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Loss Minimisation of Vector Controlled Induction Motor during Transient Loading

Ashish Kumar Gautam
Department of EEE
Mar Athanasius College of Engineering
Kothamangalam, India

Jisha Kuruvilla P
Professor, Department of EEE
Mar Athanasius College of Engineering
Kothamangalam, India

Abstract:- DC motor has high dynamic performance, became achievable from induction motors with the advances in power semiconductors, digital signal processors and development in control techniques. By using vector control, torque and flux of the induction motors can be controlled independently as in DC motors. The control performance of field oriented induction motor drive greatly depends on the stator flux estimation. In this project field oriented control (Vector control) model is using different types of pulse width modulation (PWM) technique. PWM techniques are space vector pulse width modulation (SVPWM), sine pulse width modulation (SPWM) and current controller. In these PWM techniques SVPWM is better than SPWM and current controller, because it has less total harmonic distortion (THD) and better electromagnetic torque (Te). This project is also considered about optimization technique for minimize the power loss in induction motor. The simulation is done by using MATLAB/SIMULINK R2017a software. Hardware is planned to implement using TMS320F28335 as digital signal processor.

Keywords:- *Vector Control; PWM Techniques; Power Loss; Optimization; Effienciency.*

I. INTRODUCTION

Variable speed drive systems are basically in many industrial applications. DC motors were used massively in this areas where variable speed operation was elaborated, since their flux and torque could be managed easily by the field and armature current. DC motors have certain disadvantages, which are due to the presence of the commutator and the brushes. That is, they need periodic maintenance; they cannot be used in flammable or corrosive environments and they have limited commutator potential under high speed, high voltage operational conditions. These complications can be overcome by the application of alternating current motors, which can have simple and rugged structure, high maintainability and economy; they are also robust and immune to heavy overloading. These advantages have recently made induction machines mostly used in industrial applications. However, the speed or torque control of induction motors is more arduous than DC motors due to their nonlinear and complex structure. The torque of the DC motors can be superintended by two independent orthogonal variables, stator current and rotor flux, where such a decoupling does not exist in induction motors.

The control of AC machine is essentially classified into scalar and vector control. The scalar controls are easy to implement though the dynamics are sluggish. The objective of vector control is to achieve a similar type of controller with an inner torque control loop which makes the motor respond very fast to the torque demands from the outer speed control loop. In vector control, the principle of decoupled torque and flux control are applied and it relies on the instantaneous control of stator current space vectors. Control of induction motor is complicated due to the control of decoupled torque and flux producing components of the stator phase currents. There is no direct ingress to the rotor quantities such as rotor fluxes and currents. To overcome these difficulties, high performance vector control algorithms are developed which can decouple the stator phase currents by using only the measured stator current, flux and rotor speed follow.

“Field Oriented Control has been uniquely elaborated for high-performance motor applications which can employ smoothly over the wide speed range, can fabricate full torque at zero speed, and is skilled of quick acceleration and deceleration."

A. Principal of Field Oriented Control

The principle of FOC system of an induction motor is that the d-q coordinate reference frame is locked to the rotor flux vector, this results in decoupling of the variables so that flux and torque can be individually controlled by stator direct axis current i_{sd} and quadrature axis current i_{sq} respectively like in the separately excited DC machine. Performance of DC machine can also be expanded to an induction motor if the machine is appraised in a synchronously rotating reference frame where the sinusoidal variables appears as DC quantity in steady state. The induction motor with the inverter and vector control in the front end is shown in Figure (1).

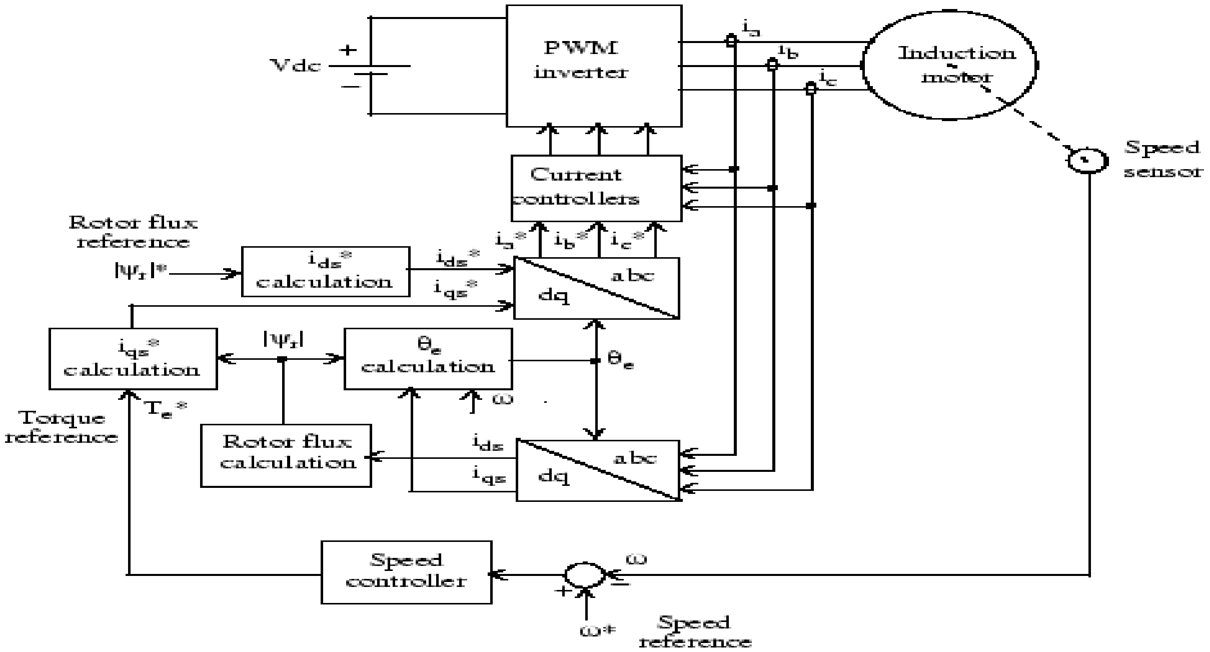

Fig 1:- Block Diagram of Field Oriented Control

The three-phase voltages, currents and fluxes of AC-motors can be inspected in terms of complex space vectors. If we take i_a, i_b and i_c as instantaneous currents in the stator phase, then the stator current vector is defined as follow:

$$i_s^{\rightarrow} = i_a + i_b e^{j2\pi/3} + i_b e^{j4\pi/3}$$

Where a, b and c are the axes of three phase system. This current space vector constitutes the three phase sinusoidal system. It needs to be transformed into a two time coordinate system. This transformation can be divided into two steps: first is (a, b, c) to (α, β) (the Clarke transformation), which gives output of two coordinate time variant system. Second is (α, β) to (d, q) (the Park transformation), which gives outputs of two coordinate time invariant system[1].

B. Clarke Transformation

Three-phase quantities either voltages or currents, varying in time along the axes a, b, and c can be mathematically transformed into two-phase voltages or currents, varying in time along the axes α and β by the following transformation matrix:

$$i_{\alpha\beta o} = (2/3)\begin{bmatrix} 1 & -1/2 & 1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

Assuming that the axis a and α are along same direction and β is orthogonal to them, we have the following vector diagram:

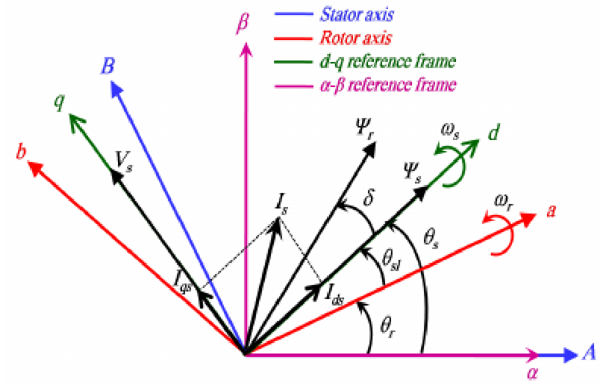

Fig 2:- Clarke and Park transformation

$$i_{s\alpha} = i_\alpha$$
$$i_{s\beta} = i_a/\sqrt{3} + i_b/\sqrt{3}$$

But these two phase (α, β) currents still depends upon time and speed.

C. Park Transformation

This is the most important transformation in the FOC. In fact, this projection modifies the two phase fixed orthogonal system (α, β) into (d, q) rotating reference system. The transformation matrix is given below:

$$i_{dqo} = (\frac{2}{3})\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

Where, θ is the angle between the rotating and fixed coordinate system. The torque and flux components of the current vector are determined by the following equations:

$$i_{sq} = -i_{s\alpha}\sin\theta + i_{s\beta}\cos\theta$$
$$i_{sd} = i_{s\alpha}\cos\theta + i_{s\beta}\sin\theta$$

These components depend on the current vector (α, β) components and on the rotor flux position. If you know the accurate rotor flux position then, by above equation, the d, q component can be easily calculated. At this instant, the torque can be controlled directly because flux component (i_{sd}) and torque component (i_{sq}) are independent now.

D. i_{qs} calculation*

The stator quadrature-axis current reference i_{qs}* is calculated from torque reference T_e* as

$$i_{qs}^* = \frac{4l_r T_e^*}{3Pl_m\varphi_r}$$

where L_r is the rotor inductance, L_m is the mutual inductance, and $[\Psi_r]$ is the estimated rotor flux linkage given by

$$\varphi_r = \frac{l_m i_{ds}}{1+\tau_r s}$$

where $\tau_r = L_r / R_r$ is the rotor time constant.

E. i_{ds} calculation*

The stator direct-axis current reference i_{ds}* is obtained from rotor flux reference input $[\Psi_r]$*.

$$i_{ds}^* = \frac{\varphi_r^*}{l_m}$$

F. Θ_e calculation

The rotor flux position θ_e required for coordinates transformation is generated from the rotor speed ω_m and slip frequency ω_{sl}.

$$\theta_e = \int(\omega_m + \omega_{sl})$$

The slip frequency is calculated from the stator reference current i_{qs}* and the motor parameters.

$$\omega_{sl} = \frac{l_m R_r i_{qs}^*}{l_r\varphi_r}$$

The i_{qs}* and i_{ds}* current references are converted into phase current references i_a*, i_b*, i_c* for the current regulators. The regulators process the measured and reference currents to produce the inverter gating signals.

II. DIFFERENT PWM TECHNIQUES

Switching techniques of pulse width modulation (PWM) have been approved in the area of power electronics and drive systems. PWM is frequently used in applications like motor speed control, converters audio amplifiers etc. The pulse width modulation (PWM) techniques are regularly used for voltage control. PWM techniques are Voltage Mode Control and Current Mode Control. In Voltage Mode Control mainly two types are Sinusoidal pulse width modulation and Space Vector pulse width modulation. In Current Mode Control one technique is current control.

A. Voltage Mode Control

Voltage mode control represents the most fundamental method, in which only the output voltage is returned through a feedback loop. The differential voltage, which is obtained to compare the output voltage with the reference voltage by an error amp, is compared with triangular waves by a PWM generator. As a result, the pulse width of the PWM signal is resolved to control the output voltage. Advantages of this method are its relative simplicity based on the use of a feedback loop consisting solely of voltages, the ability to control shorter on-time, and high noise tolerance. Possible snags are the complexity of the phase compensation circuit and a cumbersome design process.

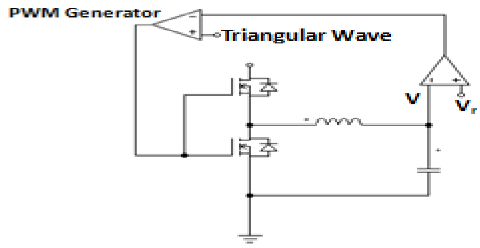

Fig 3:- Voltage Mode Control

Two types of Voltage Mode Control:

- ➢ Sinusoidal pulse width modulation (SPWM)
- ➢ Space Vector pulse width modulation (SVPWM)

➢ *Sinusoidal Pulse Width Modulation*

The sinusoidal pulse width modulation (SPWM) technique is used to produce the sinusoidal waveform by filtering an output pulse waveform with varying width. A better filtered sinusoidal output waveform can be obtained by using a high switching frequency and by varying the amplitude and frequency of a reference or modulating voltage. In SPWM technique it maintains the pulses in different widths instead of maintaining in equal widths as in multi pulse width modulation where the distortion factor (DF) and lowest order harmonics (LOH) are significantly reduced. the control signal generator for SPWM. In this we use triangular wave as carrier signal and sine wave as a reference signal and compare the two waveforms with the help of comparator.

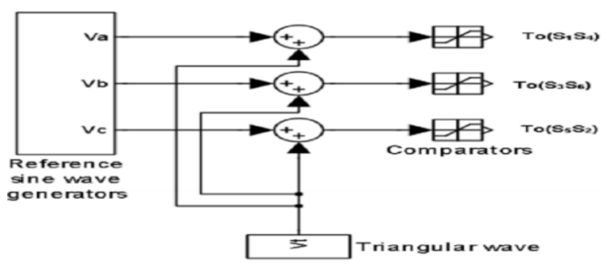

Fig 4:- Control signal generator for SPWM

➢ *SPACE Vector Pulse Width Modulation*

Another method to increase the output voltage about that of SVPWM technique is the space vector pulse width modulation (SVPWM) technique. This method is used for adjustable speed drives. This technique can increase the fundamental up to 27.3% when compared with SPWM. SVPWM uses the rotating synchronous reference frame. SVPWM works on the principle that when upper transistor is switched ON; corresponding lower transistor is switched OFF. The ON and OFF state of the upper switches (S1, S3, S5) evaluates the output voltages.

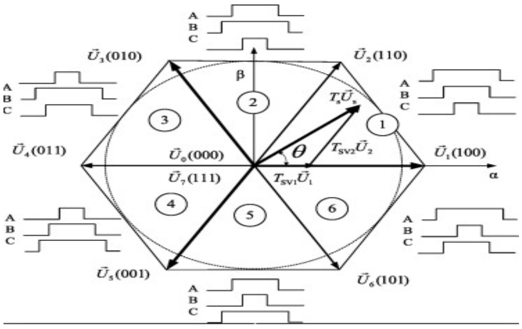

Fig 5:- SVPWM Switching States

B. Current Mode Control

The current mode is a modification of voltage mode control, where the inductor current in the circuit is detected and used instead of the triangular waveforms used in the voltage mode control. The current sensing can also be done by using the on-resistance of high side MOSFET or a current sense resistor instead of the inductor current. Since the current mode has two types of feedback loops: voltage loop and current loop, the control exerted is relatively complex. However the current mode provides the advantage of a substantially simplified phase compensation circuit design. Other benefits include the highly stable feedback loop and a faster load transient response than that of the voltage mode. A drawback is low-noise tolerance due to the high sensitivity of current detection.

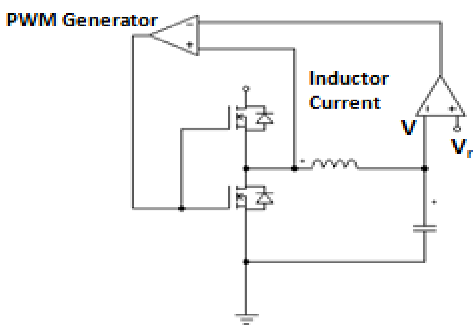

Fig 6:- Current Mode Control

III. OPTIMIZATION OF POWER LOSS IN INDUCTION MOTOR

In the simplest case, an optimization problem consists of maximizing or minimizing a real function by systematically choosing input values from within an allowed set and computing the value of the function.

Optimization technique is used to minimize the power loss of IM, in power loss two types of losses are here one is ohmic loss and other is transient loss. Two variables are ids and Te, ohmic loss is directly proportional to square ids, transient loss is inversely proportional to square ids and directly proportional to square Te and this is a non-linear equation so we need a non-linear two variables optimization technique which can minimize the power loss of IM.

$$P_{Loss} = i_{ds}^2\left(R_s + l_s^2(k_h f + k_e f^2)\right) + \frac{1}{i_{ds}^2}\left(\frac{T_e^* R_s}{k_T^2 l_m}\left(1 + \frac{R_r l_m^2}{l_r^2}\right) + \frac{\sigma^2 l_s^2}{k_T^2 l_m^2}(k_h f + k_e f^2)\right)$$

Here two types of non-linear optimization technique are used:

(1) Gradient Conjugate Method

(2) Quasi Newton Method

A. Gradient Conjugate Method

The nonlinear conjugate gradient method is generally used to find the local minimum of a nonlinear function using its gradient $\nabla_x f$ alone. It works when the function is approximately quadratic near the minimum, which is the case when the function is twice differentiable at the minimum[7] and the second derivative is non-singular there. Steps are given below:

1. Start with an initial point X_1, Set the iteration i = 1.
2. Find the search direction $S_i = -\nabla f(X_i)$.
3. Find the point X_2,

$$X_2 = X_1 + \lambda_1^* S_1$$

λ_1^* is the optimal step length in the direction S_1.

4. Set i =2 and find

$$\nabla f_i = \nabla f(X_i)$$

$$S_i = -\nabla f_i + \frac{|\nabla f_i|}{|\nabla f_{i-1}|^2} S_{i-1}$$

5. Compute the optimum step length λ_i^* in the direction S_i and find the point

$$X_{i+1} = X_i + \lambda^* S_i$$

6. Test the point X_{i+1} for optimality. If X_{i+1} is optimum, stop the process otherwise, set i = i+1 and go to step 4.

Continue this process until we get an optimum point.

B. Quasi Newton's Method

Newton's method is used for single variable function while quasi newton's method can be used for minimization of multivariable function. Solving process are given below: Consider the quadratic approximation of function f'(x) at x = x_i using Taylor series expansion[8]

$$F'(X) = F'(X_i) + F''(X_i)\{X - X_i\} = 0$$
$$\nabla F = \nabla F_i + J_i\{X - X_i\} = 0$$

Solution of next point,

$$X_{i+1} = X_i - \frac{\nabla F_i}{J_i}$$

where J_i = $[j]_{xi}$ is the matrix of second partial derivative. this iterative process can be assumed to converge when f'(x_{i+1}) is close to zero.

After substituting all constants values in equation power loss

$$P_{Loss} = 17.3432 i_{ds}^2 + \frac{1}{i_{ds}^2}\{2.0754 T_e^2 + 0.0554\}$$

Above equation two variables ids and Te are there. From two variables one is torque which we are going to assume as constant rated torque that is one type of optimization and in second type both will be consider as variables.

C. Optimization Results with Constant Torque

In this section we will see when torque is increased from one constant value to other, is this i_{ds} following torque or not? Rated torque for 1Hp induction motor is 14Nm, in first case we will take zero torque , second case we will take one by four of torque ,third case we will take one by two of torque , fourth case three by four of torque and in final case we will take full rated torque and we will see according to above cases what is the value of i_{ds} and what is minimum power loss and also efficiency with different cases.

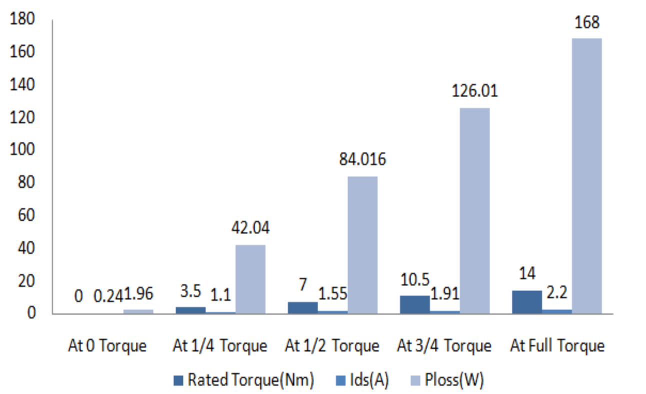

Fig 7: Optimum Value of i_{ds} and P_{Loss} with respect to Rated Torque

From above figure we can say that i_{ds} is following rated torque as torque is increasing, i_{ds} is also increasing and power loss is also increasing. Now we are assuming rated i_{ds} is equal to 8A, and going to calculate power loss for different cases after that we will calculate efficiency.

Torque	i_{ds}		P_{Loss}		Efficiency	
Rated Torque (14Nm)	Rated	Optimize Value	At rated i_{ds}	At Optimize Value	At rated i_{ds}	At Optimize Value
¼ Torque	8A	1.1A	1110.16 W	42.04W	33.12%	93%
½ Torque	8A	1.55A	1111.35W	84.02W	49.7%	93%
¾ Torque	8A	1.91A	1113.34W	126.01W	59.7%	93%
Full Torque	8A	2.2A	1116.12W	168W	66.33%	93%

Table 1:- Efficiency Table

After seen above table we can say at optimize value of i_{ds} power loss is very less compare to rated value i_{ds} due to this optimize value of i_{ds} has very good constant efficiency. At rated value i_{ds} efficiency is increasing as rated torque is increasing but not reached up to level of efficiency of optimize value of i_{ds}.

D. Optimization Results with Two Variables

After applying gradient conjugate method and quasi newton method of optimization we found at 1.9604 which is function last iteration value so it is.

$$P_{Loss} = 1.9604W$$

At last iteration which is 14, i_{ds} value is 0.2378A and torque value is -3.2336 e^{-6} Nm. Due to local minima P_{loss} minimum value is not going to change, if u place any value of starting X except [0,0] then u will get same power loss minimum value only number of iteration is going to change and ids and torque value is also same only sign will be changed according to staring value.

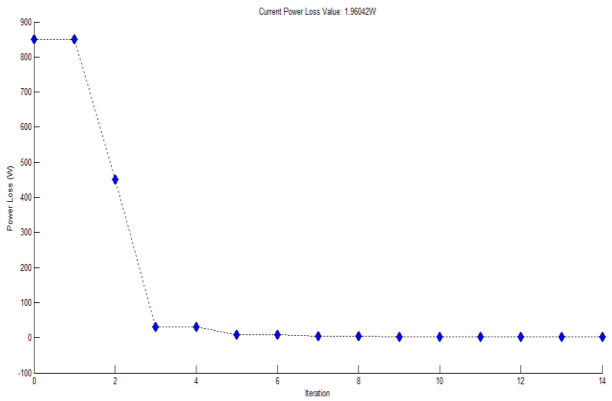

Fig 8:- By using Gradient Method Optimization

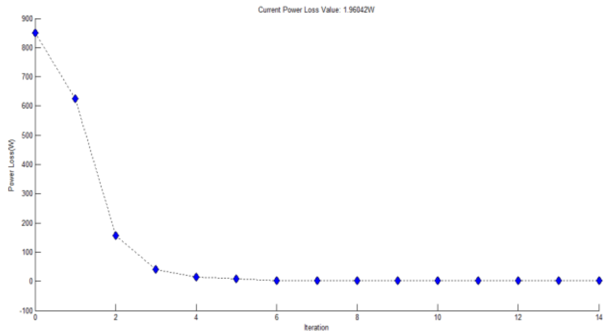

Fig 9:- By using Quasi Newton's Method

IV. SIMULIATION RESULTS AND COMPARE STUDY

A. Simulink Result with Different PWM Technique

In Simulink model of vector control induction motor drive, there is a diode rectifier, an inverter 1HP induction motor and a close control process to generate PWM. Simulation parameters are calculated by using No-load test and blocked rotor test and simulated in MATLAB 2017a. In this paper three PWM techniques are available and we will use that PWM techniques and compare their results. All parameters is going to same during simulation only PWM techniques is going to change.

1) Using Current Controller PWM Techniques

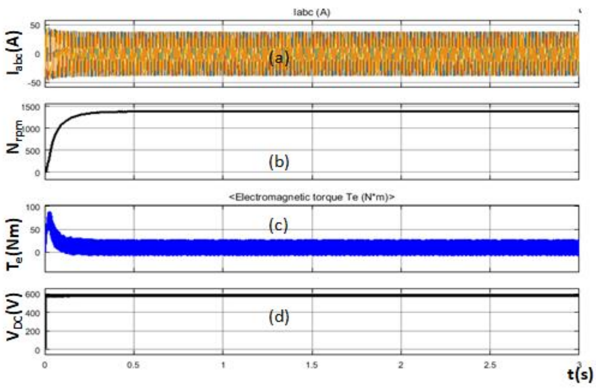

Fig 11::- Using Current Controller Simulation Result (a) I_{abc} (b) N_{rpm} (c) T_e (d) V_{DC}

2) Using Space Vector PWM Techniques

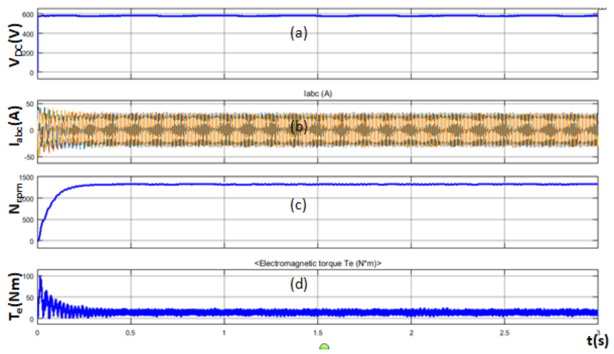

Fig 12:- Using Space Vector PWM Simulation Results (a)V_{DC} (b)I_{abc} (c)N_{rpm} (d)T_e

Figure 12 shows output of Vector control IM which is using space vector PWM technique to generate PWM, It is used for the creation of alternating current (AC) waveforms; most commonly to drive 3 phase AC powered motors at varying speeds from DC using multiple class-D amplifiers. There are variations of SVPWM that result in different quality and computational requirements. One active area of development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to these algorithms.

3) Using Sinusoidal PWM Techniques

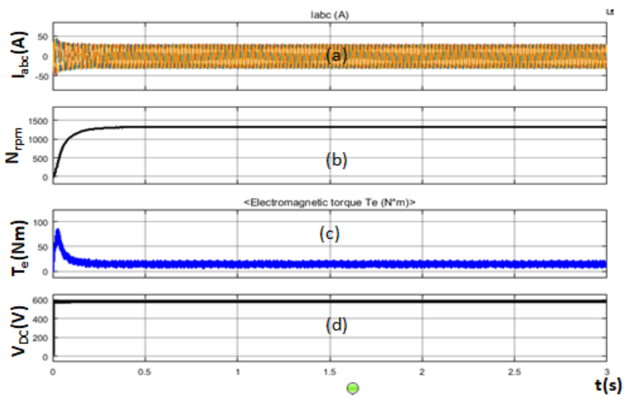

Fig 13:- Using Sinusoidal PWM Simulation Results (a)I_{abc} (b)N_{rpm} (c)T_e (d) V_{DC}

Figure 13 shows output of Vector control IM which is using Sinusoidal PWM technique to generate PWM. In sinusoidal PWM, the modulation signal is sinusoidal, with the peak of the modulating signal always less than the peak of the carrier signal.

B. Compare Study of Results

After using three PWM techniques we have three different results, that is given below:

Parameter	Current Controller	SPWM	SVPWM
THD	27%	23.9%	20.4%
T_e(Nm)	16.15	15.16	21.73

Table 2:- Comparative Study

Table 2 shows SVPWM PWM technique is better than other PWM techniques because THD is lesser and electromagnetic torque is greater than SPWM and current controller. SVPWM technique other advantages are: (1) better fundamental output voltage, (2) Useful in improving harmonic performance when vectorally adding two, otherwise identical, out of phase (by 120^0) pulses some (odd triplen) harmonics algebraically add to the (odd triplen) harmonics of the other while canceling out another group of harmonics leaving a sine-wave-like result twice as large as either of its constituent pulses, (3) Extreme simplicity and its easy and direct hardware implementation in a Digital Signal Processor (DSP), (4) SVPWM can be efficiently executed in a few microseconds, achieving similar results compared with other PWM methods.

C. Simulation Results with Transient

1) Speed is Constant and torque is varying

For simulation speed reference has taken as 1500rpm for all time period and load torque is varying at 0s torque is 0Nm, at 0.5s it is 7Nm and at 1.5s it is -7Nm[3].

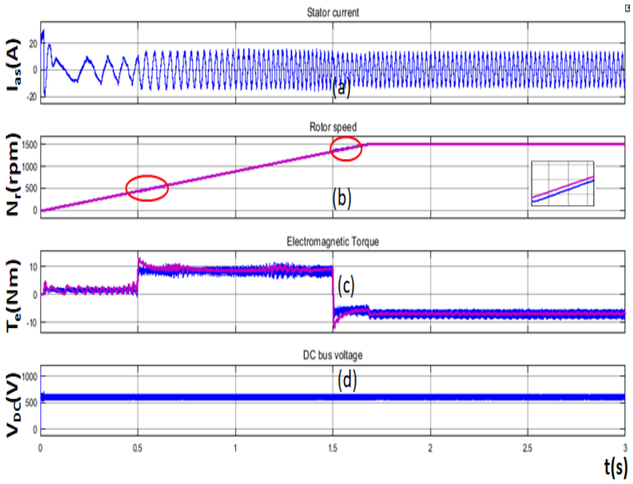

Fig 14:- (a) I_{as} (b) N_{rpm} (c) T_e (d) V_{DC}

At t=0s,the speed set point is 1500rpm and observe that the speed follows acceleration ramp. At t=0.5s the load torque 7Nm is applied to motor shaft while the motor speed is still ramping to its final value. At t=1.5s next torque load -7Nm is applied due this load it is taking more time to reach its final speed value. At t=2s speed is constant and load torque also.

2) Speed is varying and torque is constant

For simulation speed reference has taken as 500rpm at 0s, 1000rpm at 1s and 1500rpm at 2s, load torque is constant at 7Nm for all time period. In figure 15 At t=0s,due to load torque 7Nm at staring rotor speed is started from -50 rpm and it recover from that soon started to follows the speed set point 500rpm and observe that the speed follows acceleration ramp. At t=0.5s the load torque 7Nm is still to motor shaft while the motor speed is still ramping to its first reference value 500rpm. After 0.5s it reached at 500rpm and torque is also stable. At t=1s speed reference is varying from 500 to 1000rpm, so torque is also increased and both are stable after 1.5s. At t=2s next speed reference is applied that is 1500rpm so again torque is increased and both are stable at after 2.5s.

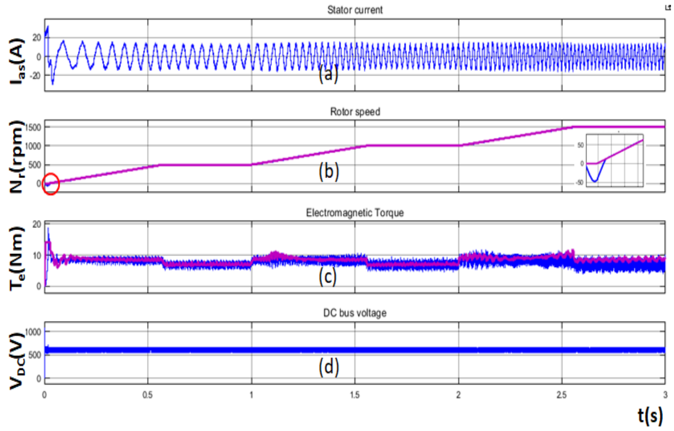

Fig 15:- (a) I_{as} (b) N_{rpm} (c) T_e (d) V_{DC}

3) Speed and torque both are varying

For simulation speed reference has taken as 500rpm at 0s, 1000rpm at 1s and 1500rpm at 2s, load torque is varying at 0s torque is 0Nm, at 0.5s it is 7Nm and at 1.5s it is -7Nm.

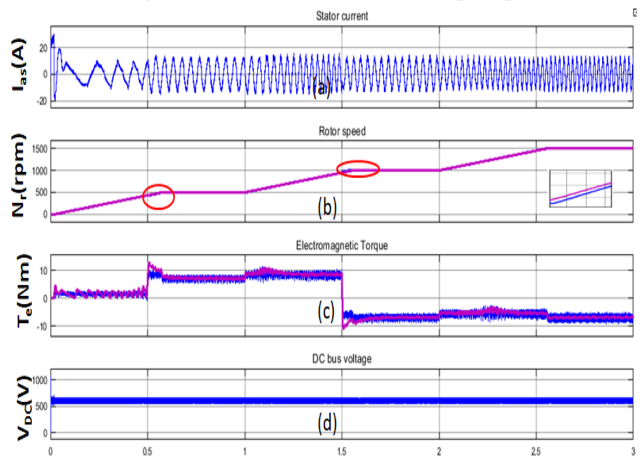

Fig 16:- (a) I_{as} (b) N_{rpm} (c) T_e (d) V_{DC}

At t=0s,the speed set point is 500rpm and observe that the speed follows acceleration ramp. At t=0.5s the load torque 7Nm is applied to motor shaft while the motor speed is still ramping to its final value. At t=1.5s next torque load -7Nm is applied due this load it is taking more time to reach its final speed value. At t=2s speed is varying to 1500rpm and load torque also increased. After 2.5s both are stable.

V. HARDWARE RESULT

The gate pulses are generated using TMS320f28335 DSP Processor[2]. It's based on Harvard Architecture with a high performance 32 bit CPU, with an on chip memory of 256K × 16 Flash, 34K × 16 SARAM. For converter and inverter part Intelligent Power Module (IPM) is used. Intelligent Power Modules (IPMs) are advanced hybrid power devices that combine high speed, low loss IGBTs with optimized gate drive and protection circuitry.

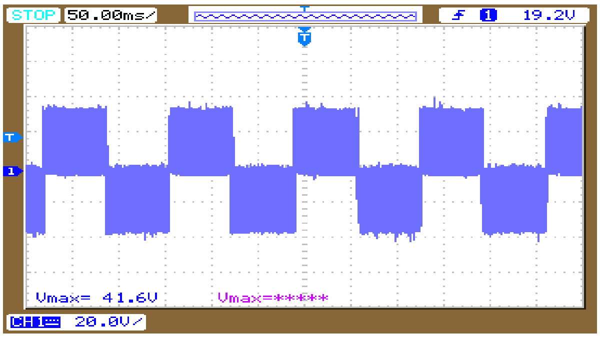

Fig 17: Line to Line voltage

Figure 17 shows line to line voltage of vector controlled Induction Motor.

VI. CONCLUSION

By using vector control using in induction motor we are getting transient response will be fast because torque control by i_{qs} does not affect flux. It allows for speed control in all four quadrants (without additional control elements) as negative torque is directly taken care of in vector control and also low power dissipation. It automatically limits operation to the stable region. In PWM technique SVPWM is better than SPWM and current controller because total harmonic distortion (THD) in SVPWM is less then SPWM and current controller, electromagnetic torque (Te) is also greater than SPWM and current controller, all results are done on same parameters value for all three PWM techniques. By applying optimization technique an optimal function value calculated to minimum the power loss in induction motor there by improving the efficiency of induction motor.

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