Design and Implementation of a Fully Digital DC Servo System Based on a Single-Chip Microcomputer

PEI-CHONG TANG, SHUI-SHONG LU, AND YUNG-CHUN WU

Abstract—**A single-chip microcomputer is used to design a fully digital dc servo system to replace the conventional analog circuits. This microcomputer performs three main tasks: the firing control of a three-phase full-wave thyristor dual converter; the compensation for the nonlinear and loading effect in the converter; and compensations of position loop and rate loop. With no current feedback and minimum components, this dc servo system provides fast transient response and high reliability.**

I. INTRODUCTION

MICROPROCESSOR applications in the industrial control are increasing rapidly in recent years. For the thyristor-driven dc servo systems, several microprocessor-based designs have been implemented to replace the conventional analog and discrete digital circuits [1]-[3]. Ohmae *et al.* [1] used a bit-slice microprocessor system to design a speed regulation system by a dual-mode current loop-control method. Chan *et al.* [2]-[3] used an 8-bit microprocessor system to control the speed and position of a dc motor by a different current loop-controlled method. In the case of thyristor-driven dc servo systems, the critical problem is to find an easy way to compensate the nonlinear and loading effect of thyristor converter. From this point of view, the methods proposed by Ohmae and Chan *et al.* are unsatisfactory.

Recently, Tang, Lu, and Wu [4] proposed a cascade nonlinear compensation scheme to compensate the nonlinear and loading effect of thyristor converter. In this scheme, no current loops were required and simple computing algorithms were used. Thus, the microprocessor-based controller design was simplified in both hardware and software. In addition, it was shown that this compensated thyristor-driven dc servo system could be regarded as a quasi-linear system. Thus, the control-loop design was simplified. In another paper, Tang, Lu, and Wu [5] introduced a microprocessor-based firing scheme to provide maximum firing range with minimum firing delay. This scheme used minimum components and no adjustment was required. In this paper, a single-chip microcomputer is used to implement a fast-response thyristor-driven dc servo system based on these two schemes. This circuit uses fully digital components with minimum hardware.

II. HARDWARE DESCRIPTION

The schematic diagram of the dc servo system based on a single-chip microcomputer is shown in Fig. 1. The three-phase full-wave thyristor dual converter is composed of twelve silicon

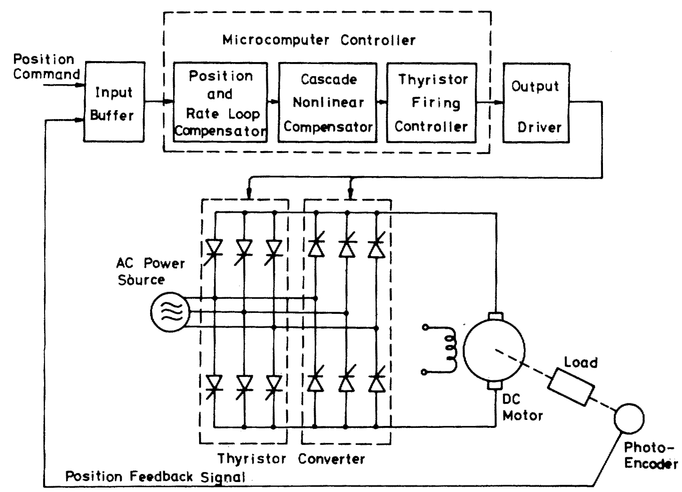

Fig. 1. Block diagram of the position servo system.

controlled rectifiers (SCR's). This converter is used to drive a separately excited dc motor in a four-quadrant operation. The motor field is maintained constant. One incremental photoencoder is coupled to the motor shaft as the only feedback transducer. Two-phase outputs of the photoencoder are used to generate the position and the derived-speed feedback. Upon receiving the pulse-train-like command, this control circuit will control both speed and position of the thyristor-driven dc motor. The block diagram of this fully digital circuit is shown in Fig. 2 and described below.

A. Input Buffer

Input buffer functions as the interface among command, photoencoder, and the single-chip microcomputer. For the purpose of tracking-system applications, command inputs are two pulse-train signals. One is the clockwise command and the other is the counterclockwise command. By using three divide-by-sixteen up-down counters, the position command is obtained by integrating these pulse-train signals.

Outputs of the incremental photoencoder are two-phase pulse-train signals. The phase difference between them is about 90°. After the multiply-by-four decoder, these two-phase signals are decoded to clockwise and counterclockwise signals. Then, the position feedback is obtained by using the 12-bit up-down counter similar to the one used for position command. A microcomputer-controlled 12-bit two-to-one multiplexer is used to read in the digitized position command and feedback. This multiplexer is desired in order to decrease the number of microcomputer I/O required.

B. Microcomputer Controller

The microcomputer used is Zilog Z8 single-chip microcomputer. The Z8 microcomputer introduces a new level of

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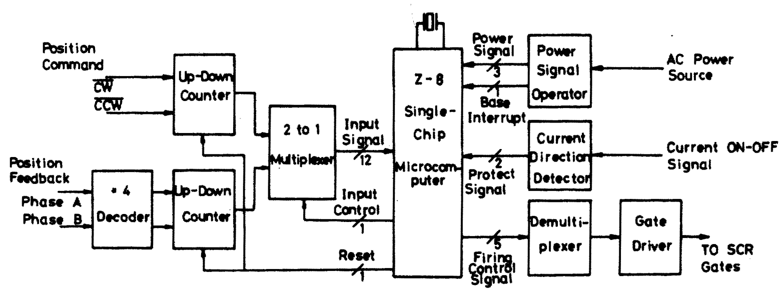

Fig. 2. Block diagram of the control circuit.

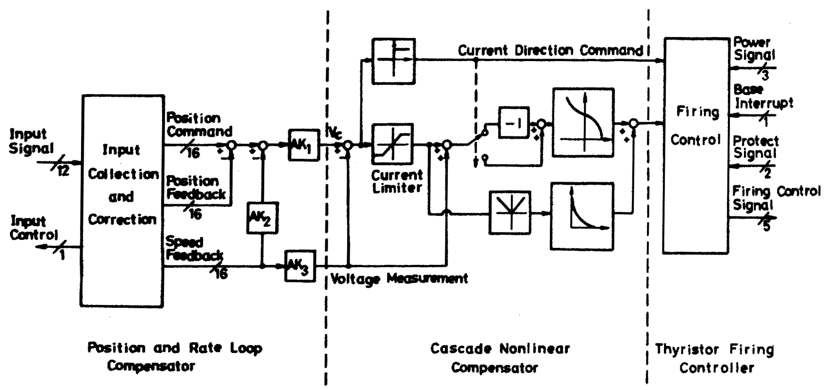

Fig. 3. Block diagram of the microcomputer controller.

sophistication of single-chip architecture with 2K bytes of internal ROM, 124 bytes of on-chip RAM, two programmable 8-bit timers, and 32 bits of programmable I/O.

The block diagram of the microcomputer controller is illustrated in Fig. 3. The functions performed by the microcomputer will be detailed in the next section. Because most complex works are executed by microcomputer software, the hardwares are just buffers and drivers.

C. Output Driver

The output driver functions as the interface between the thyristor dual converter and the single-chip microcomputer. The design of the output driver is based on the work by Tang, Lu, and Wu [5]. The three-phase ac source signals, digitized by using the power signal operator, are sent to the microcomputer for firing control. In each 60°, of ac source, the base interrupt signal is generated at each zero crossing of the three-phase ac source. This signal is used to synchronize the microcomputer and ac source.

The current direction detector is used to detect the bi-direction current ON–OFF signals. These ON–OFF signals are sent to the microcomputer for crossover damage protection of thyristor dual converter.

The demultiplexer and the gate driver are used to distribute the SCR firing signals to each gate of chosen SCR's. These SCR firing signals are generated by the microcomputer under the control of a firing control software.

III. SOFTWARE DESCRIPTION

Most functions of the servo controller are performed by the microcomputer software. As shown in Fig. 3, there are three main tasks in the microccomputer software which includes position and rate-loop compensation, cascade nonlinear compensation, and thyristor firing control.

A. Position and Rate-Loop Compensation

The position and rate-loop compensator compares the position command and feedback, then generates a voltage command VC as its output. The first important job is to obtain the correct position, command, and feedback. Because the length of hardware counter is only 12 bits, the overflow of counter happens frequently. To correct the overflow error of the counter, the following code correction technique is used.

Due to the frequency response of the photoencoder, it is assumed that the input signal frequency is less than 700 kHz. In one period of 360-Hz sampling time, the maximum number integrated by the counter is less than 2047 pulses, which can be handled by an 11-bit counter. Thus, the remaining bit in the 12-bit counter is used to check the overflow of 11-bit data, and the software counter can then be constructed by integrating these overflows. In this way, the 16-bit position command and feedback are constructed by combining the 4-bit software counter and the 12-bit hardware counter.

By differentiating the position feedback, the speed feedback is obtained for rate-loop compensation. Due to the linear relationship between the motor speed and the induced EMF, the speed signal can be used as the voltage measurement by multiplying a gain constant $AK3$. The other two parameters, $AK1$ and $AK2$, are used to construct a proportional controller with inner rate loop.

B. Cascade Nonlinear Compensation

The cascade nonlinear compensation is based on the design by Tang, Lu, and Wu [4]. Using the difference between the voltage command and voltage measurement as a new parameter, the firing-angle command is obtained by searching two tables. One is used to get the firing angle under the continuous current mode and the other is used to modify this firing angle

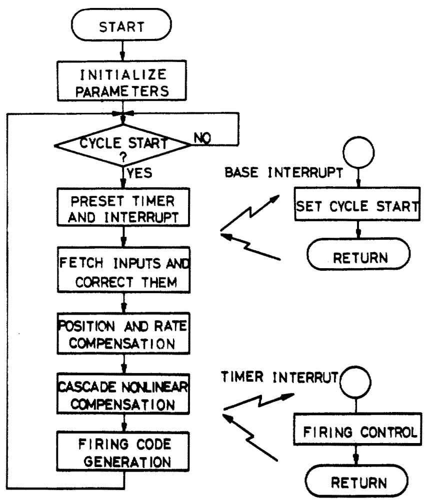

Fig. 4. Flow chart of the microcomputer controller.

under the discontinuous current mode. In addition to the compensation of nonlinear and loading effect in the thyristor dual converter, the difference between the voltage command and voltage measurement can be limited to a safe region so that it functions as a current limiter. The sign of this voltage difference is also used as the current direction command for the thyristor dual converter. Thus, the cascade nonliner compensation software computes the thyristor firing angle and direction commands used for the thyristor firing control.

C. Thyristor Firing Control

This controller is based on the design by Tang, Lu, and Wu [5]. The flowchart is shown in Fig. 4. The control cycle has a period of about 2.7 ms and is synchronized with the ac source. At the start of each control cycle, the firing-angle command calculated in last control cycle is used to set the delay time of the timer, then the microcomputer proceeds to calculate the next firing angle command. When the timer counts down to zero, a signal is generated to interrupt the main process, and the SCR firing signals are sent to fire the chosen SCR's.

IV. SERVO SYSTEM DESIGN

The overall system is a nonlinear, sampled-data control system. The sampling rate is 360 Hz and the maximum delay time including computing time and firing delay is two sampling periods, about 5.5 ms. The exact analysis of the overall system is difficult, but the approximate solution is simple [4]. Because the system time constant is much greater than the sampling period and due to the linearization effect of the cascade nonlinear compensation, the overall system can be approximated to a linear and continuous control system. Thus, most of the design methods based on the linear and continuous control theory can be applied to this microcomputer-based dc servo system.

One of the simplest methods used is a proportional control with inner rate loop, as shown in Fig. 5. The step-by-step design from inner loop to outer loop is chosen to solve this problem. In the experiment, the motor used is a 0.5-kW permanent magnet dc motor (90 V, 15 A, 3000 rpm). The only feedback transducer is a photoencoder with 2000 ppr.

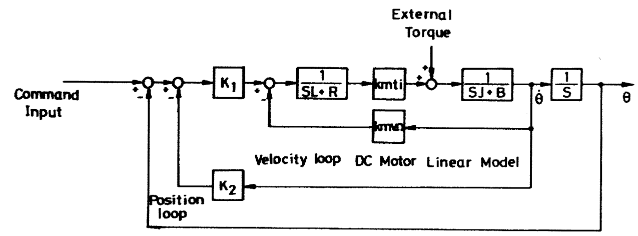

Fig. 5. Linear model of the position servo.

With a 200-V peak-to-peak ac source and the parameters $AK1, AK2$, and $AK3$ set at 0.039, 5.45, and 0.98, respectively, the open-loop gain is 43.3/s.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

The open-loop step response of the uncompensated thyristor dual converter is shown in Fig. 6(a). Because of the semiconductor characteristics of SCR's, no decelerating torque is applied to the motor during the transcience from high speed to low speed. The settling times in each transcience of acceleration and deceleration are approximately 220 ms and 660 ms, respectively. With the use of the cascade nonlinear compensator, the transient response is improved in both transience of acceleration and deceleration. The settling time of compensated thyristor dual converter is about 160 ms for both acceleration and deceleration, as shown in Fig. 6(b). In the experiments, the current limiter in the cascade nonlinear compensator is set at about 5 A to show its effect. As is evident from Fig. 6(b), both the acceleration and deceleration are limited by this current limiter. If the open-loop command change is so small that the current limit does not occur, as in the case of Fig. 6(c), the transient response are very fast and the same for both acceleration and deceleration. The settling time in this case is about 40 ms.

As can be seen from Fig. 6, the benefit of the cascade nonlinear compensation is obvious. With the use of the cascade nonlinear compensation, the step responses of the rate loop and the position loop are shown in Figs. 7 and 8, respectively. The settling time of the rate-loop response and the position-loop response are about 80 ms under the condition of current limiting. The transient responses are the same in both directions. Because only a simple proportional controller is used for the rate loop, there is some steady-state error in the rate-loop response, as shown in Fig. 7. For a type-1 control system, no steady-state error exists in the response of position loop if there is no external torque.

The memory used in this system is about 1.4K bytes and the maximum computing time in one control cycle is about 1.5 ms, as shown in Table I. In most servo control systems, some complex controllers are usually used to achieve the higher performance, such as a lead-lag compensator, a PID controller, or a second-order compensator. The on-line capability in the microcomputer used in this system is so small that a more complex compensator can also be implemented. In addition, the fully digital organization and microcomputer software control make it easy to link this system with other microcomputer systems. Thus, this system can be part of a computer network for adaptive control, automatic testing, automatic design, or other processes for industrial application needs.

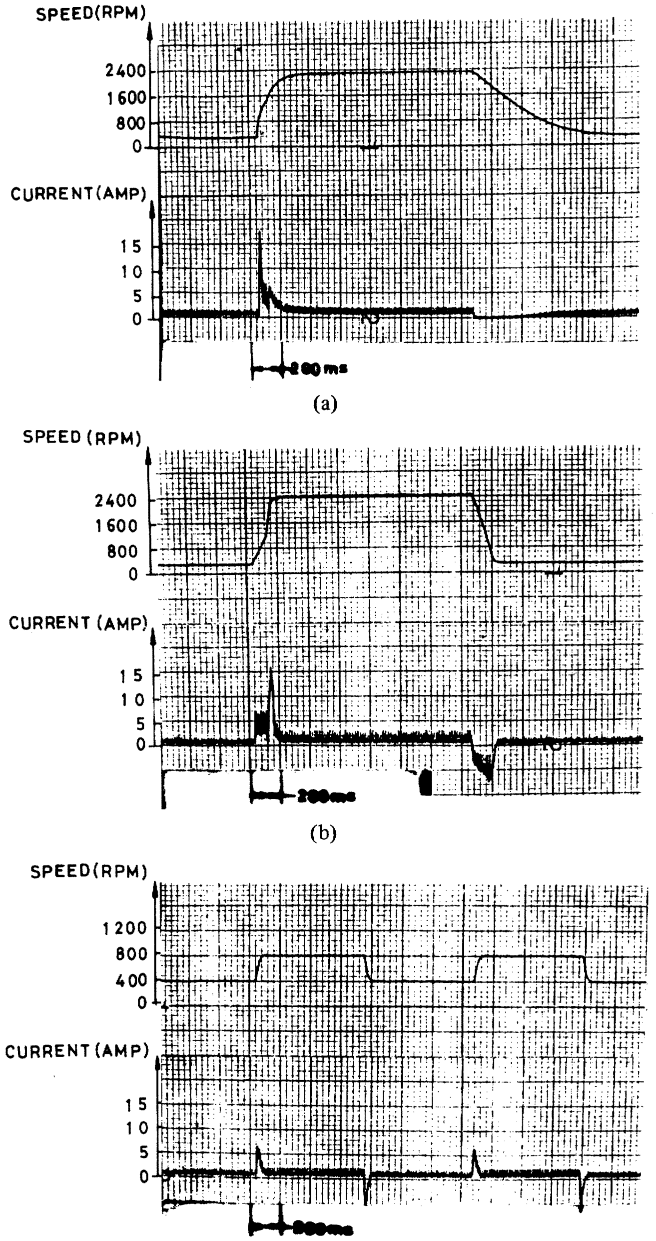

Fig. 6. Step response of the compensated thyristor dual converter with dc motor. (a) Without cascade nonlinear compensator; firing-angle command from 100° to 60°. (b) With cascade nonlinear compensator; voltage command from 6 V to 70 V. (c) With cascade nonlinear compensator; voltage command from 12 V to 24 V.

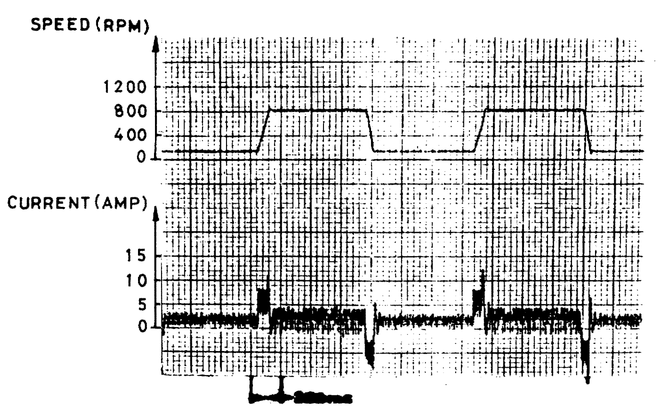

Fig. 7. Step response of rate loop; rate command from 180 rpm to 1400 rpm.

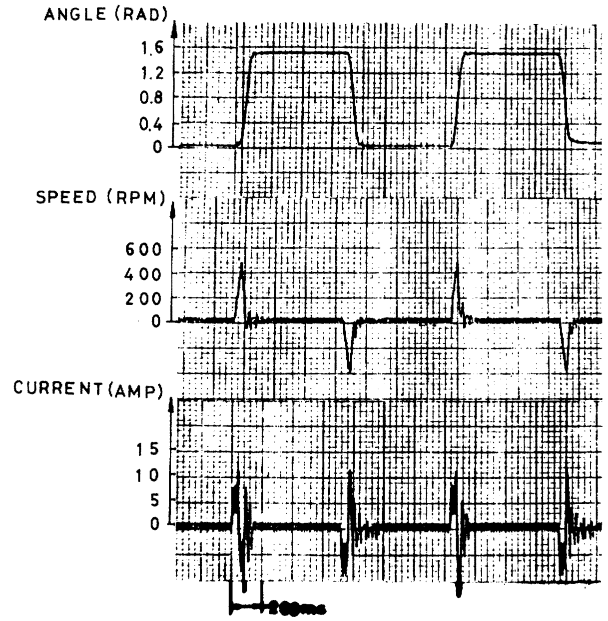

Fig. 8. Step response of position loop; position command from 0 rad to 1.57 rad.

TABLE I
LIST OF MEMORY AND TIME USED

	memory used(kbytes)	time used (ms)
position and rate compensation	0.41	1.05
cascade nonlinear compensation (including tables)	0.52	0.1
thyristor firing control (including tables)	0.2	0.4
initialization program	0 27	—
total	1.4	1.55
z 8 provided	2.0	—
sampling period	—	2.77
reserved for future use	0.6	1.22

VI. CONCLUSION

The quasi-linearization effect of a compensated thyristor dual converter based on the principle of cascade nonlinear compensation proposed by Tang, Lu, and Wu is confirmed by the experiment. Also, the equivalent effect of current limiting is possible through software control without using any current feedback.

With minimum hardware and good performance, this single-chip microcomputer design is suitable for a fast-response high-power dc servo system for industrial control.

REFERENCES

[1] T. Ohmae *et al.*, "A microprocessor-controlled fast-response speed regulator with dual-mode current loop for DCM drives," *IEEE Trans. Ind. Appl.*, vol. IA-16, pp. 388–394, May 1980.

[2] Y. T. Chan *et al.*, "A Microprocessor-based current controller for SCR-DC motor drivers," *IEEE Trans. Ind. Electron. Contr. Instrum.*, vol. IECI-27, pp. 169–176, Aug. 1980.

[3] J. B. Plant *et al.*, "Microprocessor control of position or speed of an SCR-DC motor drive," *IEEE Trans. Ind. Electron. Contr. Instrum.*, vol. IECI-27, pp. 228–234, Aug. 1980.

[4] P. C. Tang *et al.*, "A cascade nonlinear compensation of the thyristor dual converter for DC motor drives," to be published.

[5] P. C. Tang *et al.*, "Microprocessor-based design of a firing circuit for a three-phase full-wave thyristor dual converter," *IEEE Trans. Ind. Electron.*, vol. IE-29, pp. 67–73, Feb. 1982.