A Sensor-less Ultra-high Speed Motor Driver

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Abstract

An ultra-high speed motor is important in machine tools. A speed sensor-less ultra-high speed motor driver is proposed in this paper. Due to cost, only few drivers build up a closed-loop control, which could improve driver's performance. Therefore, a sensor-less speed estimation for ultra-high speed motors is developed. The design and implementation of the driver and feedback circuits are detailed in this paper. And experimental results show that the proposed system is workable.

Keywords: Ultra-high Speed Motor, Speed sensor-less Control, Motor Driver, VVVF Control

Introduction

Ultra-high speed motors are important in machine tools, and most motors are induction motor, IM, because of its high reliability and low cost. There are some studies discussed about driver method, such as variable voltage variable frequency, VVVF, and vector control; and some focused on control method including proportional-integrated (PI) control, fuzzy control and neural network. Due to cost, only few drivers build up a closed-loop control, which could improve driver's performance. Therefore, a sensor-less speed estimation for ultra-high speed motors is developed.

However, only few literatures discussed about ultra-high speed motors. [1] optimized the best driver efficiency based on the total harmonic distortion (THD) of motor current with auto-adjust driver voltage. In [2], an ultra-high speed soft switch inverter was developed to improve driver efficiency. Both proposed new driver methods. Conventional IM driver methods are open-loop scalar control, VVVF, due to easy implement. However, some papers tried to use closed-loop control. [3] used fuzzy rules to determine the VVVF command and increased efficiency. [4] proposed a slip frequency compensation method to decrease the speed error. [5] discussed two vector control methods: field orientation control, FOC, and direct torque control, DTC. The torque responds of both controls are better than scalar control. Complex calculations are necessary in above controls, so they are not suitable for ultra-high speed motor. For speed estimation, [6] described two methods. Model Reference Adaptive System, MRAS, could be used wider speed range but too sensitive to motor parameters. Another method, Least Square Method, LSM, calculated speed by iteration, but only suitable for narrow speed range. In this paper, an easier speed estimation method is used: the motor slip speed is calculated with the motor model, and then motor speed is estimated by taking induction magnetic field speed to minus the slip angle.

Slip speed estimation

The calculation of slip speed is based on rotor flux field orientation control. It can simplify the motor model by referring to rotor flux filed. The derivation is described as (1) - (5). The equation of calculating the slip, (4), can be derivate by substituting that flux on the q-axis is zero into (3). In (4), there is a variable flux on d-axis. It can be calculate by (5) using the current on d-axis.

$$\left.\begin{aligned} &\phi_r^r = L_m i_s^r + L_r i_r^r . \\ &\rightarrow i_r^r = \frac{1}{L_r}(\phi_r^r - L_m i_s^r). \end{aligned}\right\} (1)$$

$$\left.\begin{aligned} &V_r^r = 0 = R_r i_r^r + \frac{d}{dt}\phi_r^r + j\omega_{sl}\phi_r^r . \\ &\rightarrow \frac{d}{dt}\phi_r^r = \frac{L_m}{L_r} R_r\, i_s^r - (\frac{R_r}{L_r} + j\omega_{sl})\phi_r^r . \end{aligned}\right\} (2)$$

$$\left.\begin{aligned} &\frac{d}{dt}\phi_{dr}^r = \frac{Lm}{L_r} R_r i_{ds}^r - \frac{R_r}{L_r}\phi_{dr}^r + \omega_{sl}\phi_{qr}^r . \\ &\frac{d}{dt}\phi_{qr}^r = \frac{L_m}{L_r} R_r i_{qs}^r - \frac{R_r}{L_r}\phi_{qr}^r - \omega_{sl}\phi_{dr}^r . \end{aligned}\right\} (3)$$

$$\left.\begin{aligned} &\frac{d}{dt}\phi_{qr}^r = \frac{L_m}{L_r} R_r i_{qs}^r - \frac{R_r}{L_r}\phi_{qr}^r - \omega_{sl}\phi_{dr}^r . \\ &\rightarrow 0 = \frac{L_m}{L_r} R_r i_{qs}^r - \omega_{sl}\phi_{dr}^r . \\ &\rightarrow \omega_{sl} = \frac{L_m R_r}{L_r}\frac{i_{qs}^r}{\phi_{dr}^r} . \end{aligned}\right\} (4)$$

$$\left.\begin{aligned} &\frac{d}{dt}\phi_{dr}^r = \frac{L_m}{L_r} R_r i_{ds}^r - \frac{R_r}{L_r}\phi_{dr}^r + \omega_{sl}\phi_{qr}^r . \\ &\rightarrow \frac{d}{dt}\phi_{dr}^r = \frac{L_m}{L_r} R_r i_{ds}^r - \frac{R_r}{L_r}\phi_{dr}^r . \\ &\rightarrow \frac{\phi_{dr}^r}{i_{ds}^r} = \frac{L_m}{\frac{L_r}{R_r}s + 1} . \end{aligned}\right\} (5)$$

where

ϕ_r^r	:	rotor flux refer rotor field	ϕ_{dr}^r	:	flux on the d-axis refer rotor field
ϕ_{qr}^r	:	rotor flux on the q-axis refer rotor field	R_r	:	rotor resistor
L_m	:	mutual inductance	L_r	:	rotor inductances
ω_{sl}	:	slip speed	V_r^r	:	rotor voltage refer rotor field
i_s^r	:	stator current on rotor flux	i_r^r	:	rotor current refer rotor field
i_{ds}^r	:	stator current on d-axis refer rotor field flux	i_{qs}^r	:	stator current on q-axis refer rotor field flux

The block diagram of estimator the slip speed is shown in Fig 1. The $\theta_{\phi r}$ is calculated by (6). And the σ is defined as (7). In Fig 1, (4) and (5) are performed to estimate slip speed and the rotor flux on d-axis. The inputs of these two blocks are stator current referring the rotor flux.

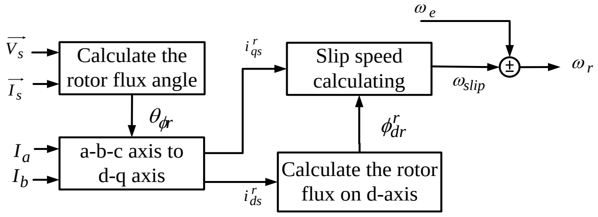

Fig 1. Block of slip speed estimator

$$\phi_r = \int \frac{L_r}{L_m}(V_s - R_s i_s - \sigma L_s \frac{d}{dt} i_s)dt. \quad (6)$$

$$\sigma = 1 - (\frac{L_m^2}{L_s L_r}). \quad (7)$$

where

ϕ_r	:	rotor flux	V_s	:	stator voltage
i_s	:	stator current	L_s	:	stator inductance

Scalar control

Scalar control drives motor by suitable waveform. In Fig 2, the curve of speed to voltage for a 200Krpm motor is provided by the motor manufactory. To drive motor in 30Krpm, the inverter should provide a three-phase sinusoidal 57 volts and 500Hz wave. However, the real rotor speed is different to the driving speed due to slip speed. Therefore, a PI controller is used in the proposed system to compensate the speed error caused by slip speed. As shown in Fig 3, the input of controller is the speed error, and the output is the index of the VVVF table to set inverter.

Motor parameter measurement

The IM's electric parameters are a key in slip speed estimation. Three parameter measuring tests are used in this paper. First, DC test is used to measure the stator resistor. Second, stall test could measure the sum of stator and rotor resistor, and the sum of stator and rotor leakage inductance. Then the rotor resistor can be got, and the stator and rotor leakage inductances, L_{ls} and L_{lr}, are assumed equal. Third, no load test is adopted for the stator inductance, and then the mutual inductance could be derived. A virtual stall test is adopted, because a traditional stall test is not convenient due to extra stalling equivalent. Fig 4 is the wiring diagram of virtual stall test.

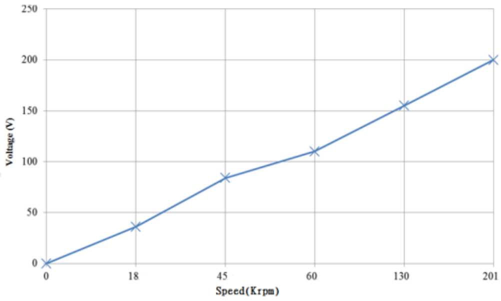

Fig 2. Speed-Voltage characteristic curve of 200Krpm motor

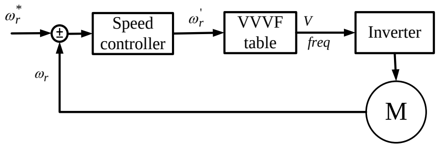

Fig 3. Block of scalar control

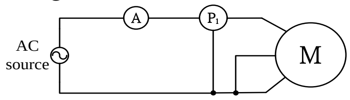

Fig 4. Wiring diagram of virtual stall test

In this paper, two ultra-high speed motors are installed in experiments. The parameters of 200Krpm and 300Krpm motors are measured and shown in table 1.

Table 1. Parameters of 200Krpm and 300Krpm motor

Motor	R_S	L_{ls}	R_r	L_{lr}	L_m
200K	1Ω	0.43mH	2.84Ω	0.43mH	5.22mH
300K	1.78Ω	0.21mH	4.33Ω	0.21mH	2.99mH

System architecture and hardware implementation

The control block diagram of system is shown in Fig 5. Scalar control is used in the speed controller. A PI controller is adopted to create the speed command which is the index of the voltage-frequency curve. Here, lookup table and interpolation method is used to index the suitable voltage and frequency commands for the inverter. And, the feedback speed is calculated by speed of synchronization field and the slip speed computed from current and voltage.

Fig 6 presents the system architecture diagram. The feedback circuit is used to sense the motor current and DC BUS states for speed estimation. The microcontroller is applied to speed estimation and speed control, and generate driving signals for the inverter circuit. The inverter circuit converts DC voltage to AC driving waveform.

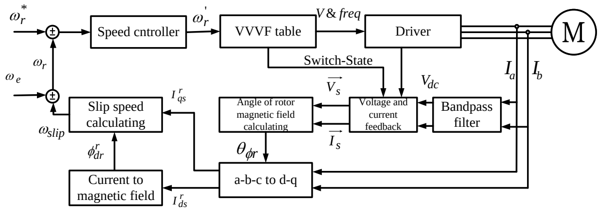

Fig 5. Control block diagram of system

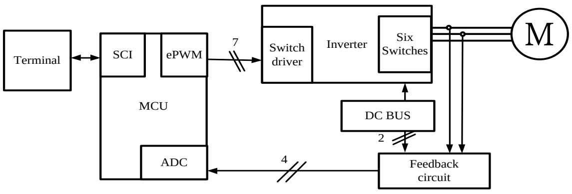

Fig 6. System architecture diagram

Fig 7 is the photo of the system proposed in this paper. At upper left corner is TMS320F28335, lower left corner is an isolated power board, middle is inverter, lower middle is the current feedback circuit and lower right corner is the DC BUS feedback circuit.

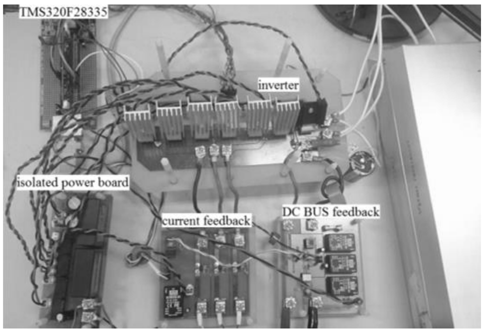

Fig 7. System photo

Experimental results

Two experiments are shown in this paper: step and ramp acceleration. Drilling function is performed when the motor achieves the rated speed, but no more speed control, due to the fast working moment. Controller is mainly used to accelerate. The experimental power supply is limited, so step range and ramp acceleration of

Table 2. Step and ramp acceleration of 200Krpm motor

	Step			Ramp acceleration		
Speed command(rpm)	40000	50000	60000	100000	120000	160000
Improved speed error(rpm)	44	94	132	940	1600	4900
Percentage error(%)	0.11	0.18	0.22	0.94	1.33	3.06
Improved stability time(s)	0.281	0.228	X	0.34	0.9	1.43

speed are limited. Fig 8 shows the experimental results under 100Krpm ramp command.

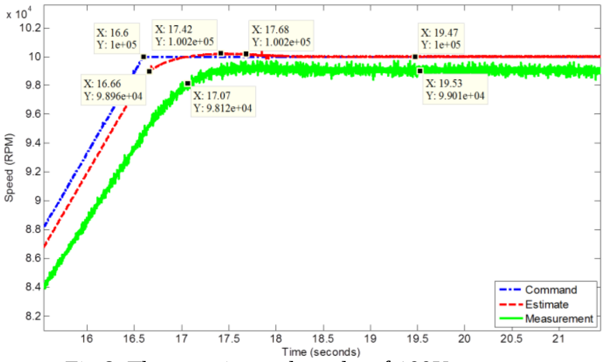

Fig 8. The experimental results of 100Krpm ramp

The experimental results are shown in table 2, and the improved numbers of the proposed controller are compared with an open-loop driver. The speed error is reduced and proportional to speed command, and then stability time is improved in 0.2 to 1 seconds. Note, proposed controller experimental results of the 60Krpm step are not shown in this table, because the required inrush current is over the capability of power supply.

In order to verify the proposed method is suitable for different motors, the other motor, rated 300Krpm, is adopted in the experiment. The speed errors of different commands in a 200Krpm motor are shown in Fig 9 and 300Krpm motor in Fig 10. Though the errors of 300Krpm motor are bigger than 200Krpm'motors, but the trends in two figures are the same. And error rate of 200Krpm motor is low than 1.5%, the same as 300Krpm motor is low than 3.5%.

Conclusion

As shown in experimental results, the motor with the proposed ultra-high speed motor driver can fast run stability. Though speed error is proportional to speed command, speed estimator can effectively estimate motor speed and react load fluctuation, and speed error rate is low than 1.5%. Closed-loop controller actually improves system responding time by low cost feedback circuit. The controller proposed in this paper is also suitable for different motors.

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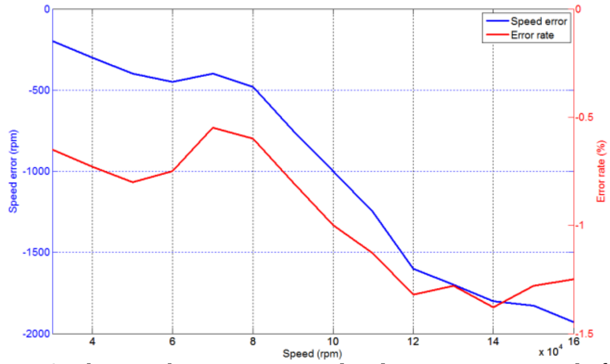

Fig 9. The error between estimated and measurement speed of 200Krpm motor

Fig 10. The error between estimated and measurement speed of 300Krpm motor

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