Full Digital Control of Permanent Magnet AC Servo Motors

Jin-Won Lee, Dong-Il Kim, Sang-Hyun Jin, In-Hwan Oh, and Sungkwun Kim
Control R/D Team, Factory Automation Research Institute
Production Engineering Center, Samsung Electronics
416, Maetan-3-Dong, Paldal-Ku, Suwon City, Kyungki-Do 442-742, KOREA

ABSTRACT

In this paper, we present a full digital control scheme which controls currents and speed of the permanent magnet AC servo motor with large range of bandwidth and high performance.

The current equations of the permanent magnet AC servo motor are linearized by feedback linearization technique. Both acceleration feedforward terms and IP controllers, whose gains are functions of motor speed, are used in order to control motor currents. In addition, the phase delays in current control loops are compensated by placing phase lead-lag compensators after current commands, which make it possible to avoid high gains in the current controllers. Unity power factor can be achieved by the proposed current controller. Pulsewidth modulation is performed by way of the well-known comparison with a triangular carrier signals. The velocity controller is designed on the basis of the linearized model of the permanent magnet AC servo motor by the proposed current controller.

The performance of the entire control system is analyzed in the presence of uncertainty in the motor parameters. The proposed control scheme is implemented using the digital signal processor-based controller composed of an Analog Device ADSP 2111 and a NEC78310. The pulsewidth modulation (PWM) signals are generated through a custom IC, SAMSUNG-PWM1, which has the outputs of current controllers as inputs. The experimental results show that the permanent magnet AC servo motor can be always driven with high dynamic performance by the proposed full digital control scheme of motor speed and motor current.

1. INTRODUCTION

Electrical servo systems are being used more and more owing to the ever-increasing automation in industry. The field of application is wide and ranges from CNC (computerized numerical controller) machine tools, industrial robots, and precise positioning devices to specialized applications such as steppers for manufacturing semiconductors. The characteristics of the electrical servo systems are summarized as high servo response and noise suppression, high overload capability, wide speed range, and good smoothness of movement at very low speeds. To date, DC servo motors have been widely used in obtaining such characteristics, which, however, have some disadvantages such as the mechanical commutation, the regular maintenance due to brush wear, and the losses in the rotor.

AC servo motors with permanent magnet rotors have the inherent advantages such as rugged construction, easy maintenance, high efficiency, high power factor, and the precise synchronous operation compared with DC servo motors. The majority of the disadvantages of DC servo motors can be overcome by AC servo motors. Recent researches have shown that AC servo motors with permanent magnet rotors could become serious competitors to DC servo motors in electrical servo systems (Alfio and Alfonso(1986), Pillay and Krishnan(1988), Gerhard and Albert(1984)).

Conventionally, the motor speed and the motor current have been controlled by analog circuits to obtain high dynamic performance. Especially, the analog controller with wide bandwidth for direct current control is still a powerful method to drive AC servo motors in impressed currents. In spite of good control performance, there are some inherent disadvantages in the analog control system. The analog circuit requires a lot of adjustments, and its performance is sensitively affected by the drift in supply voltage or parameter variation due to the change of temperature as well. To overcome these demerits, digital control schemes of the AC servo motor have been recently developed with the help of high performance microprocessors such as digital signal processors (DSPs) (Matsui and Ohashi(1992)). Recently, the digital control schemes of the AC servo motor are being applied to machining or tracking a desired trajectory in industrial robots or CNC machine tools where high precision is required.

This paper proposes the digital controller which control currents(i.e. torque) and speed of the AC servo motor with permanent magnet rotor in the discrete time domain. This proposed controller drives the permanent magnet AC servo motor in impressed currents with comparable performancre to that of analog controller. Especially, it makes the AC servo motor driven at very low speed to adopt the pulse interval measurement method combined with the frequency dividing circuit of the encoder pulse train in the proposed controller. The entire control algorithm is implemented on the control system of which CPU is DSP ADSP2101. The experimental results demonstrate that AC servo motors which are controlled by the proposed digital controllers are effectively used as actuators of the axes of motion of the SCARA robot.

II. Digital Current Control Scheme

In the stationary d-q coordinate frame, the dynamic equations of a 2 pole permanent magnet AC servo motor are described by:

$$\frac{dids}{dt} = -\frac{Rs}{Ls-M}ids + \frac{\Phi m}{Ls-M}\omega r\cos\theta r + \frac{1}{Ls-M}Vds,$$

$$\frac{diqs}{dt} = -\frac{Rs}{Ls-M}iqs - \frac{\Phi m}{Ls-M}\omega r\sin\theta r + \frac{1}{Ls-M}Vqs, \quad (1)$$

$$\frac{d\omega r}{dt} = -\frac{B}{J}\omega r - \frac{3\Phi m}{2}(iqs\sin\theta r - ids\cos\theta r) - \frac{TL}{J},$$

$$\frac{d\theta r}{dt} = \omega r,$$

where the generated torque Te is

$$Te = \frac{3\Phi m}{2}(iqs\sin\theta r - ids\cos\theta r). \quad (2)$$

In (1), Vds and Vqs, d-axis and q-axis voltages, are the control inputs and

ids(iqs)	d-axis (q-axis) stator current
ωr	rotor angular speed
Φm	rotor flux
θr	rotor angular displacement
Ls	stator self-inductance
Rs	stator resistance
J	momentum of inertia of the rotor
M	mutual inductance
TL	disturbance torque
B	damping coefficient

As is shown in (1), the permanent magnet AC servo motor is coupled nonlinear system. If we choose the following Vds and Vqs to compensate the counterelectromotive force terms by nonlinear feedback control,

$$\begin{vmatrix} Vds \\ Vqs \end{vmatrix} = \begin{vmatrix} -\Phi m\,\omega r\cos\theta r + (Ls-M)u1 \\ \Phi m\,\omega r\sin\theta r + (Ls-M)u2 \end{vmatrix}, \quad (3)$$

where u1 and u2 are new inputs, the current equations of the permanent magnet AC servo motor are given by linear equations:

$$\frac{dids}{dt} = -\frac{Rs}{Ls-M}ids + u1, \quad (4)$$

$$\frac{diqs}{dt} = -\frac{Rs}{Ls-M}iqs + u2,$$

To obtain high dynamic performance, that is to control the motor torque directly, it is required to make the permanent magnet AC servo motor be fed by impressed currents. In this paper, we choose current controllers as IP (Integral-Proportional) controllers in order to make motor currents track current commands:

$$u1 = -Kpids + Ki\int_0^t (ids* - ids)dt,$$

$$u2 = -Kpiqs + Ki\int_0^t (iqs* - iqs)dt, \quad (5)$$

where Kp, Ki are control gains and ids*, iqs* are current commands, which are time-varying sinusoidal functions at the transient state.

Because the current control loops consisting of (4) and (5) are second order delay systems, Kp, Ki must be chosen as high gains to make motor currents track current commands completely both at transient state and in the steady state. While the inherent advantage of itself is lost in this case, the IP controller behaves like the bang-bang controller or the hysteresis controller. To avoid this problem, the phase delays of current control loops are compensated by placing phase lead-lag compensators after the current commands:

$$Gc = \frac{(1+aT1s)(1+bT2s)}{(1+T1s)(1+T2s)}, \qquad (6)$$

where $a > 1$ and $b < 1$, s is the Laplace operator, and T1, T2 are time constants of lead and lag compensators, respectively. The power factor near 1 can be obtained by (3), (5), and the phase lead-lag compensator in (6).

Because the parameters of the permanent magnet AC servo motors change with temperature, magnetic saturation, and so on, and the precise measurement of them is practically difficult, (3) can not compensate the nonlinear coupling terms in (1) completely. Accordingly, the current controllers which consist of (3), (5), and (6) have limitations in feeding impressed currents to the permanent magnet AC servo motor both at the transient state and in the steady state. In the actual implementation, the IP controllers in (5) are modified and feedforward terms are incorporated to them as follows:

$$u1 = Kfcids* - KPids + KI\int_0^t (ids* - ids)dt,$$
$$u2 = Kfciqs* - KPiqs + KI\int_0^t (iqs* - iqs)dt, \qquad (7)$$
$$KP = Kp1(\omega r) + Kp2, \quad KI = Ki1(\omega r) + Ki2,$$

where Kp1, Ki1 are control gains depending on the motor speed, Kp2, Ki2 are constant control gains, and Kfc is the current feedforward gain. In addition to (7), the compensation method of dead zone in the current control loop is described in the final manuscript.

If current commands are given as $ids* = -Im\cos\theta r$, $iqs* = Im\sin\theta r$, the current controllers which consist of (3), (5), (6), and (7) make the dynamic behavior of the permanent magnet AC servo motor expressed by the following linear equation:

$$\frac{d\omega r}{dt} = -\frac{B}{J}\omega r - \frac{3\Phi m}{2}Im - \frac{TL}{J}. \qquad (8)$$

On the basis of (8), the velocity controller can be designed as

$$Im = Kfw\omega r* - Kpw\omega r + Kiw\int_0^t (\omega r* - \omega r*)dt, \qquad (9)$$

where Kpw, Kiw are control gains, Kfw is the speed feedforward gain, and $\omega r*$ is the commanded motor speed.

As mentioned in the above, the output of the speed control loop, the amplitude of current commands, is multiplied by $-\cos\theta r$ and $\sin\theta r$ to become d-axis and q-axis current commands. Based on these commands, the motor currents are controlled by the proposed controller in (3), (5), (6), and (7). Through 2Φ-3Φ transformation, the control outputs are transformed into the reference values of phase voltages to be applied to the permanent magnet AC servo motor.

III. Digital PWM Generation

As described in Section 2, the output of velocity controller (9) and the commutation information generate the stator current commands ids*, iqs*. The error between the current command and the actual motor current is controlled by current controller (7) to drive the permanent magnet AC servo motor in the impressed current mode. The comparison of the controlled error with a triangular waveform generates the digital value corresponding to the pulsewidth of the PWM signal. Then, digital comparator in Fig.1 is loaded with this digital value and the loaded value is compared with the triangular waveform generated from the up/down counter to generate the PWM signals, which will be transmitted to the gate drive circuits of the MOSFET half-bridge power inverter.

If the actual motor current exceeds the current command, the PWM signals are generated to turn off the upper power switching element and turn on the lower power switching element in the MOSFET half-bridge power inverter. On the contrary, if the current command exceeds the actual motor current, the PWM signals are generated to turn on the upper power switching element and turn off the lower power switching element in the MOSFET half-bridge power inverter. Fig.1 shows the block diagram of the PWM signal generator for one phase. The digital current and velocity controller in (7), (9) and this digital PWM in the microprocessor makes the AC servo motor fed by impressed currents, so behave like a DC servo motor.

IV. DIGITAL SPEED MEASUREMENT

The precise detection of the motor speed and the motor position is essential to the high dynamic performance of the permanent magnet AC servo motor in the microprocessor-based control system. Here, the speed measurement method based on pulse interval measurement is proposed. This method, of which block diagram representation is shown in Fig.2, makes it possible to detect the motor speed precisely with the same resolution in the whole speed range (Kim et al.(1992)). Fig. 2 shows that the motor speed is apparently given by

$$\omega_r = 6 * 10^4 f_c/(Mn), \tag{10}$$

where f_c is the clock frequency in MHz, M the number of the pulses from the incremental encoder per revolution, and n the number of the clock pulses for interval T_w. In this method, the higher f_c is required in order to enhance the accuracy of the speed measurement because fewer clock pulses are obtained over T_w as the motor speed increases. However, increasing f_c both can not guarantee the same measurement resolution in the whole speed range and is limited by the physical limitation in hardware. Such problems can be eliminated by utilizing the pulse trains whose frequencies are 1/N (N=1,...,127) times as high as that from the incremental encoder. Such pulse trains provide the most appropriate pulse intervals to accurate speed measurement, which are N times as long as that of T_w. If the frequency dividing ratio 1/N is determined optimally according to the motor speed, the motor speed from a standstill to the rated speed is measured with the same resolution with the help of new pulse trains. The new pulse trains are obtained from the hardware structure of which block diagram is shown in Fig.3. In Fig.3, INA and INB are new encoder pulse trains.

In experiments, the whole speed range of the tested motor is divided into 9 steps for simplicity of implementation. The relationship between the motor speed and the frequency dividing ratio 1/N, which was used in experiments, is shown in Table 1.

V. Experimental Results

The proposed control scheme is implemented using the digital signal processor-based control system composed of an Analog Device ADSP 2111 and a NEC78310. A 4 pole permanent magnet AC servo motor is chosen for the experimental work, whose nominal data are listed in Table 2. The speed drive system implemented for the experimental work consists of a ADSP2101, a MOSFET PWM inverter, and the predescribed permanent magnet AC servo motor. The block diagram representation of the speed drive system is shown in Fig.4 while the actual speed drive systems are shown in Fig.5. For the detection of motor speed and motor position, an incremental encoder whose resolution is 1000 pulses/rev per phase is coupled to the motor shaft and the pulses whose frequency is 4 MHz are integrated over the pulse interval Tw of the pulse train from the incremental encoder. Signals between the digital signal processor-based control system and the permanent magnet AC servo motor are processed through 12 bit A/D converters, and rotor speed and rotor position are detected by counter/timers and an optical encoder with resolution of 4000 pulses/rev. which outputs serial absolute pulse train. The control gains can be adjusted by digital key inputs. A 1KW 4 pole permanent magnet AC servo motor is chosen for the experimental work.

In the first experiment, the tracking performance of motor current was investigated. The experimental result in Fig.6 shows that the proposed current controller in (3), (5), (6), and (7) is practically make the permanent magnet AC servo motor fed by impressed currents, so unity power factor is obtained. While the upper waveform in Fig.6 is the current command of A phase, the lower waveform is the actual motor current of A phase. The experimental results in the final manuscript will demonstrate that the permanent magnet AC servo motor can be always driven with high dynamic performance by the proposed full digital control scheme of motor speed and motor current.

In the second experiment, the positioning repeatabilty is investigated when the proposed digital controllers are applied to Samsung SCARA robot-FARA SM3 with AC servo motors as actuators of axes of motion. The specified positioning repeatabilty of the SCARA robot used as a test

The proposed control scheme is implemented using the digital signal processor-based control system composed of an Analog Device ADSP 2111 and a NEC78310. A 4 pole permanent magnet AC servo motor is chosen for the experimental work, whose nominal data are listed in Table 2. The speed drive system implemented for the experimental work consists of a ADSP21 1, a MOSFET PWM inverter, and the predescribed permanent magnet AC servo motor. The block diagram representation of the speed drive system is shown in Fig.4 while the actual speed drive systems are shown in Fig.5. For the detection of motor speed and motor position, an incremental encoder whose resolution is 1000 pulses/rev per phase is coupled to the motor shaft and the pulses whose frequency is 4 MHz are integrated over the pulse interval Tw of the pulse train from the incremental encoder. Signals between the digital signal processor-based control system and the permanent magnet AC servo motor are processed through 12 bit A/D converters, and rotor speed and rotor position are detected by counter/timers and an optical encoder with resolution of 4000 pulses/rev. which outputs serial absolute pulse train. The control gains can be adjusted by digital key inputs. A 1KW 4 pole permanent magnet AC servo motor is chosen for the experimental work.

In the first experiment, the tracking performance of motor

current was investigated. The experimental result in Fig.6 shows that the proposed current controller in (3), (5), (6), and (7) is practically make the permanent magnet AC servo motor fed by impressed currents, so unity power factor is obtained. While the upper waveform in Fig.6 is the current command of A phase, the lower waveform is the actual motor current of A phase. The experimental results in the final manuscript will demonstrate that the permanent magnet AC servo motor can be always driven with high dynamic performance by the proposed full digital control scheme of motor speed and motor current.

In the second experiment, the positioning repeatabilty is investigated when the proposed digital controllers are applied to Samsung SCARA robot-FARA SM3 with AC servo motors as actuators of axes of motion. The specified positioning repeatabilty of the SCARA robot used as a test bed is ±0.05mm. The experimental result in Fig.7 shows that the control performace of the proposed digital controller is good enough to gurantee the specified repeatabilty positioning in case of rated load. As is shown in Fig.7, it is shown that the maximum repeatabilty positioning in case of rated load is within ±0.03mm.

VI. Conclusion

This paper proposes a digital control scheme which controls currents and speed of the permanent magnet AC servo motor with wide bandwidth and high performance. The current equations of the permanent magnet AC servo motor are linearized by feedback linearization technique. Both acceleration feedforward terms and IP controllers, whose gains are functions of motor speed, are used in order to control motor currents. In addition, the phase delays in current control loops are compensated by placing phase lead-lag compensators after current commands, which make it possible to avoid high gains in the current controllers. Unity power factor can be achieved by the proposed current controller. The velocity controller is designed on the basis of the linearized model of the permanent magnet AC servo motor by the proposed current controller.

The digital control scheme is implemented using the digital signal processor-based controller composed of an Analog Device ADSP 2111 and a NEC78310 to investigate its performance through experiments. The experimental results show that the AC servo motor can be always driven in impressed currents by the proposed digital controller. Furthermore, it is demonstrated that AC servo motors which are controlled by the proposed digital controllers are effectively used as actuators of the axes of motion of the SCARA robot.

Further researches should be directed toward the mathematical analysis of the overall control system in order to improve control performance further.

References

[1] Alfio, C., and Alfonso, A., 1986, Transient Performance of Permanent Magnet AC Servo Motors, IEEE Trans. Ind. Appl., 22, pp.32-41.

[2] Pillay, P. and Krishnan, R., 1988, Modelling of Permanent Magnet Motor Drives, IEEE Trans. Ind. Elec., 35, pp.537-541.

[3] Gerhard, P., Alois, W, and Albert, F. W., 1984, Design and Experimental Results of a Brushless AC servo Drive, IEEE Trans. Ind. Appl., 20, pp.814-821.

[4] Erland, K. P. and Saeid, M., 1985, Brushless Servo System with Expanded Torque-Speed Operating Range, MOTORCON'85, pp.96-106.

[5] Samsung Electronics, 1990, AC Servo Drives-SSV Series User's Manual.

[6] Kim, D. I., Lee, J. W., and Kim, S., 1991, Control of Permanent Magnet AC Servo Motors without Absolute Position Transducers, IEEE PESC'91, Boston, U.S.A., pp.578-585.

[7] Kim, D. I., Lee, J. W., and Kim, S., Control of Permanent Magnet AC Servo Motors via Fuzzy Reasoning, will appear to IEEE '92 IAS Annual Meeting.

[8] Matsui, N. and Ohashi, H., 1992, DSP-Based Adaptive Control of a Brushless Motor, IEEE Trans. Ind. Appl., 28, pp.448-454.

[9] Brod, D. M. and Novotny, D. W., 1985, Current Control of VSI-PWM Inverter, IEEE Trans. Ind. Appl., 21,pp.562-570.

Table 1. The relationship between 1/N and the motor speed.

Speed(rpm)	1/N	Speed(rpm)	1/N
0 - 200	4	1600 - 2000	1/5
200 - 400	2	2000 - 2400	1/6
400 - 800	1/2	2400 - 2800	1/7
800 - 1200	1/3	1600 - 3200	1/8
1200 - 1600	1/4	3200 -	1/8

Table 2. The nominal parameters of the tested permanent magnet AC servo motor.

number of pole pairs	4	rated speed	3000rpm
rated output	300W	rotor inertia	0.69gcms^2
rated torque	9.7kgcm	torque constant	2.14kgcm/A
instant max torque	29.1kgcm	mech. time constant	1.9ms
power rate	8.01kW/s	elec. time constant	2.7ms
armature resistance	1.22Ω	armature inductance	3.3mH

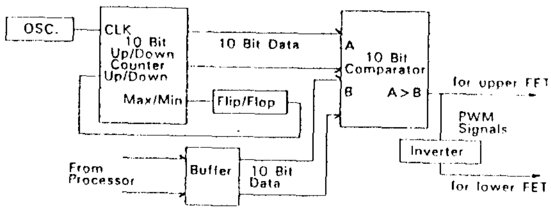

Fig.1. The block diagram of the digital PWM generator.

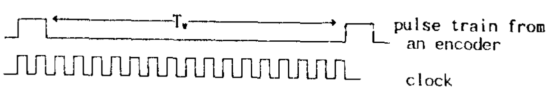

Fig.2. Digital speed measurement principles from incremental encoders

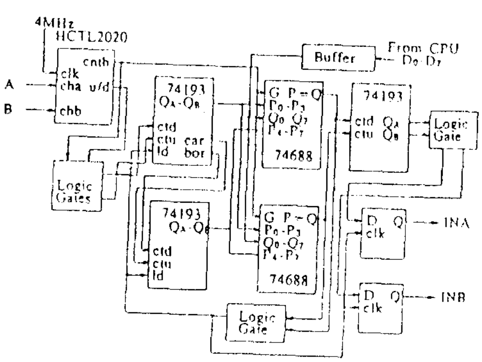

Fig. 3. The hardware structure for new pulse trains.

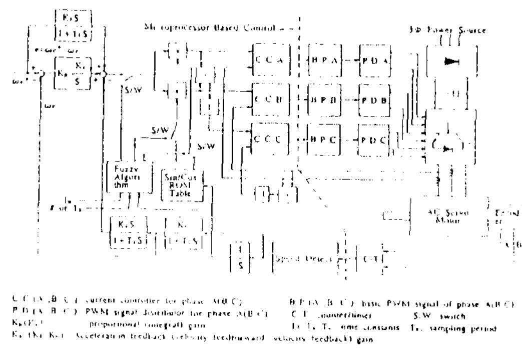

Fig.4. The speed drive system implemented for the experimental work

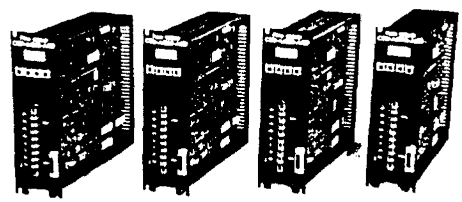

Fig.5. The picture of the actual speed drive systems.

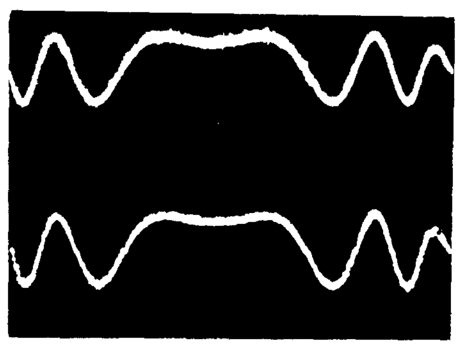

Fig.6. The experimental result for digital current control

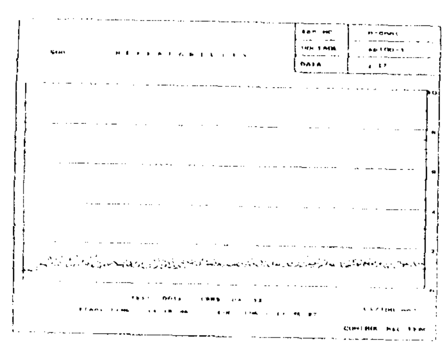

Fig.7. The positioning repeatability of SCARA robot