Latest Control Technology in Inverters and Servo Systems

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1. Introduction

Inverters and servo systems have achieved small size and high performance through the progress of semiconductor devices with high intention and low power consumption. Among these devices, the high performance microprocessors used for control possess high computing power that enables complex and minute operation, thereby enhancing the intelligence of the equipment.

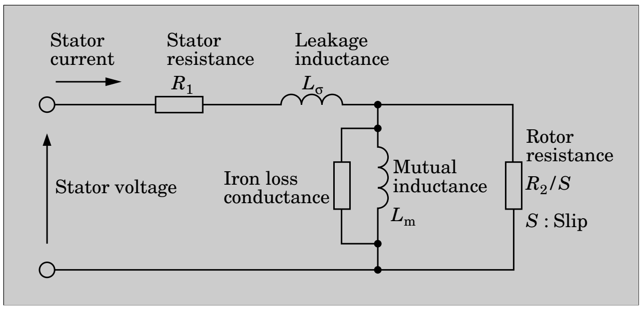
In addition, highly integrated ASICs (application specific ICs) enable the process sharing between software and hardware to shift optimization to the hardware side, and realize higher performance of the equipment.

In this paper, an overview of the latest control technology in inverters and servo systems is introduced.

2. Inverter Control Technology

Because of the advanced control technology for output voltage and the state estimation algorithm for induction motors, the latest control technology is realizing a greater range of speed control and smooth rotation with small torque ripple and high speed response. At present, Fuji Electric is developing a technology in which performance and convenience will be further improved based on the above mentioned technology, and as a part of such development, the "torque control accuracy improvement technology" and the "free run speed estimation technology" are introduced here.

Fig.1 Equivalent circuit of induction motor (single phase)



2.1 Torque control accuracy improvement technology

The main factors of torque error in the inverters, iron loss of the induction motor and thermal drift of the equivalent circuit parameters can be enumerated. For applications in which high accuracy is required, compensation of the control error through these factors is necessary. Details of the compensation technology are described below.

(1) Iron loss compensation

The iron loss of the silicon steel sheet used in the induction motor causes power and torque loss that is not negligible when performing accurate control within an error of several percent. An example equivalent circuit that accounts for iron loss is shown in Fig. 1. The iron loss consists of eddy current loss and hysteresis loss. Since the eddy current loss can be expressed through a linear resistance, it is easily considered for analysis of a control system and can be compensated simply. On the other hand, since the hysteresis loss has a non-linear characteristic depending upon the flux level, it has not been given much consideration in the past. However, as the speed range becomes wider, the hysteresis loss affects torque accuracy greatly at low speed.

Figure 2 shows schematically the relation between frequency, the eddy current loss component and the

Fig.2 Iron loss component of stator current vs. primary frequency (constant flux)

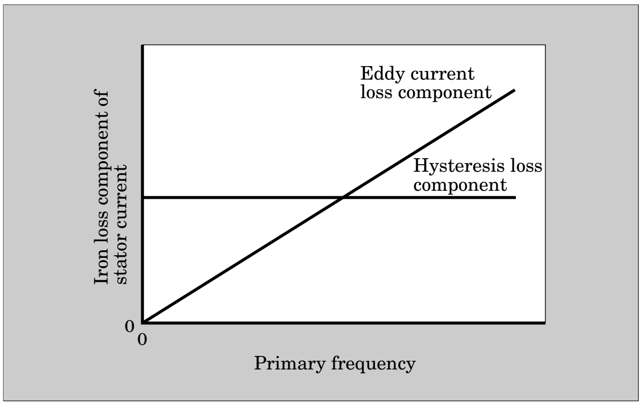


Fig.3 Characteristics of torque calculation

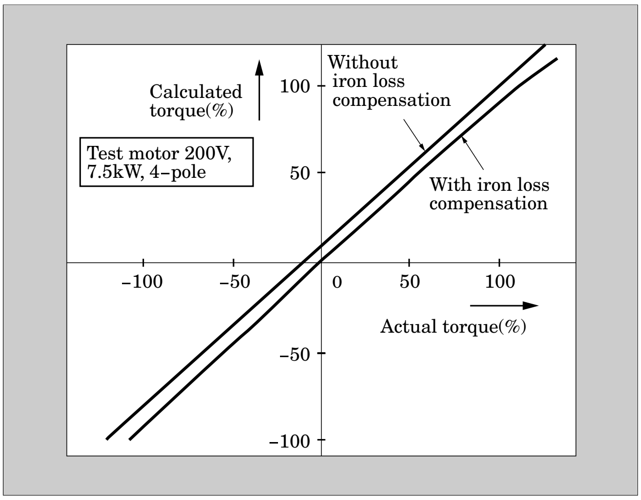
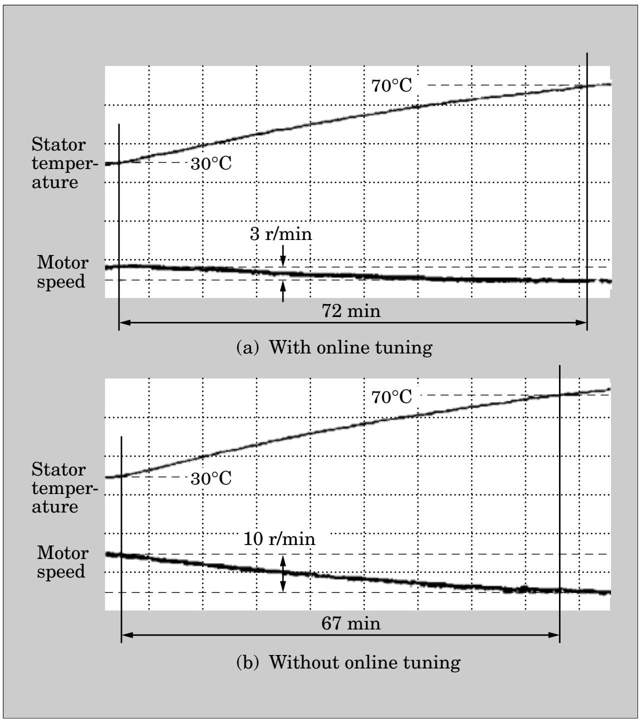


Fig.4 Effect of online tuning



hysteresis loss component in the iron loss converted into torque current. Since the magnitude of the hysteresis loss component does not depend upon frequency, it has a significant effect at low speeds. Figure 3 shows a torque calculation result at 5Hz in which the iron loss is compensated with consideration of the hysteresis loss component. The iron loss compensation improves the torque calculation accuracy, and contributes notably to the improvement of calculation at low speed.

(2) Online tuning

The parameter of the induction motor equivalent circuit that shows the largest variation during operation is rotor resistance. Because the magnitude of slip frequency of *V/f* controlled induction motors is proportional to the rotor resistance, if the rotor resistance changes due to the temperature rise during loaded operation, the speed also varies. In order to maintain constant speed regardless of temperature rise, the function of online tuning is required. Here, a tuning method is described that utilizes the property that stator resistance varies almost proportionally to rotor resistance.

In the case of induction motor, the following relation exists between stator resistance R_1, magnetizing current i_{1d} and their setting values R_1* and i_{1d}*.

$$\frac{R_1}{R_1{}^*} = \frac{i_{\mathrm{ld}}{}^*}{i_{\mathrm{ld}}} \quad \cdots\cdots \quad (1)$$

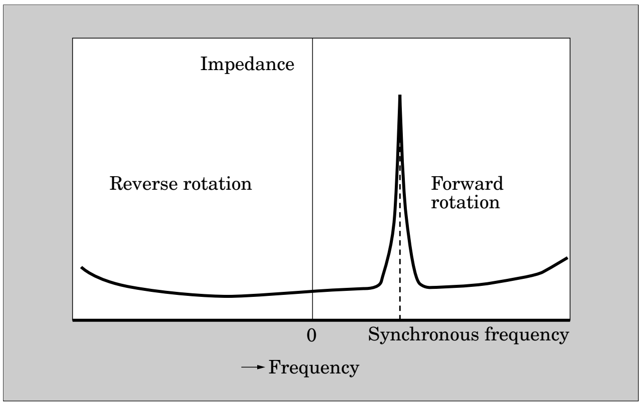
The slip frequency is proportional to R_2/i_{1d} (R_2: rotor resistance). Therefore, when the slip frequency is compensated according to the following equation, the speed can be maintained constant even if R_2 changes.

$$\hat{R}_2 = R_2{}^* \left(\frac{i_{\mathrm{ld}}{}^*}{i_{\mathrm{ld}}} \right)^2 \quad \cdots\cdots \quad (2)$$

$\hat{R}_2$: Compensated rotor resistance

Figure 4 shows the comparison of the powering condition. This online tuning method enables an improvement in speed drift to about 1/3 in spite of the simplified calculation.

Fig.5 Frequency characteristics of induction motor impedance

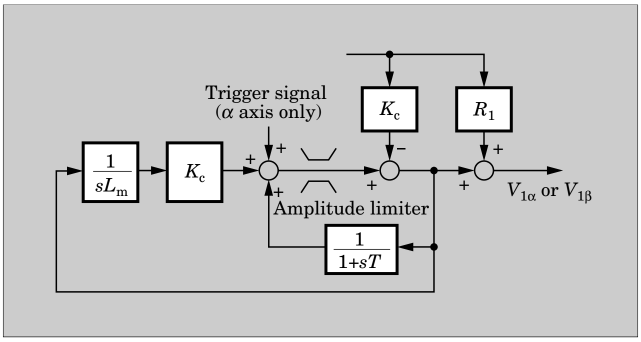


2.2 Free run speed estimation technology

The induction motor sometimes enters a free run condition due to the instantaneous power interruption or external force. If a speed sensor is not provided as in the case of *V/f* control, when the inverter starts while the motor is rotating, the rush current might cause an emergency stopping of the inverter or the torque shock. In order to start smoothly, the frequency should be set to the optimum estimated free run speed of the motor when starting the inverter. A free run speed estimation method that utilizes self-excited oscillation is introduced below.

Figure 5 shows the impedance characteristics of induction motor. The impedance of the induction motors becomes maximum at the synchronous frequency (zero slip). Utilizing this characteristics, by means

Fig.6 Structure of controller (one phase)



of appropriate positive feedback through control of the microprocessor and the inverter, self-excited oscillation occurs near the synchronous frequency and speed estimation is possible. Figure 6 shows a control block diagram (stationary frame α, β axis) for self-excited oscillation. With the control, the inverter can excite the induction motor near the synchronous speed regardless of the motor speed by supplying the reactive power needed by the induction motor.

Figure 7 shows the current waveform of the induction motor at the self-excited oscillation, and Fig. 8 shows an example of the speed detection result. The free run speed is detected precisely over the entire speed range including forward rotation, reverse rotation and the stop. Because this method of free run speed estimation allows frequency detection including rotational direction, the realization of non-shock starting without abnormal torque in either forward rotation or reverse rotation is possible.

3. Latest Servo System Control Technology

"Small sizing of the motor" and "auto-tuning of control parameters" can be listed as trends of the latest servo system technology.

In contrast, servo control technology has the following themes.

(1) Achievement of minimum response time corresponding to a small moment of rotor inertia.
(2) High gain control achieves robustness for disturbance, high stability and low rotational fluctuation during small motor inertia.
(3) Auto-tuning system achieves the performance of (1) and (2).

The high speed control response of (1) which can achieve the minimum response time and the achievement of the high gain control of (2) have the same meaning for the control technology.

To achieve high speed control response, improvement of low speed performance with a high resolution rotary encoder is indispensable. At low speed and stand still, non-negligible shaft vibration caused by resolution of the rotary encoder occurs, and the magnitude of vibration is nearly in proportion to the control response. A high resolution rotary encoder is

Fig.7 Waveform of α, β axis current in case of self-excited oscillation

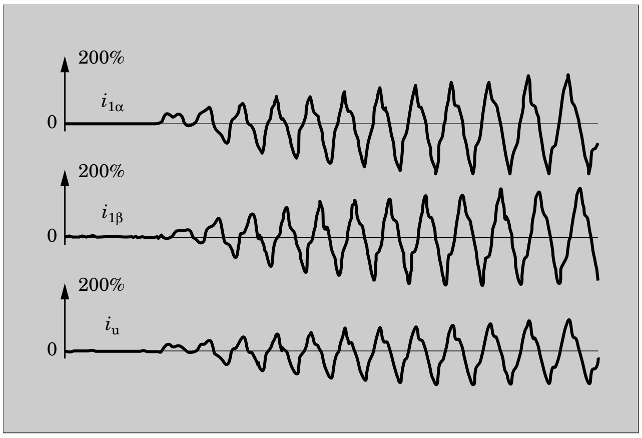
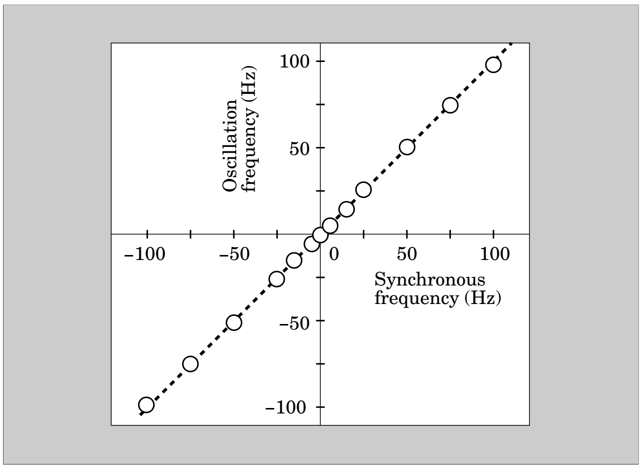


Fig.8 Relation between rotor speed and oscillation frequency



necessary in order to realize both the high speed control and the low vibration.

Low speed performance improvement that uses high speed control response and a high resolution rotary encoder, and a novel method of auto-tuning technology are introduced below.

3.1 High response speed control

To achieve high speed control response the following two items were developed.

- ○ Hardware for current control
- ○ Application of a high speed RISC (reduced instruction set computer) processor to the servo control

The control period can be shortened by performing the current control calculation with a hardware algorithm, instead of calculating by software as in the past. In addition, the speed control calculation period can be shortened by reducing the calculation time by utilizing a high speed RISC processor as well as the hardware for current control.

As a result, a speed control response of 5 times faster compared to the past has been achieved. Figure 9 shows frequency characteristics of the speed control response. It can be seen that the −3 dB point of cutoff

Fig.9 Frequency characteristics of speed control

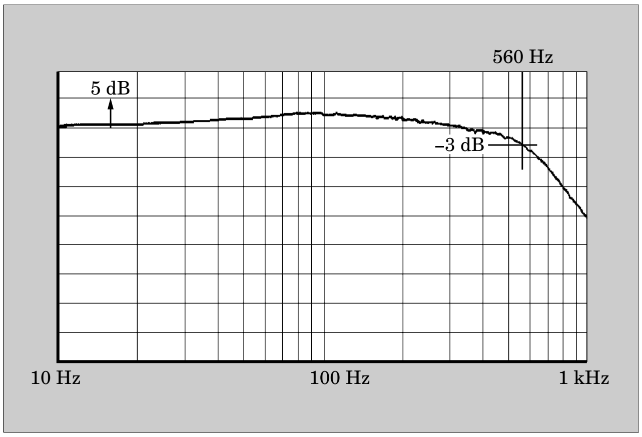


Fig.10 Rotational fluctuation characteristics

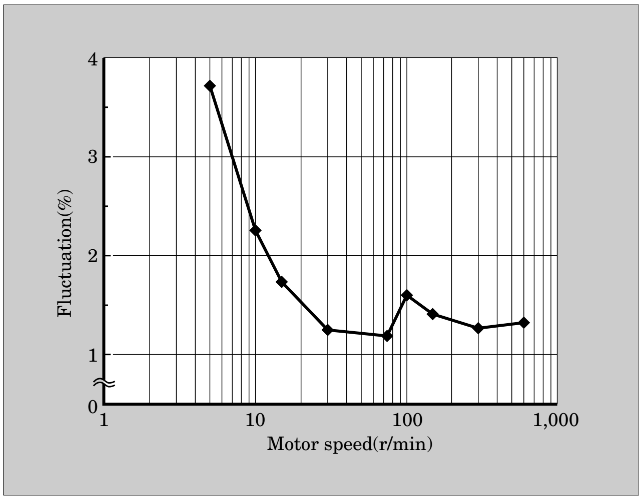


Fig.11 Settling time of positioning

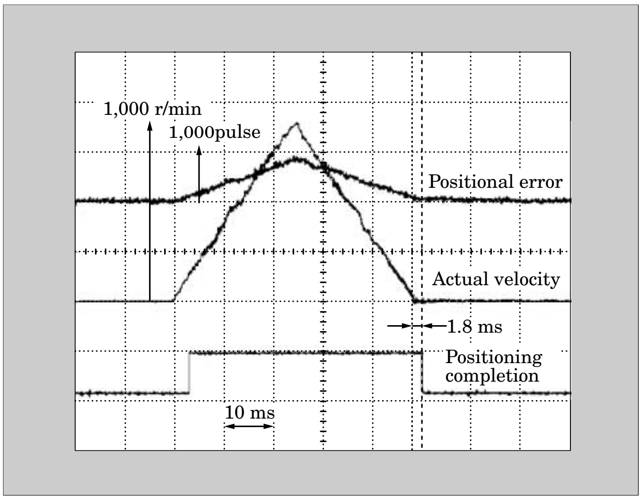
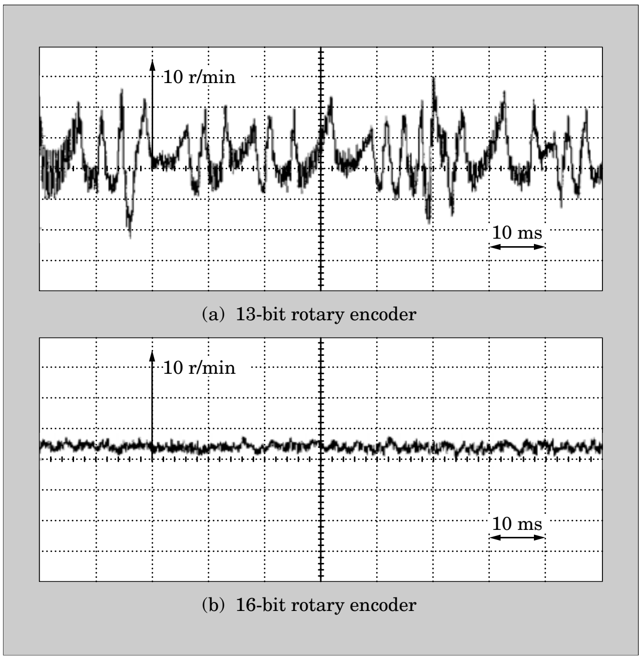


Fig.12 Comparison of shaft vibration



frequency indicates 560Hz.

Figure 10 shows the rotational fluctuation characteristics. It is clear that low fluctuation of 4% or less is achieved throughout the whole range. Since the response of 500Hz can be obtained, by heightening the control gain the rotational fluctuation can be restricted.

Figure 11 shows the settling time of positioning. Acceleration and deceleration of up to 1,000r/min are each performed for approximately 25ms, and the settling time from zero speed to signal-on of positioning completion is 2ms or less. Achievement of such high speed positioning is attributable to the speed control response of 500Hz.

3.2 Improvement of low speed characteristics by high resolution rotary encoder

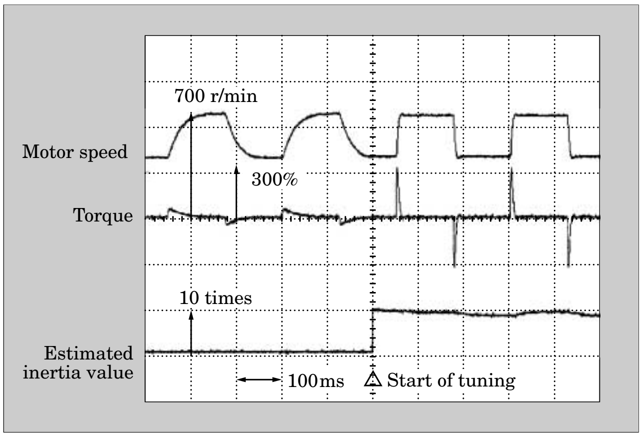
A 16-bit serial communication interface rotary encoder (corresponding to 16,384 pulses) has been newly developed. By using this encoder to control feedback, low speed performance is dramatically improved. Figure 12 shows a comparison of shaft vibration during a 1r/min command operation. Both waveforms are for the conditions of no load and tuned 500Hz response. With the 13-bit rotary encoder, shaft vibration of 12r/min (p-p) is generated due to ripple of the detected velocity caused by the low resolution. In many cases, this vibration induces mechanical resonance or acoustic noise. From this viewpoint, it is understood that obtaining a 500Hz response using a 13-bit rotary encoder is not practical. On the other hand, with the 16-bit rotary encoder, only a small amount of 1.5r/min (p-p) vibration is generated, solving the vibration problem.

3.3 Novel auto-tuning method

A novel auto-tuning method that tunes servo control gain instantaneously based on estimated load inertia is introduced here.

Figure 13 shows an example of the inertia estimation waveform, and speed and torque response wave-

Fig.13 Real-time auto-tuning action waveform



forms. When the total inertia value is 10 times the motor inertia, the initial value of inertia is estimated as unity. When real-time auto-tuning is started at point △ mark, the inertia is instantaneously estimated correctly. Since the appropriate control gain is set in real-time based on the estimated inertia value, it is clear that the response of motor speed after the start of tuning becomes approximately 10 times faster.

Thus, through high speed and high accuracy of the tuning action, instantaneous adjustment of various machines is possible, and the range of applications for these machines can be extended.

4. Conclusion

As the latest control technology, the improvement of torque control accuracy of the inverter, initial speed estimation technology, high speed response control of the servo system, improvement of low speed characteristics by the high resolution rotary encoder and a novel auto-tuning method have been introduced above.

We are endeavoring further development of novel functions and high performance in response to market demands.