EFFECTS OF LOAD AND SPEED VARIATIONS IN A MODIFIED CLOSED LOOP V/F INDUCTION MOTOR DRIVE

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Abstract

This paper investigates the effects of load and reference speed variations in a modified closed loop v/f induction motor drive. A modified approach, involving the addition of a low frequency boost voltage, is developed and adopted as an enhancement to the conventional closed loop v/f speed control of a three phase squirrel cage induction motor modelled in the stationary qd reference frame using six-step voltage source inverter waveform. The results obtained show a superior dynamic and steady state performance in the two basic mechanical characteristics: motor speed and electromechanical torque under load variation. The performance of this scheme is simulated in MATLAB/SIMULINK.

Keywords: induction motor, stationary reference frame, Volts/Hertz v/f control, reference speed, load torque

1. Introduction

Induction machine is the most used in industry because of its high robustness, reliability, low cost, high efficiency and good self-starting capability [1,2,3]. The recent improvements in power semiconductors devices and fast digital signal processing hardware have further accelerated this progress. The induction motor, particularly with a squirrel cage rotor, is the most widely used source of mechanical power fed from an AC power system. Its low sensitivity to disturbances during operation makes the squirrel cage motor the first choice when selecting a motor for a particular application [4]. In spite of this popularity, the induction motor has two inherent limitations: (1) the standard motor is not a true constant-speed machine, its full-load slip varies from less than 1% (in high-horsepower motors) to more than 5% (in fractional-horsepower motors) and (2) It is not, inherently, capable of providing variable speed operation [5,6].

With respect to the control method, ac drives are classified into two basic categories. The first category motors are the ones with reduced dynamic requirements. The standard drives such as pump and fan with electric motor operating at a maximum efficiency point are the examples of this category. In the second category, dynamically high performance industrial drives are grouped [7].

During start-up and other severe motoring operations, the induction motor draws large currents, produce voltage dips, oscillatory torques and can even generate harmonics in the power system [8,9]. It is, therefore, important to be able to predict these phenomena. Various models have been developed and the qd or two axis model for the study of transient behaviours has been tested and proven to be very reliable and accurate [10]. This method of modelling has been applied by several authors in their analysis [11,12]. Since it is usually more convenient to simulate an induction machine and its converters on a stationary reference frame, the model presented in this paper is on the stationary reference frame. The complete model equations for the induction motor in the stationary reference frame is derived in [13].

2. Closed Loop V/F Controlled Induction Motor Drive

When accuracy in speed response is a concern, closed-loop speed control can be implemented with the constant v/f principle through the regulation of slip speed. A PI controller is employed to regulate the slip speed of the motor to keep the motor speed at its set value. Figure 1 shows a typical closed-loop speed control scheme which uses volts/hertz and slip regulation [14].

The major blocks consist of a DC source, a three phase inverter, and an induction motor with load. The
speed loop error generates the slip speed command $\omega_{sl}^*$ through the proportional-integral controller and limiter. The slip is added to the speed feedback signal, $\omega_r$ to generate the slip frequency command, $\omega_{e}^*$. The slip frequency command generates the voltage command $V_s$ through a Volts/Hz function generator [7, 14].

A step increase in slip frequency command, $\omega_{e}^*$ produces a positive speed error and the slip speed command $\omega_{sl}^*$ is set at the maximum value. The drive accelerates at the permissible inverter current, producing the maximum available torque, until the speed error is reduced to a very small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

A step decrease in slip frequency command, $\omega_{e}^*$ produces a negative speed error. The slip speed command is set at the maximum negative value. The drive accelerates under regenerative braking; at the maximum permissible current and the maximum available breaking torque, until the speed error is reduced to a small value. Now the operation shifts to motoring and the drive settles at the slip speed for which the motor torque equals the load torque. Several other closed loop control schemes utilizing PWM inverters are discussed in [15].

3. Modified V/F Control Versus Basic V/F Control

The major deficiency of the basic $v/f$ control is stator impedance drop at low frequencies. The modified $v/f$ control method, unlike the basic $v/f$ control method, provides a boost-voltage at low frequencies thereby compensating for the stator impedance drop, enabling the motor to offer constant flux operation with maximum motoring torque from zero to rated speed. Analytical reference is made to the exact equivalent circuit of induction motor to evaluate an offset voltage which is incorporated in the $v/f$ block of figure 1 to serve as a boost voltage during low frequency operation.

4. Evaluation of Low Frequency Boost Voltage

The voltage relationships in the exact equivalent circuit of figure 2 are analyzed to determine the low frequency boost voltage $V_o$ needed to sustain motor flux even at zero frequency. The parameter ‘$a$’ known as the per-unit frequency, is defined as the ratio of the operating speed to the rated speed as

$$a = \frac{f_s}{f_{rated}} = \frac{\omega_s}{\omega_{sr}}$$

From figure 2,

$$V_s = a E_{ar} + (I_m + I_r)(r_s + jax_{ls})$$

Where

$$I_m + I_r = \left( \frac{E_{ar}}{jx_{m}} + \frac{aE_{ar}}{\frac{r_s}{s} + jax_{lr}} \right)$$

Therefore,

$$V_s = aE_{ar} + (r_s + jax_{ls}) \left( \frac{E_{ar}}{jx_{m}} + \frac{aE_{ar}}{\frac{r_s}{s} + jax_{lr}} \right)$$
A plot of the terminal voltage $V_s$ as $a$ varies in the range $0.1 \leq a \leq 1$ is shown in figure 3. where slip $s = s_r/a$ and $s_r$ is the rated slip.

By extrapolation, it can readily be shown that the terminal voltage $V_o$ at $a = 0$ is 13.3261V. This low frequency boost voltage is utilized in the constant Volts/Hertz generator in the closed loop arrangement of figure 1.

5. Induction Machine Model in Stationary Reference Frame

Making reference to the induction machine model in the arbitrary reference frame and substituting $\omega = 0$, the induction machine model in the stationary reference frame is realized. This is called the stationary reference frame because the qd axis does not rotate and is said to be fixed in the stator. The analysis done above recognizes that in a vast majority of cases, the machine is connected in delta or wye such that the neutral current does not flow. In this case, the neutral axis voltages and currents are identically zero. The machine model in stationary reference frame for a squirrel cage induction machine is well known and given by

$$
\begin{bmatrix}
  v_{qs} \\
  v_{ds} \\
  0
\end{bmatrix}
= \begin{bmatrix}
  r_s + L_s p & 0 & L_{m,p} & 0 \\
  0 & r_r + L_r p & -\omega_r L_r & -\omega_r L_m & r_r + L_r p
\end{bmatrix}
\begin{bmatrix}
  i_{qs} \\
  i_{ds} \\
  i_{qr} \\
  i_{dr}
\end{bmatrix}
$$

(5)

where, $v_{qs} = \sqrt{2} V_s \cos \omega_e t$, $v_{ds} = -\sqrt{2} V_s \sin \omega_e t$, $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$. The electromechanical torque developed is given by

$$
T_{em} = T_l + \frac{2}{P} \int \frac{d\omega_e}{dt}
$$

(6)

Where $p$ is the operator $d/dt$, $r_s$ is the stator resistance, $r_r$ is the rotor resistance referred to the stator side, $L_{ls}$ and $L_{lr}$ are the stator and rotor leakage inductance respectively. $L_m$ is the magnetizing inductance, $T_l$ is the load torque, $P$ is the number of pole pairs, $J$ is the moment of inertia, $\omega_r$ is the rotor electrical speed, and $\omega_e$ is the supply synchronous speed.

6. Dynamic Performance Under Reference Speed Variation

A closed loop $v/f$ controlled induction motor is simulated in the stationary reference frame using MATLAB/SIMULINK. The parameters of the sample motor are shown in Table 1 below.
Table 1: Sample machine data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Rating</td>
<td>2 Hp</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>400V</td>
</tr>
<tr>
<td>Winding Connection</td>
<td>Star</td>
</tr>
<tr>
<td>Rated Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>6</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>960rpm</td>
</tr>
<tr>
<td>Stator Resistance</td>
<td>0.4Ω</td>
</tr>
<tr>
<td>Rotor Referred Resistance</td>
<td>0.2Ω</td>
</tr>
<tr>
<td>Stator Reactance</td>
<td>1.5Ω</td>
</tr>
<tr>
<td>Rotor Referred Reactance</td>
<td>1.5Ω</td>
</tr>
<tr>
<td>Magnetizing Reactance</td>
<td>30Ω</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>2.1kgm²</td>
</tr>
</tbody>
</table>

Figure 6: Speed reversal due to change in reference speed.

6.1. Effect of a step change in reference speed

The speed reference is changed from 25Hz to 50Hz at load torque $T_L = 0$Nm. The effect on motor speed is observed in figure 4, while the effect on electromechanical torque delivered by the motor is shown in figure 5. A sudden jerk is noticed on the load torque at the time the sudden change in reference speed occurred.

6.2. Effect of reversal in speed reference

With a load torque of 0Nm, Figure 6 shows the rotor speed due to the reference speed reversal in the sequence [0 50 -50 50 0]Hz while figure 7 shows the effect on the electromechanical torque. The speed and torque transients are, as expected, observed each time the reference speed crosses the zero point. The transient effects need definite time to settle as can be observed in the curves.

Figure 7: Electromechanical torque due to change in speed reference.

Figure 8: Rotor speed for programmed changes in load torque.

7. Dynamic Performance Under Load Torque Variation

7.1. Sequential changes in load torque at reference speed of 50Hz

Dynamic performance is observed when load torque changes in the sequence [0 30 15 30 0] Nm at a reference speed of 50Hz. Figure 8 shows the speed changes due to the programmed sequence of load torque variation while figure 9 shows the change in electromechanical torque due to the load torque changes.

7.2. Step change in load torque at a reference speed of 25Hz

Figures 10 and 11 show the rotor speed and electromechanical torque respectively due to the load torque changes from 0 Nm to 50 Nm at a reference speed of 25Hz.

8. Conclusion

The scheme presented here has successfully incorporated the estimated low frequency boost voltage to the conventional closed loop $v/f$ control modelled in the stationary qd reference frame. The choice of the stationary reference frame is made because of its compatibility with the three phase six step inverter waveform used in place of actual inverter model. This modification is validated for the dynamic performance by subjecting it to reference speed and load torque variations. The ripple in motor speed and electromechanical torque due to sudden changes in reference speed
and load torque are observed as expected. This modified closed loop $v/f$ control method shows a better dynamic and steady state performance when compared to the conventional $v/f$ control method of three phase squirrel cage induction motors.

References

1. Leonhard, W. Controlled AC Drives, A Successful Transfer from Ideas to Industrial Practice. CETTI 95, Brazil, 1995, pp. 1-12.


