω_{r1}^* and actual measure speed, ω_{r1} with the speed PI controller. Then the i_q^* is compared with the actual torque current component, i_q and this gives the torque current error. This error is processed to generate the reference voltage torque component, V_{q1}^* . On the other hand, the reference flux component current, i_d^* which has been set earlier to a constant value is compared with the actual values of this variable, i_d . The error signal is applied to PI controller to generate the command values of flux voltage components, V_{d1}^* . These reference voltages are then transformed into stationary reference frame voltage by dq to $\alpha\beta$ transformation for SVPWM modulation process.

Meanwhile the DTC method block diagram is used to control the speed of M2. The value of stator voltage and stator current in stationary reference can be calculated from equation below:

$$V_{sa} = \frac{V_{dc}}{\sqrt{3}} (2S_a - S_b - S_c)$$

$$V_{sb} = \frac{V_{dc}}{\sqrt{3}} (S_b - S_c)$$

$$V_{sc} = \frac{1}{\sqrt{3}} (2I_{sa} - I_{sb} - I_{sc})$$



International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 12, December 2017

$$V_{s\beta} = \frac{1}{\sqrt{3}}(I_{sb} - I_{sc})$$

Torque is derived from the motor equation in stationary reference form given is:

$$\hat{\psi}_s = \int (\hat{V}_s - \hat{I}_s R_s) dt$$

$$\hat{T}_e = \frac{3P}{4} (\hat{\psi}_{ds} \hat{I}_{ds} - \hat{\psi}_{qs} \hat{I}_{qs})$$

The difference between speed reference, ω_r^* and speed feedback is amplified in the speed control amplifier of the PI controller and the output of the speed controller serves as the reference input to the torque component loop. The reference torque, T_e^* is compared with the estimated torque component, T_e to produce torque error. This error is amplified through PI controller to generate the reference voltage torque component V_{sq}^* . The stator flux component, $|\psi_s|$ is set to a constant value and compared with the estimated value for stator flux ψ ; and is converted to direct axis voltage demand, V_d^* . Then, both voltage components in rotating reference frame are transformed to the stationary reference frame by dq to $\alpha\beta$ transformation. The second set of reference voltage vector is synthesized through the modulation of the FLI.

IV. SIMULATION RESULT OF SPEED CONTROL OPERATION

A. Parameter Set-up for FOC and DTC and FOC

The induction motor is fed by a PWM voltage source inverter which is built using a Universal Bridge Block. The speed control loop uses a proportional-integral controller to produce the flux and torque references for the DTC & FOC block. The DTC/ FOC block computes the motor torque and flux estimates and compares them to their respective reference. The comparators outputs are then used by an optimal switching table which generates the inverter switching pulses. Motor current, speed, and torque signals are available at the output of the block.

Table I Induction motor parameters

Motor Specifications	Values
Rated Power	2800 VA
Rated Voltage	415 V
Rated Frequency	50 Hz
Poles pairs	2
Rated Speed	1430 rpm
Stator Resistance	0.435Ω
Rotor Resistance	0.816Ω
Stator Inductance	0.002 H
Rotor Inductance	0.002 H
Magnetizing Inductance	0.0069 H
Inertia	0.089kgm ²

B. DTC Simulation Results

Figure 4 shows the simulation results of Direct Torque control method which is applied to motor of 3 HP, the parameters of which are mentioned in the modelling section. The analysis is done on the basis of speed and torque references as mentioned in the modelling chapter. As seen from the figure for the reference speeds and torques the variation of stator current actual rotor speed and the DC bus voltage is observed. It is clear from the figure that initially as the rotor speed up for the reference speed of 700 RPM; the stator current is very high. This is due to the fact that the

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 12, December 2017

induction motor takes heavy current during starting. Then as the system becomes stable the current reduces to the stable value. Then the variable speed and torque requirement is fed to the controller and the current as well as electromagnetic torque varies. The pink lines are the reference values and the yellow ones are the actual measured parameters.

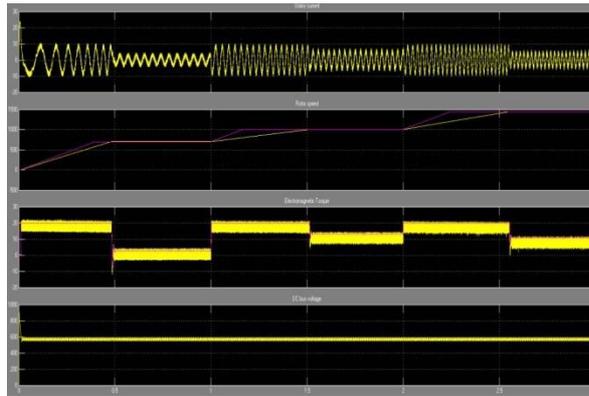


Fig. 4 DTC Simulation results

C. Vector Control Simulation Results

Figure 5 shows the simulation results of Vector control method which is applied to motor of 3 HP, the parameters of which are mentioned in the modeling section. The analysis is done on the basis of speed and torque references as mentioned in the modeling section. The parameters for analysis of FOC are the same as that of DTC as the comparison has to be done on a common platform. As seen from the figure 5 for the reference speeds and torques the variation of stator current actual rotor speed and the DC bus voltage is observed. It is clear from the figure that initially as the rotor speed up for the reference speed of 700 RPM; the stator current is very high. This is due to the fact that the induction motor takes heavy current during starting. Then as the system becomes stable the current reduces to the stable value. Then the variable speed and torque requirement is fed to the controller and the current as well as electromagnetic torque varies.

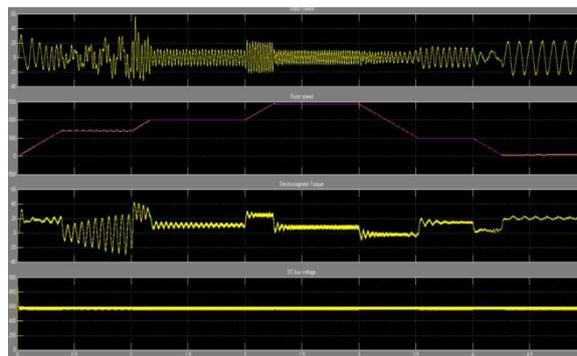


Fig. 5 Vector Control Simulation results

In the normal operation case, the speed response resultant from the FOC is faster and more robust than the DTC. The DTC technique has a better torque response, which is following the load torque smoothly instead of having the torque overshoot to a higher value than the required. That is a distinct disadvantage, because of the higher current that the motor must draw. The DTC has a faster stator magnetic flux response and when the motor is loaded the stator keeps following the flux band that is desired. In contrast, in the FOC technique the stator flux is slowly reaching the desired value and when the motor is loaded it might deviate from the desired values, especially the fully mechanical loaded case. DTC is easier to implement but FOC is more complicated because of the coordinate transformation which helps in the decoupling control. Thus, it is hard to definitely say that DTC is better than FOC each of the techniques has the excellence in

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 12, December 2017

some of the comparison aspects on the other. In general each technique has advantages and disadvantages, so we cannot say that one of them is completely better than the other but that is based on particular application.

D. Parameter Set-up for combined FOC and DTC

Simulations have been carried out for the two motor controls for the FLI by using SVPWM method. A dedicated speed range and torque load is applied to understand the performances of the FOC and DTC method with the FLI through the motors performances. Two similar types of three- phase induction motors are used in the simulation studies and details about the motor parameters are shown in Table I.

Based on the two induction motor drives fed by a single inverter principle, the summed voltage requirement of both motors must be within the DC bus voltage supply. The FLI is supplied by using 537V DC supply and carrier frequency is set at 3 kHz. Thus, this simulation is performed with a few speed ranges for forward and reverse operation by abiding to this principle in order to understand the speed behaviors. The analysis is limited to the half rated speed and half rated load for performance comparison. The motors are set to follow the speed operating demand and external torque load applied as follows:

- M1-400 rpm is applied from zero to 0.4s, and then the speed is increased to 600rpm until it reaches 1s and suddenly step changed to -750rpm at 1s until it reaches 2s.
- Torque load 1(TL1): 3Nm external load torque is applied to the M1 from 0.6s to 1.5s
- M2-400 rpm is set from zero to 0.4s, and then the speed is increased to 750rpm until it reaches 1s and suddenly step changed to -750rpm at 1s until it reaches 2s.
- Torque load 2(TL2): 5Nm external load torque is applied to M2 from 0.6s to 1.5s

By referring to the vector control block diagram in Figure 1, three PI controllers are used for the speed, torque and flux controlled for FOC and DTC. All the PI controllers are tuned manually to produce a periodic speed response with minimum settling time to the applications of 50% rated speed command under no load conditions with rated inertia. Table III shows the PI controller parameters for speed, torque and flux components.

Table III. Speed, torque and flux controller parameters

PI controller	FOC PI value	DTC PI Value
Speed Controller	Kp=2.55 Ki=80	Kp=25 Ki=50
Torque Controller	Kp=45 Ki=90	Kp=150 Ki=5000
Flux Controller	Kp=25 Ki=60	Kp=440 Ki=70000

E. Combined DTC and FOC Simulation Results

The performance investigation of the FOC and DTC method fed the FLI is conducted to understand the behavior of the motors under different speed command change, load disturbance, steady state stability and transient response.

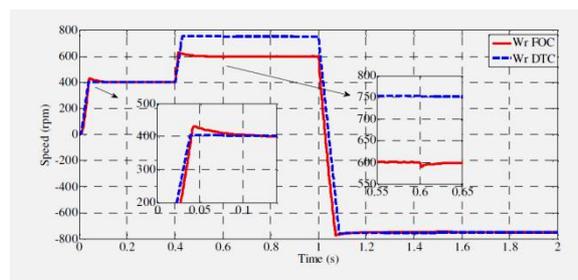


Fig. 6 M1 and M2 Speed Response

Figure 6 shows the speed response for M1 and M2 motors based on FOC and DTC method respectively. Both motors are able to operate in forward and reverse direction. Different speed demand can be seen during 0.4s to 1s

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 12, December 2017

show the ability of the FLI to independently control the motors using combined FOC and DTC method. At -750rpm demand, the result shows the ability of the system to perform at 50% voltage utilization factor with FLI. Further analysis of the speed response during 400rpm speed and no load demand conclude that the DTC method produced lower percent overshoot (%OS) and faster speed response compared to FOC with about 1%OS and 8%OS respectively. Both methods are able to absorb different external loads applied with a minor speed drop at 0.6s to the motors and before recovering in a few milliseconds.

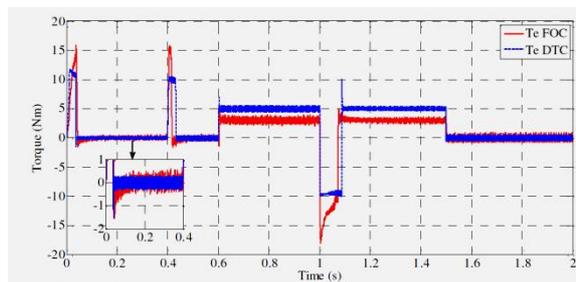


Fig. 7: M1 and M2 Torque Characteristic Performances

Based on the torque characteristics in Figure 5, DTC has experienced lower electrical torque response compared to the FOC which are about 12Nm and 16Nm respectively. In this case, the torque component is limited to 10Nm for DTC or 10A for FOC. In DTC, torque is directly controlled while in FOC the torque is controlled by the torque current component. The torque can be analyzed during no load condition at 400rpm, DTC experienced 0.3Nm while FOC shows 0.5Nm. Overall, torque analysis has shown the FOC has a higher torque ripple compared to DTC.

Figure 7 depicts phase A current of M1 and M2. Based on the current responses, the higher currents occurred during start up condition, during speed reversal and when external loads were applied. From the torque response, higher load condition experience higher stator current and vice versa. This is in line with the motor operation principle.

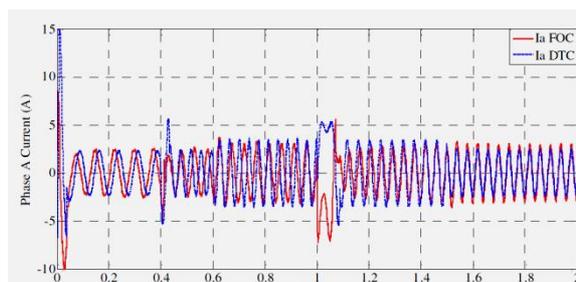


Fig. 8 M1 and M2 Phase A stator current characteristic performances

V. CONCLUSION

This paper presents two induction motor drive techniques (FOC and DTC) which are simulated by using MATLAB/SIMULINK and are compared and analysed. The results show that the DTC and FOC methods are their own merits and demerits and it cannot be judged completely which one method is better. Then, the development of a combined vector control and DTC methods to independently control two induction motors fed by single FLI is presented. The results show the ability of the proposed method to control motor speed independently under forward-reverse step speed command and load disturbance condition. The combined method using FLI is also cost effective and has the combined advantages of FOC and DTC.



ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 12, December 2017

REFERENCES

- [1] M.H.N. Talib, Z.Ibrahim, N.Abdul Rahim, N.Mohd Yaakop, “Development of Combined Vector & Direct Torque Control methods for independent two Induction motor drives”, in 2012 IEEE International Power Engineering & optimization conference(PEOCO20120), Melaka, Malaysia, 6-7 June 2012
- [2] Masahiro Taniguchi, Takashi Yoshiunaga, Kauki Matsuse, “Speed-sensor less Vector control of Parallel-connected Multiple Induction Motor Drives with Adaptive Rotor Flux observers”. Department of Electrical and Electronic Engineering
- [3] Fathalla Eldali , “A comparative study between vector control and direct torque control of induction motor and partial fulfilment of the requirements For the Degree of Master of Science Colorado State University Fort Collins, Colorado ,Fall 2012
- [4] M.H.N. Talib, Z.Ibrahim, N.Abdul Rahim, N.Mohd Yaakop, “Speed performance of SVPWM direct torque control for five leg inverter served dual threephase induction motor””, in 2012 IEEE International Power Engineering & optimization conference (PEOCO20120), Melaka, Malaysia, 6-7 June 2012
- [5] M. Jones, S.N Vukosavic, D. Dujic, E.Levi, P.Wright, “Five-leg inverter PWM technique for reduced switch count two-motor constant power applications,” IET Electr. Power Appl., 2008, vol.2, no. 5, pp. 275-287