A Stator Flux Oriented V/f Control of Induction Motor in Low Speed Range

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Abstract - In this paper, closed loop V/f control of induction motor has been implemented by the estimated speed. Closed loop V/f control improve the performance of induction motor drive system at low speed compared to open loop V/f control. However, closed loop V/f control need speed sensor. By using the estimated speed, closed loop V/f control is possible without speed sensor. Rotor speed is calculated from the difference between synchronous frequency and slip angular frequency. 3-phase voltage reference is obtained from synchronous frequency. And the PWM technique using space vector PWM is applied in this scheme. In the space vector PWM, effective time of 3-phase voltage reference is used to simplify the calculation of effective voltage time. This scheme is simple to implement and one chip microprocessor was used in experimental system.

1. INTRODUCTION

Open loop volt/hertz speed control of induction motor is very simple and widely used in general purpose drive application. In steady state operation, the machine air gap flux is approximately proportional to v_s/ω_e.

Therefore maintaining the rated air gap flux will provide maximum torque sensitivity with stator current. In open loop volt/hertz control, the voltage drop across the stator resistance R_s, and leakage inductance L_s is considered small.

However, if the frequency approaches zero near zero speed, the stator voltage tend to be zero and it will be absorbed by the stator resistance. In this case, the motor output torque decreases and the efficiency of the motor is reduced. Therefore, an auxiliary voltage V_o is need to be injected to overcome the effects of stator resistance. In this scheme, the speed will tend to drift with variation in load torque and fluctuation of supply voltage. To overcome this problem, a closed loop speed control of v/f inverter can be provided. However, the speed sensor such as pulse encoder has problem of cost, motor size, noise, and reliability.

Therefore, even in high performance vector control drive system, using speed sensor is unfavorable.

This paper presents the closed loop V/f control using estimated speed feed back. With speed feedback, the problem of reduced torque by stator resistance at low speed can be solved. And we don't have to modify the voltage to frequency ratio at low speed to overcome the voltage drop at stator resistance. Because the speed control is performed by the estimated speed, it has not a problem of pulse encoder. This scheme can be used to general purpose drive system or somewhat low performance drive with the economical point of view.

2. INDUCTION MOTOR MODEL

The induction machine model in terms of current and voltage in the synchronous rotating reference frame can be given as following eqn in matrix form.

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_m & (\omega_e - \omega_r)L_m & R_r + SL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & SL_m & -(\omega_e - \omega_r)L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{1}$$

where S : Laplace operator

The flux linkage expression in terms of the current are as followings.

$$\begin{aligned} \Psi_{qs} &= L_{ls} i_{qs} + L_m(i_{qs} + i_{qr}) \\ \Psi_{qr} &= L_{lr} i_{qr} + L_m(i_{qs} + i_{qr}) \\ \Psi_{ds} &= L_{ls} i_{ds} + L_m(i_{ds} + i_{dr}) \\ \Psi_{dr} &= L_{lr} i_{dr} + L_m(i_{ds} + i_{dr}) \end{aligned} \tag{2}$$

These eqns can be combined with eqn.(1), then machine model eqns are obtained as eqn.(3)

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s & O & S & \omega_e \\ O & R_s & -\omega_e & S \\ -R_r' - SL_r' & -\omega_{sl} L_r' & \frac{R_r'}{L_s} + S\frac{L_s L_r}{L_m^2} & \omega_{sl}\frac{L_s L_r}{L_m^2} \\ \omega_{sl} L_r' & -R_r' - SL_r' & -\omega_{sl}\frac{L_s L_r}{L_m^2} & \frac{R_r'}{L_s} + S\frac{L_s L_r}{L_m^2} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ \Psi_{qs} \\ \Psi_{ds} \end{bmatrix} \quad (3)$$

where, $R_r' = (\frac{L_s}{L_m})^2 \cdot R_r$,

$L_r' = (\frac{L_s L_r}{L_m^2} - 1)$

3. SPEED ESTIMATION

In the eqn.(3), Vqr and Vdr is zero, and Ψqr is assumed to be zero. Then, we can calculate the slip angular frequency $\widehat{\omega_{sl}}$ as eqn.(4) and ids as in eqn.(5)

$$\widehat{\omega}_{sl} = \frac{\left\{(\frac{L_s}{L_m})^2 \cdot R_r + SL_s(\frac{L_s L_r}{L_m^2} - 1)\right\} i_{qs}}{\frac{L_s L_r}{L_m^2} \cdot \Psi^*_{ds} - L_s(\frac{L_s L_r}{L_m^2} - 1) i_{ds}} \quad (4)$$

$$i^*_{ds} = \frac{\Psi^*_{ds}}{L_s} + \frac{L_s}{\Psi^*_{ds}}(\frac{L_s L_r}{L_m} - 1) \cdot i^{*}_{qs}{}^2 \quad (5)$$

From eqn.(4) and eqn.(5), slip angular frequency $\widehat{\omega_{sl}}$ is calculated as eqn.(6)

$$\widehat{\omega}_{sl} = \frac{\left\{(\frac{L_s}{L_m})^2 \cdot R_r + SL_s(\frac{L_s L_r}{L_m^2} - 1)\right\} i_{qs}}{\Psi^*_{ds}\left\{1 - (\frac{L_s}{\Psi^*_{ds}})^2 (\frac{L_s L_r}{L_m} - 1)^2 \cdot i_{qs}^2\right\}}$$

$$\doteqdot \left\{1 + (\frac{L_s}{\Psi^*_{ds}})^2 (\frac{L_s L_r}{L_m} - 1)^2 I_{qs}^2\right\} \times \frac{\left\{(\frac{L_s}{L_m})^2 R_r + SL_s(\frac{L_s L_r}{L_m^2} - 1)\right\}}{\Psi^*_{ds}} i_{qs} \quad (6)$$

The machine rotational speed $\widehat{\omega_r}$ can be calculated from synchronous speed reference ω_e^* and estimated slip angular frequency $\widehat{\omega_{sl}}$ as eqn(7).

$$\widehat{\omega_r} = \omega_e^* - \widehat{\omega_{sl}} \quad (7)$$

4. V/f CONTROL AND SPACE VECTOR PWM

Fig.1 shows the block diagram of induction motor drive system in this paper.

In this method, synchronous angular frequency ω_e^* is calculated from slip angular frequency reference ω_{sl}^* and estimated rotor speed $\widehat{\omega_r}$ as following eqn.

$$\omega_e^* = \omega_{sl}^* + \widehat{\omega_r} \quad (8)$$

In the conventional V/f control, if ω_e^* is calculated, v_{as}, v_{bs}, v_{cs} can be calculated linearly.

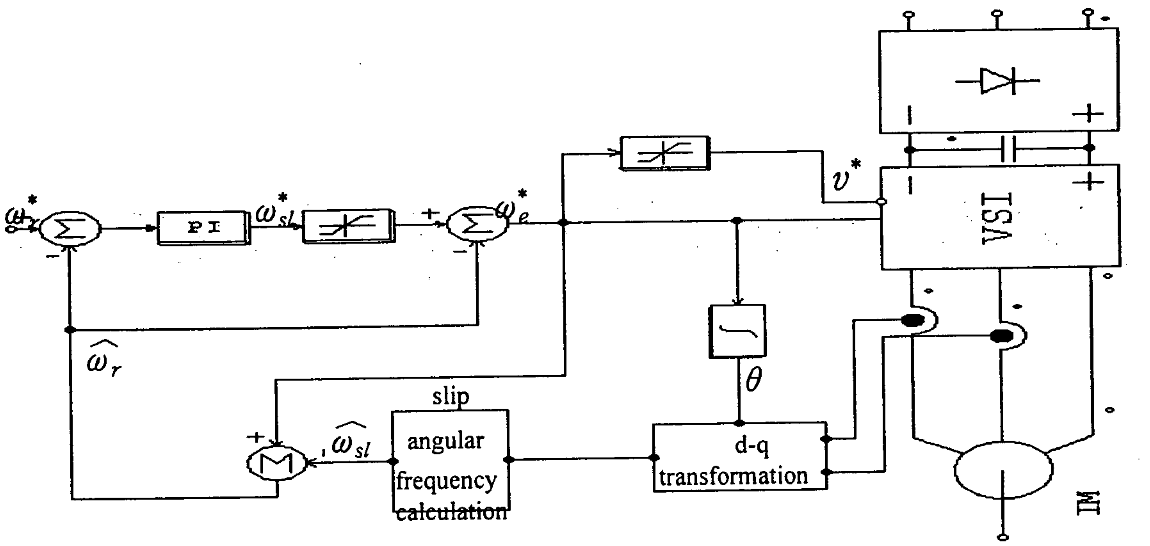


Fig.1 Block diagram of closed loop v/f speed control by estimated speed.

In this paper to compensate the voltage drop at stator resistance, the voltage drop is added to the reference voltage. And the reference voltage is calculated in the synchronously rotating d-q reference frame.

$$\begin{bmatrix} V^*_{qs} \\ V^*_{ds} \end{bmatrix} = \begin{bmatrix} \omega_e^* \Psi_{ds} \\ 0 \end{bmatrix} + R_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} 0 \\ \Delta V^*_{ds} \end{bmatrix} \quad (9)$$

where, $\Delta V^*_{ds} = K\ (i^*_{ds} - i_{ds})$

$$i^*_{ds} = \frac{\psi^*_{ds}}{L_m} + \frac{L_r'}{\psi^*_{ds}} i^{*2}_{qs}$$

The d-q reference voltage in the synchronously rotating reference frame can be transformed to d-q reference voltage in the stationary reference frame v_q^{s*}, v_d^{s*}, and they can be changed to a-b-c reference voltage.

$$\begin{bmatrix} v^*_{as} \\ v^*_{bs} \\ v^*_{cs} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & +\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v^{s*}_q \\ v^{s*}_d \end{bmatrix} \quad (10)$$

In the space vector PWM , the effective voltage is applied to inverter during time T_1 and T_2, and zero vector is applied during time T_0.

$$T_1 = T_s \cdot \frac{[V^*]}{\frac{2}{3} V_{dc}} \cdot \frac{\sin(\frac{\pi}{3} - \alpha)}{\sin\frac{\pi}{3}} \quad (11)$$

$$T_2 = T_s \cdot \frac{[V^*]}{\frac{2}{3} V_{dc}} \cdot \frac{\sin\alpha}{\sin(\frac{\pi}{3})}$$

$$T_0 = T_s - (T_1 + T_2)$$

The effective time T_1 and T_2 can be calculated from the a-b-c stationary voltage reference without sector detection or complicate calculation.[4] In case the reference voltage is in sector I, the effectives time T_1 and T_2 are as following eqns.

$$T_1 = \frac{\sqrt{3} \cdot T_s}{V_{dc}} \cdot \left[\frac{\sqrt{3}}{2} \cdot V^*_{qs} + \frac{1}{2} V^*_{ds} \right]$$

$$= \frac{T_s}{V_{dc}} \left[V^*_{qs} + \left(\frac{1}{2} V^*_{qs} + \frac{\sqrt{3}}{2} V^*_{ds}\right) \right]$$

$$= \frac{T_s}{V_{dc}} (V^*_{qs}) + \frac{T_s}{V_{dc}} \left(\frac{1}{2} V^*_{qs} + \frac{\sqrt{3}}{2} V^*_{ds}\right)$$

$$= \frac{T_s}{V_{dc}} \cdot V^*_{as} - \frac{T_s}{V_{dc}} V^*_{bs}$$

$$= T_{as} - T_{bs} \quad (12)$$

$$T_2 = \frac{\sqrt{3} T_s}{V_{dc}} \cdot [0 \cdot V^*_{qs} + 1 \cdot V^*_{ds}]$$

$$= \frac{T_s}{V_{dc}} \cdot \left[\left(-\frac{1}{2} V^*_{qs} - \frac{\sqrt{3}}{2} V^*_{ds}\right) - \left(-\frac{1}{2} V^*_{qs} + \frac{\sqrt{3}}{2} V^*_{ds}\right) \right]$$

$$= \frac{T_s}{V_{dc}} \left(-\frac{1}{2} V^*_{qs} - \frac{\sqrt{3}}{2} V^*_{ds}\right) - \frac{T_s}{V_{dc}} \left(-\frac{1}{2} V^*_{qs} + \frac{\sqrt{3}}{2} V^*_{ds}\right)$$

$$= \frac{T_s}{V_{dc}} \cdot V^*_{bs} - \frac{T_s}{V_{dc}} V^*_{cs}$$

$$= T_{bs} - T_{cs} \quad (13)$$

Similarly, in case when the reference voltage is in other section, the T_{as}, T_{bs}, T_{cs} are calculated by DC link voltage V_{dc} and reference phase voltage as in eqn.(14)

$$T_{as} = T_s \cdot \frac{V^*_{as}}{V_{dc}} \quad (14)$$

$$T_{bs} = T_s \cdot \frac{V^*_{bs}}{V_{dc}}$$

$$T_{cs} = T_s \cdot \frac{V^*_{cs}}{V_{dc}}$$

where, $V^*_{as} + V^*_{bs} + V^*_{cs} = 0$

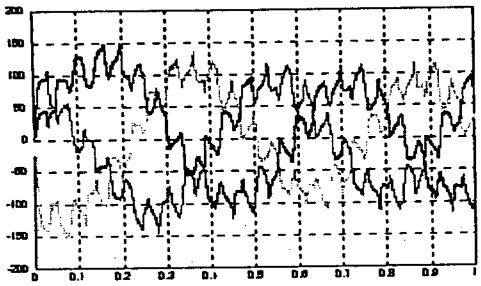
$T_{as} + T_{bs} + T_{cs=0}$

5. SIMULATION RESULTS AND EXPERIMENTAL SYSTEM

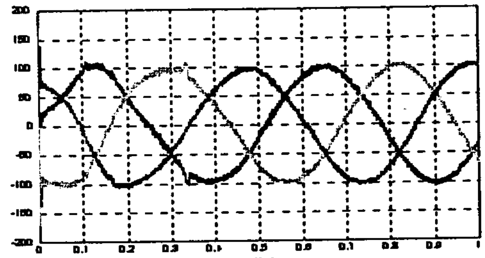
Fig. 2 shows the simulation results of the system. The induction motor parameters used in the simulation is listed in the table 1. Fig. 2(a) shows the 3-phase current wave forms at 2Hz(60rpm) without speed feedback, that is, open loop V//f control, and 2(b) shows the wave form in case of speed feedback by estimated feedback.

Table 1. Induction Motor Parameters(in the simulation)

Rs[Ω]	0.032[Ω]
Rr[Ω]	0.022[Ω]
Ls, Lr[mH]	0.1[mH]
Lm[mH]	4.9[mH]
P[kW]	37[kW]
J[kg · m²]	0.3[kg · m²]

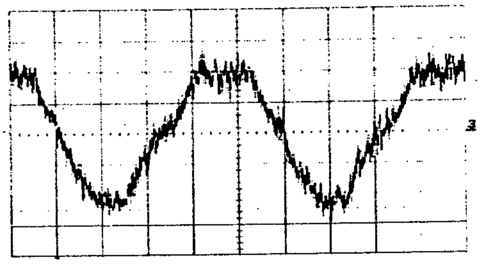


(a)

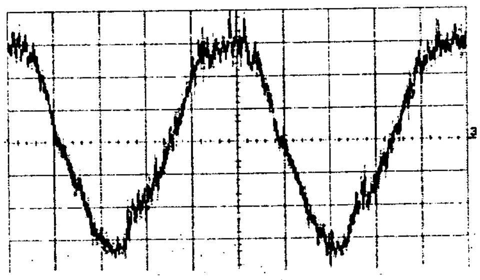


(b)

Fig. 2 Current wave form at 60[rpm]
(a) Open loop V/f
(b) speed feedback by estimated speed



(a)



(b)

Fig. 3 Current wave form at 60[rpm]
(a) Open loop V/f
(b) speed feedback by estimated speed

Fig. 3 shows the wave forms of experimental system. In the experimental system 5Hp(3.5kW) induction motor was used.

Fig. 3(a) shows the results at 2Hz(60rpm) of open loop V/f control, and 3(b) shows the results with speed feedback using estimated speed. The system is implemented with 80C196 micro controller. The IGBT inverter is used for induction motor controller.

The switching frequence of IGBT is 2kHz. From the results of Fig. 2 and Fig. 3, we can see that at low speed, the current waveform of closed loop v/f control is better than open loop v/f control. The speed of induction motor is improved by speed feedback using estimated speed. Using inexpensive micro controller like a 80C196, we can implement a closed loop v/f control using estimated speed. Therefore, we can improve the performance of induction motor speed control at low speed .

6. CONCLUSION

The closed loop v/f speed control method using estimated speed is proposed in this paper. By using estimated speed, this scheme doesn't need a speed sensor. It doesn't need a high performance DSP or expensive micro processor board either. It was implemented with 80C196 and has a enough performance to use for general purpose induction motor drive system. The experimental results of the proposed system shows a resonable performance at low speed. The speed estimation algorithm is not so difficult as in vector control.

7. REFERENCES

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