Abstract-- The objective of this paper is to provide the
precise solution for speed control of three phase induction
motor for high speed variable speed drives. In this paper,
Implementation of indirect vector control induction motor
drive has been developed, which provide quick torque &
good dynamic responses near zero speed & high speed. The
simulation result of IVCIMD shows four quadrant
operation of drive. The performance of indirect vector
control induction motor drive is enhanced using different
controller & comparative performance has been presented
& analysed in this work. This paper also present different
speed control methods of induction motor. In addition,
MATLAB code results for variable stator voltage, variable
rotor resistance, constant Volts/Hz control & variation of
direct-axis stator current, quadrature-axis stator current
with variation in stator voltage is also present &
comparative study has been made between us.

Keywords-- Indirect Vector Control Induction Motor
Drive (IVCIMD), Stationary Reference Frame, Open Loop
Control, Synchronous Rotating Reference Frame, Variable
Speed Drives.

I. INTRODUCTION

Electric drive has evolved over the year & so have the
techniques to control their speed & torque. There are a
large number of researches activities taking place in
order to achieve stable control techniques with growing
capabilities in similar fields, the control techniques are
also become better with time.

In 1980s, DC motor drives were generally used in
variable speed drives because of the simplicity of control
due to decoupling between armature current & the field
current. But DC motor has several disadvantages such as
regular maintaine of commutator, brushes & brushes
holder, limited current carrying capacity during high
speed applications etc. Therefore squirrel cage induction
motor are widely used as they have highly reliable,
robust construction & free from regular maintaine &
become work horses in the industry for the variable speed
application in a wide power range. This is the main
reason to replace the DC motor with an induction is to
merge the advantage of both motor together into a
variable speed drives & eliminate the associate problem.
These applications include pumps & fans, paper mill,
subway & locomotive propulsions, electric & hybrid
vehicles, machine tools & robotics, home appliances,
heat pumps etc.

Performance & Comparison Analysis of Indirect Vector
Control of Three Phase Induction Motor

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The control & estimation of ac drives in general is
considered more complex than those of dc drives, & this
complexity increase substantially if performance are
demanded.[1][20]

To control the induction motor there are different
types of control are there they are:

- Variable supply voltage control
- Variable rotor resistance control
- Constant Volts/Hz control (scalar control)
- Direct torque control
- Vector Control

II. SPEED CONTROL METHOD OF INDUCTION MOTOR

A. Variable Rotor Resistance control

In this method of speed control an resistances can be
connected in the rotor circuit externally during starting.
At starting slip s =1, this increases the starting torque and
reduces the starting current. The maximum torque during
starting can be achieved by using appropriate value of
resistors. Once the motor is started acceleration, the
resistance can be connect externally should be cut out to
obtain high torque throughout the accelerating range. As
external resistances are connected, most of the I^2R loss
is dissipated through them thus the rotor temperature rise
during starting is limited. This method can be used in
applications requiring high starting torque. This method
is used only for wound motor, an external resistance is
added to it through slip rings. [36][67]

B. Variable Stator Voltage

The developed torque of an induction motor is
proportional to square of the supply voltage to its stator
terminals, by varying the supply voltage, the
electromagnetic torque developed by the motor can also
be varied. The value of maximum torque also decreases,
with decrease in supply voltage. But it still occurs at the
same slip as earlier. This method is generally used for
small rating cage type motors where cost is an important
factor. However, this method has rather limited range of
speed control. [36]
C. Scalar control (constant v/f control)

The name scalar (constant v/f) control indicates the variation of magnitude of control variables only. The control of an induction motor requires a variable voltage, variable frequency three phase source. With advent of the voltage source inverter (VSI), constant voltage/hertz (scalar) control has become the simplest & cheapest popular methods of speed control of induction motor.

The principle of v/f control is that, the base speed of induction motor is proportional to the supply frequency so, the best way of vary the speed of induction motor by varying the frequency of supply. The developed torque of motor is directly proportional to the ratio of the supply voltage & frequency. So the main aim to maintaining the same terminal voltage to frequency ratio constant so as to torque developed can be kept constant give constant flux over a wide range of speed variation. Since the flux is kept constant, full load torque capability are maintained constant under steady state condition except low speed. [70]

In this control scheme, the performance of induction motor improves in the steady state only, but the transient state response is poor. More over Constant voltage/hertz (scalar) control keeps the stator flux linkage constant in steady state without maintaining the decoupling between flux and torque. So the dynamic response of the drive is poor due to inherent coupling effect. These foregoing problems can be solved by vector control or field oriented control. [37]

D. Vector control

The vector control scheme is being invented in 1970s, and its demonstrate that an induction motor (Ac motor) can be controlled like a separately excited dc motor, brought a renaissance in the high speed performance control of ac drives. The vector control is also known as decoupling, orthogonal, or transvector control because of the separately excited dc motor like performance. The vector control is applicable to both induction and synchronous motor drives. There are two methods of vector control, Direct or feedback method &Indirect or feed forward method [9].

In direct vector control method, directly measures the rotor flux & using that flux to determine the transformation angle. This method also called as open loop vector control. Direct measurement of flux is physically difficult, so estimated value of flux is calculated using stator voltages & currents value. At higher speed, value of estimated flux may be reliable but at lower speed, this is subjected to errors from harmonics.[39]

The direct method of vector control attempts to directly measure or estimate the machine flux, and use this to determine the transformation angle. While direct flux measurements are difficult physically, an estimate value of flux is calculated using the stator voltages and currents equations. At the higher speed ranges, the flux estimate may be reliably estimated from the integral of the stator voltage. However, this method is subject to errors from harmonics, and is not useful at lower speeds. Due to the difficulty in reliably obtaining an estimate of the rotor flux direction, the direct method of vector control is not commonly used. Instead, the indirect method has gained popularity. [1][41]

III. PRINCIPLE & BLOCK OF INDIRECT VECTOR CONTROL OF INDUCTION MOTOR

Blaschke in 1972, has introduced the principle of vector control of induction motor, to realize the characteristics of d.c motor in an induction motor drive. In vector control, both flux & torque are control independently i.e both are decoupled in nature.

An a.c machine is not simple because of the interaction between stator & rotor field, whose orientation is not held at 90 degree but vary with operating conditions. We can obtain d.c machine like performance, by considering the induction motor in synchronous rotating reference frame. Where all sinusoidal variables appear like d.c quantity in steady state.

The block diagram of indirect vector control method is shown in figure 3.1. The control scheme generate inverter switching commands to achieve the desired electromagnetic torque at the shaft of motor.
The algorithm of indirect vector control is given as:

1. The induction motor is fed by a variable frequency, variable voltage PWM inverter, which operates in current control mode. The motor speed $\omega$ is compared with the reference speed $\omega^*$ and the error is produced which is fed to the speed controller. The output of speed controller is electromagnetic torque $T_e^*$.

2. The quadrature-axis stator current reference $i_{qs}^*$ is calculated from electromagnetic torque reference $T_e^*$ as

$$i_{qs}^* = \left(\frac{2}{3}\right) \left(\frac{2}{P}\right) \left(\frac{L_r}{L_m}\right) \left(\frac{T_e^*}{\psi_r}\right)$$

Where $\hat{\psi}_r = |\psi_r|_{est}$ is the estimated value of rotor flux linkage given by

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

Where, $\tau_r = \frac{L_r}{R_r}$ is the rotor time constant.

3. The direct-axis stator current reference $i_{ds}^*$ is obtained from reference rotor flux input $|\psi_r|^*$.

$$i_{ds}^* = \frac{|\psi_r|^*}{L_m}$$

4. The rotor flux position $\theta_e$ required for coordinates transformation is obtained from the rotor speed $\omega_r$ and slip frequency $\omega_{sl}$. $\theta_e$ is calculated as

$$\theta_e = \int \omega_r dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl}$$

5. The slip frequency $\omega_{sl}$ is calculated from the stator reference current $i_{qs}$* and the motor parameters. $\omega_{sl}$ is given by from eqn 4.31,

$$\omega_{sl} = \frac{L_m R_r}{\psi_r L_r} i_{qs}$$

6. The $i_{qs}^*$ and $i_{ds}^*$ current references are converted into phase current references $i_a^*$, $i_b^*$, $i_c^*$ using inverse park transform (two phase to three phase conversion) & fed to the current controller. The controller processes the measured and reference currents to produce the inverter gating signals.

    The main role of the speed controller is to keep the motor speed equal to the speed reference input in steady state and to provide a good dynamic response during transients & the closed loop current control operates the voltage source inverter in current control mode which ensures that the winding current follow same pattern as that reference currents generated from control logic.

IV. SIMULATION RESULTS & DISCUSSION

This section summarise the results of proposed algorithms. The indirect vector control induction motor models tested in MATLAB/Simulink & result of proposed models are discussed in this section.

4.1: Simulation Result of Induction Motor Using Open Loop Model

The open loop model of induction motor was implemented in MATLAB/Simulink in stationary references frame. Simulation results are shown in figure 4.1 for stator voltage, rotor speed, electromagnetic torque & stator current waveform.
4.2: Indirect Vector Control Simulation Result

The results shown below were obtained using different speed controller from figure 4.2 to 4.4, for stator voltage, stator current, rotor speed & electromagnetic torque.

Figure 4.2: Starting & full load (200 nm) response of Indirect vector control induction motor drive (IVCIMD) with (a): PI controller & (b): PID controller
Figure 4.3: Performance of IVCIMD during speed reversal from (+171 rad/sec) to (-171 rad/sec) with 
(a): PI controller & (b): PID controller

Figure 4.4: Performance of IVCIMD during speed reversal from (-171 rad/sec) to (+171 rad/sec) with 
(a): PI controller & (b): PID controller

4.3 Matlab Code Result

A MATLAB Code result is present below for Speed Control of 3-phase Induction motor using Variable Rotor Resistance, Variable Stator Voltage, Constant V/F Control (Scalar control) & Variation of d-axis stator current, q-axis stator current with change in voltage to observe Torque-Speed characteristics.

Figure 4.5: Torque Vs Rotor Speed for variable rotor resistance
Figure 4.6: Torque vs Rotor Speed for variable Stator Voltage

Figure 4.7: Torque Vs Rotor Speed for using Constant V/f contro

Figure 4.8: Variations in q-axis & d-axis stator currents with change in stator voltage
(a): q-axis current Vs Vrms & (b): d-axis current Vs Vrms

4.5 simulation result discussion

The performance of open loop model of induction motor & indirect vector control induction motor drive (IVCIMD) has been simulated in MATLAB environment using simulink & simpower toolboxes. A comparative study has been made based on different operating condition such as starting, loading, speed reversal. A MATLAB code result for different speed control method of induction motor is also present & compare with the simulation results of IVCIMD.

The figure 4.1 & 4.2 shows starting & full load response of open loop model & IVCIMD with PI & PID speed controller. The Table-1, given below shows the comparative results during starting.

<table>
<thead>
<tr>
<th></th>
<th>Open loop control</th>
<th>IVCIMD using PI controller</th>
<th>IVCIMD using PID controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS A.C mains starting current (A)</td>
<td>620</td>
<td>452</td>
<td>397</td>
</tr>
<tr>
<td>Speed (rad/sec)</td>
<td>187.7</td>
<td>186.3</td>
<td>134.1</td>
</tr>
<tr>
<td>Starting torque (Nm)</td>
<td>1657</td>
<td>310.2</td>
<td>302.8</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>0.71</td>
<td>1.23</td>
<td>0.85</td>
</tr>
<tr>
<td>Current drawn during loading condition (A)</td>
<td>81.76</td>
<td>94.2</td>
<td>88.1</td>
</tr>
</tbody>
</table>

The results of open loop control shows high starting current as compare to IVCIMD. The ripple content in speed waveform of open loop model during starting has been eliminated in IVCIMD.
The IVCIMD reaches to steady state earlier & torque settle faster as compare with open loop response. The load torque of 200 Nm is applied at 1.51 sec, so the momentary speed decreases is little less in IVCIMD with PID as compare with open loop & IVCIMD with PI controller response.

The figure 4.3 & 4.4 shows the IVCIMD response during speed reversal with PI & PID controller & its comparison is given in Table 2 shown below:

<table>
<thead>
<tr>
<th>Reversal time (sec)</th>
<th>IVCIMD using PI controller</th>
<th>IVCIMD using PID controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed during reversal (rad/sec)</td>
<td>+186.3 to -186.3</td>
<td>+134.1 to -134.1</td>
</tr>
<tr>
<td>RMS A.C current drawn during reversal (A)</td>
<td>120</td>
<td>101</td>
</tr>
<tr>
<td>Electromagnetic torque during reversal (Nm)</td>
<td>-303</td>
<td>-303</td>
</tr>
<tr>
<td>Forward braking time duration (sec)</td>
<td>1.5 to 2.4</td>
<td>1.1 to 1.73</td>
</tr>
<tr>
<td>Reverse motoring time duration (sec)</td>
<td>2.4 to 3.6</td>
<td>1.73 to 2.23</td>
</tr>
</tbody>
</table>

The overall performance of IVCIMD is improved with PID controller & speed response also reaches the reference values earlier with PID as compare to PI controller.

The figure 4.5 shows Torque-speed characteristics of 3-phase induction motor with variable rotor resistance. With increase in value of rotor resistance from 0.228 ohm to 0.9 ohm results shows increase in stator torque value with reduce in starting current. After maximum torque, the value of torque decrease with increase in rotor resistance. Such method is highly in sufficient. The figure 4.6 shows Torque-speed characteristics for variable supply voltage from 200v to 460 v. The developed torque varies square of the supply voltage so, increase in supply voltage result in increase in electromagnetic torque. However it will occur at same slip. Even the starting & over all torque is reduced. The figure 4.7 shows constant v/f characteristics. By varying the voltage & frequency by same ratio, flux & hence the torque can be kept constant through the speed range.

The last characteristic in figure 4.8 shows characteristic between d-axis & q-axis current versus stator voltage, as stator voltage increase with simultaneously increase in q-axis current & decrease in d-axis current.

V. CONCLUSION

In this paper different speed control method of three phase induction motor has been made under various operating condition such as starting, speed reversal, load perturbation. From the result of implementation , carried out in MATLAB ,it has been found that indirect vector control drive with PID controller has better response as compare with PI controller. It obtained reduced starting current, less ripple content in torque waveform & settle faster. The open loop results contain high ripple during starting of speed response. The indirect vector control drive reaches earlier to steady state as compare with other result of Matlab code. So, the overall performance of indirect vector control induction motor drive is better & gives quick torque response near zero speed. It control both phase as well as magnitude & fulfil the requirement of wide speed control range & individual torque control

Acknowledgement

The authors would like to express their sincerest gratitude to the Dr.Shailendra Sharma, SGTIS indore & Prof.Rahul Agrawal, Head of Department,VITs indore for providing all the possible better facilities to carry out the research work.

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