Single-Chip Microprocessor Control for Switched Reluctance Motor Drive

Hao Chen* and Jin-Woo Ahn**

Abstract - The paper introduces a switched reluctance motor drive system based on an 80C31 and an Intel 80C196KB single-chip microprocessor control. Advance schemes are used in turn-on and turn-off angles with the power converter's main switches during traction and regenerative braking. The principles of traction speed control and braking torque control are given. The hardware and software patterns in the 80C31 and the Intel 80C196KB single-chip microprocessor control system are also presented.

Keywords: switched reluctance, motor control, computer control, single-chip microprocessor

I. INTRODUCTION

A prototype controlled by the Intel 8031, and the Intel 8098 single-chip microprocessor was used for controlling the switched reluctance motor drive [1]. It was a kind of quasi-16-bit single-chip microprocessor: it has a 16-bit system bus and only an 8-bit address/data bus. The limited I/O interfaces limited the performance of the controlled switched reluctance motor drive, and now it is unavailable in the electronics market. A series of single-chip microprocessors are now common in market, such as the Intel, Philips, and Motorola series. The Intel 80C196 series single-chip microprocessor has the following features:

1) CHMOS technology, which aids in saving electric energy and enhancing the interference rejection;
2) High operational speed, which contributes to achieving real-time control;
3) Resource-rich software and hardware;
4) Low initial costs and low simulator costs.

Thus, to improve the performance of the switched reluctance motor drive and to reduce the costs of the drive, controlling the switched reluctance drive with Intel 80C196 series CPU is appropriate. The Intel 80C196KB-CPU is the cheapest of the series.

The costs of the switched reluctance motor drive depend on its scheme. The commutation strategy [2] and the certain variable speed control strategy [3][4] of the switched reluctance motor drive contribute to enhance performance-to-cost ratio. While the switched reluctance motor drive is applied to drive an electric vehicle, it could be operated during traction and braking. The controller of the switched reluctance motor drive could be implemented by low-cost hardware without the microprocessor [5], but the switched reluctance motor drive based on Intel 80C31 or Intel 80C196KB single-chip microprocessor control could have a high performance-to-cost ratio and could be used as the drive for electric vehicles with good performance in the transformation of traction/braking. This paper introduces switched reluctance motor drives based on the two types of the single-chip microprocessor and operates at the condition of traction/braking.

2. Variable-speed Control Strategy

In the switched reluctance motor drive system, the average electromagnetic torque, T_{em}, the average phase winding voltage, U, and the rotor speed, n, has the relationship

$$T_{em} = K_1 \frac{U^2}{n^2} \tag{1}$$

where K_1 is the coefficient relating to the structure parameters and the control parameters of the drive. So the variable speed control of the switched reluctance motor drive with constant electromagnetic torque or constant electromagnetic power could be achieved by regulating the average phase winding voltage.

The fixed angle PWM control strategy could be adopted in the developed switched reluctance motor drive based on the Intel 80C31 or the Intel 80C196KB single-chip microprocessor, as follows.

* Department of Automation, China University of Mining & Technology, Xuzhou, 221008, China and is now visiting Kyungsung University (chenhaocumt@163.net)
** Department of Electrical and Computer Engineering, Kyungsung University, Busan, 608-736, Korea (jwahn@ks.ac.kr.)
Received May 17, 2002 ; Accepted October 18, 2002

1) *At the condition of traction*: The turn-on and turn-off angle of the main switches in the power converter are fixed at an optimized value so that the phase windings could be supplied at the ascending region of the phase inductance. The triggering signals of the main switches in the power converter are modulated by the PWM signal so that the tractive velocity and the tractive power could be controlled by adjusting the duty ratio of the PWM signal.

2) *At the condition of braking*: The turn-on and the turn-off angle of the main switches in the power converter are fixed at an optimized value so that the phase current flows through the phase windings at the descending region of the phase inductance. The triggering signals of the main switches are also modulated by the PWM signal so that the braking torque could be controlled by adjusting the duty ratio of the PWM signal. The phase inductance is shown in Fig.1, where the maximum value of the phase inductance, L_{max}, is at the rotor position, θ_m, and the minimum value of the phase inductance, L_{min}, is at the rotor position, $\theta=0^0$ or θ_r.

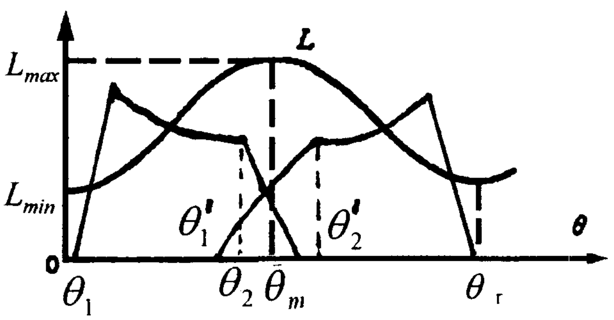


Fig. 1 Schematic diagram of phase inductance and phase current

At the condition of traction, the turn-on angle of the main switches could be postponed a certain angle, θ_a, based on the rotor position, $\theta=0^0$, to reduce the peak value of the phase current and ratings of the main switches:

$$\theta_1=\theta_a. \tag{2}$$

The main switches could be turned-off with a certain advance angle, θ_b, based on the rotor position, θ_m, to reduce the part of the braking torque while the flywheel current flows through the phase windings at the descending region of the phase inductance and to enhance the output

$$\theta_2=\theta_m-\theta_b. \tag{3}$$

At the condition of braking, the turn-on angle of the main switches could be advanced a certain angle, θ_c, based on the rotor position, θ_m, to satisfy the requirement of excitation:

$$\theta_1'=\theta_m-\theta_c. \tag{4}$$

The main switches could be turned-off with a certain postponed angle, θ_d, based on the rotor position, θ_m, to avoid the flywheel current flowing through the phase windings at the ascending region.

$$\theta_2'=\theta_m+\theta_d \tag{5}$$

The schematic diagram of the phase current at the condition of traction with the turn-on angle of the main switches, θ_1, and the turn-off angle of the main switches, θ_2, and at the condition of braking with the turn-on angle of the main switches, θ_1', and the turn-off angle of the main switches, θ_2', are shown in Fig.1.

The closed-loop speed control is implemented by the digital PID control algorithm, the rotor speed of the switched reluctance motor is given by the keyboard circuit or the variable resistance, and the digital rotor speed feedback value could be obtained by reading the interval time of the rotor position feedback signal. The period measured method is adopted, so the rotor speed of the motor is

$$n=\frac{\alpha_p f_0}{96\Delta N} \tag{6}$$

where f_0 is the frequency of the CPU crystal oscillator and ΔN is the count value in the time register while the motor is rotated a step angle degree, α_p. For the three-phase 6/4 structure switched reluctance motor, α_p is 30^0.

In the prototype, the incremental algorithm is adopted. The manipulated variable is the duty ratio of the PWM signal. The algorithm of the software follows

$$\Delta D=K_P(e_k-e_{k-1})+K_I e_k +K_D(e_k-2e_{k-1}+e_{k-2}) \tag{7}$$

where ΔD is the increment of the duty ratio, e_k, e_{k-1}, and e_{k-2} is the deviation between the given value of the rotor speed and the measured value of the rotor speed at the moment of t_k, t_{k-1}, and t_{k-2}, respectively, K_P is the proportional coefficient, K_I is the integral coefficient, and K_D is the differential coefficient. The manipulated variable is

$$D_k=\Delta D+D_{k-1} \tag{8}$$

where D_k is the duty ratio at the moment of t_k, and D_{k-1} is the duty ratio at the moment of t_{k-1}.

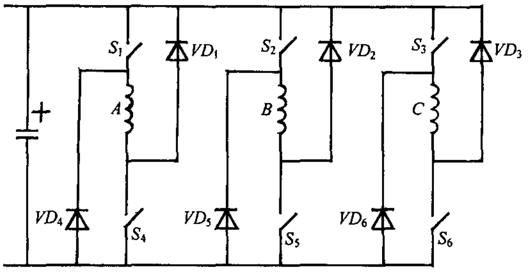


Fig. 2 Main circuit of the power converter

3. Component parts

The developed switched reluctance motor drive prototype is a three-phase 6/4 structure system, which consists of the three-phase 6/4 structure, the three-phase asymmetric bridge power converter shown in Fig.2, and the single-chip microprocessor controller.

In the developed prototype, the basic triggering pulse of the main switches in the power converter, S_1, S_2, and S_3 are modulated by the PWM signal.

Fig.3 gives the scheme of the rotor position detector for the prototype. The slotted disk is four teeth, each 45^0 wide, four slots, each 45^0 wide, and three transducers to be installed with a 30^0 interval. The output signals of the transducers used as the commutation signals and the rotor speed feedback signals are shown in Fig.4.

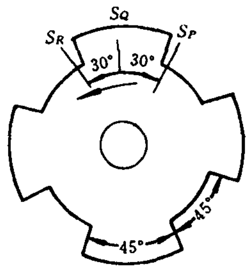


Fig. 3 Rotor position detector

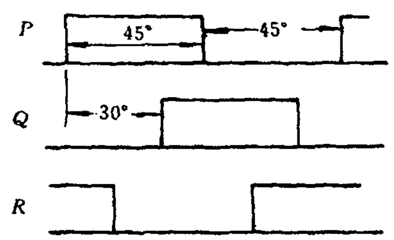


Fig. 4 Output signals of the transducers

3.1 Intel 80C196KB single-chip microprocessor control system

The block diagram of the system with the Intel 80C196KB-CPU is shown in Fig.5. The controller has the following components: (1) the single-chip compute part includes (a) one Intel 80C196KB-CPU, (b) one RAM-6264, (c) one EPROM-2764, (d) the 4×4 keyboard circuit, and (e) the speed and fault display circuit; (2) the control part includes (a) the rotor position detecting circuit, (b) the control logic circuit, (c) the current/voltage measurement and protective circuit; and (3) the main switches' gate drive circuit. The microprocessor part and the control part are isolated by the optocouplers. The main switches' gate drive circuit acts as the tie and the electric isolator between the control part and the power converter.

A PWM signal output unit is controlled by an I/O controller IOC2.2. But the frequency of the PWM signal, f_p is determined by the frequency of the CPU crystal oscillator, f_0, such that f_0 = 12 MHz, f_p = 23.6 KHz while IOC2.2 = 0, or f_p = 11.8 KHz while IOC2.2 = 1. The frequency of the PWM signal is too high to control the rotor speed and the torque of the switched reluctance motor. A special circuit, which is designed to connect the T_2CLK of the CPU, acts as the clock pulse source of T_2, so the frequency of the PWM signal given at the P2.5 of the CPU is set at 2.5 KHz.

The output signals of the rotor position detector, P, Q, and R, are used as the input signals of the high-speed input interface on the CPU, HSI.0, HSI.1, and HSI.2, respectively. The high speed output interfaces on the CPU, HSO.0, HSO.1 and HSO.2, are used as the basic triggering pulse of the three-phase main switches, respectively. The commutation of the switched reluctance motor could be implemented by the high- speed interrupt while the P, Q and R signals are varied with the rotation of the motor. The output signals at HSO.0, HSO.1, and HSO.2 are integrated with the PWM signal by the control logic circuit at P2.5 so that the PWM signal modulation in the basic triggering pulse of the main switches, S_1, S_2 , and S_3, could be achieved.

3.2 Intel 80C31 single-chip microprocessor control system

The block diagram of the system with the Intel 80C31-CPU is shown in Fig.6. The output information of the rotor position isolation and enlargement in the device could be used to control the conduction and the closing of the main switches in the power converter so that the motor could be operated by the power supply with certain phase sequential current. The electric energy generated by the power supply is converted into mechanical energy by the motor's magnetic field so that the motor could be driven. A "Traction/Braking" stick could be used to control the operation of the motor so that the traction control and the regenerative braking control [6] of the drive could be implemented.

The protection circuit could be used to implement voltage protection and current protection of the power switch components in the power converter to prevent drive overload from damaging the power converter. The "Variable-speed control" stick could be used to adjust the velocity of the motor. All these features could be implemented by the single-chip microprocessor control system with an 80C31-CPU, a program storage, a watchdog chip, an A/D converter, and a series of the logic chip. The analog voltage reference for the reference speed signal could be set up by the variable resistance, while the contact of the variable resistance could be moved with synchronous adjustment of the stick. The reference could be transformed into the digital signals by the A/D converter and could be used as the basis for the variable-speed signal output of the 80C31-CPU.

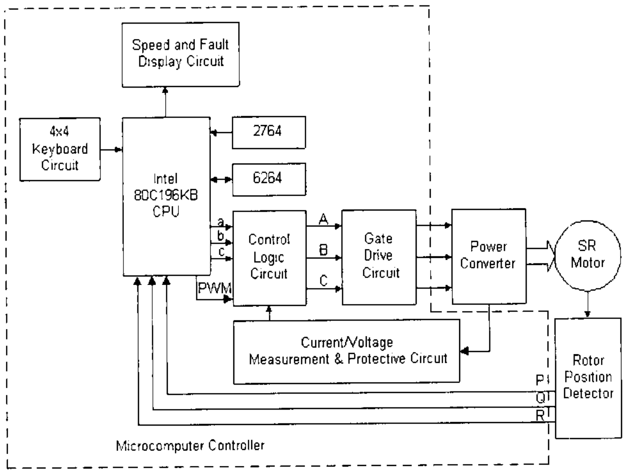


Fig. 5 The block diagram of the switched reluctance motor drive with the Intel 80C196KB-CPU

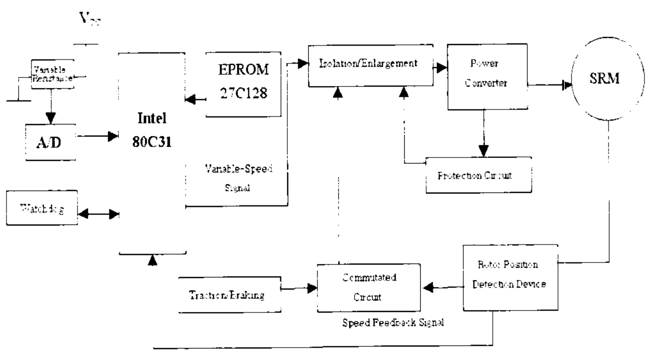


Fig. 6 The block diagram of Switched Reluctance motor drive with the Intel 80C31-CPU

Since the turn-on and turn-off angle of the power converter's main switches are fixed, the output signals of the rotor position detector are used to control the turn-on and the turn-off angle of the per phase main switches in the power converter with handled, isolated and amplified. This efficiency contributes to the implementation of the commutation control of the drive system by using the hardware without occupying the resources of the CPU.

In the Intel 80C31 single-chip microprocessor, interfaces P12, P13, and P14 of the Intel 80C31-CPU are used to measure the frequency of the output signals of the rotor position detector and to attain the rotor speed feedback of the motor. The given rotor speed is supplied by the variable resistance and the A/D converter. Comparing the given rotor speed and the rotor speed feedback, interface P15 of the Intel 80C31-CPU supplies the PWM signal, and the duty ratio of the PWM signal is regulated by the software.

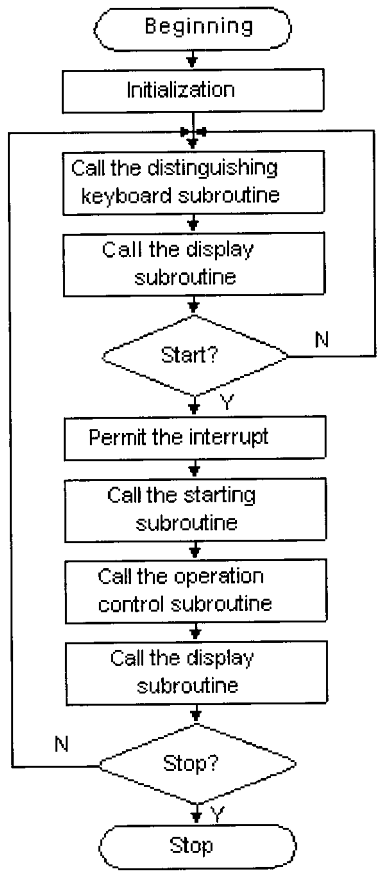


Fig. 7 Flow diagram of the main procedure for the Intel 80C196KB-CPU

4. Software

The control software of the Intel 80C196KB control system is compiled by the PL/M96 language. Fig.7 illustrates the flow of the main procedure and two interrupt procedures. The commutation of the motor can be achieved by the HSI interrupt procedure, testing the variation of the rotor position feedback signals. The over-current signal, the over- or under-voltage signal and the over-heating signal are watched by the fault interrupt procedure, and the fault codes are also displayed. The 0 ~ 9 numeric keys and six other functional keys are distinguished by the keyboard subroutine. When the motor is motionless, the rotor position is stochastic. At an arbitrary rotor position, self-starting of the motor can be achieved by the starting subroutine. The PID control algorithm of the rotor speed is implemented by the operation control subroutine. The function of the rotor speed display can be fulfilled by the display subroutine.

The control software of the Intel 80C31 control system is compiled by the PL/M51 language. The software of the 80C31 single-chip microprocessor control system consists of the main procedure and the function subroutines. The main procedure includes initialization and calling the function subroutines, and the flow diagram of the main procedure is shown in Fig.8. In the initialization, the variates could be initialized, the operational method of the external interface could be selected, and the function components inside the CPU could be initialized. The function subroutines are the measuring speed subroutine and the fuzzy algorithm subroutine. In the measuring speed subroutine, the real speed of the motor could be calculated by measuring the frequency of the rotor position signals. Increase of PWM signal's duty ratio could be attained by the calculation of the fuzzy algorithm subroutine based on the given speed and the speed feedback.

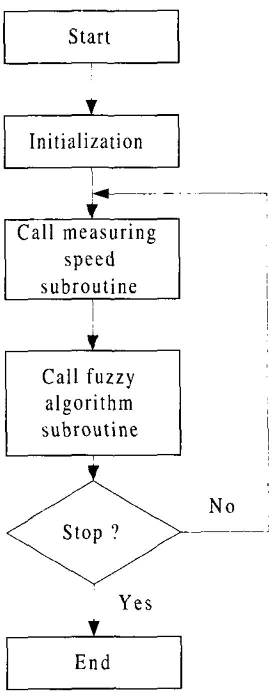


Fig. 8 Flow diagram of the main procedure for the Intel 80C31-CPU

5. Experiments

The rated output of the switched reluctance motor is 7.5 KW while the rated rotor speed is 1110 r/min. The variable speed range is from 100 r/min to 2220 r/min, while the rated constant output traction torque is 60.2 N.m from 100 r/min to 1110 r/min, the rated constant output is 7.5 KW from 1110 r/min to 2220 r/min, and the starting torque is 126.4 N.m. The insulated-gate bipolar transistors (IGBT) are used as the main switches of the power converter. The DC supply voltage of the power converter is 88V. The frequency of the PWM signal is 5.0KHz.

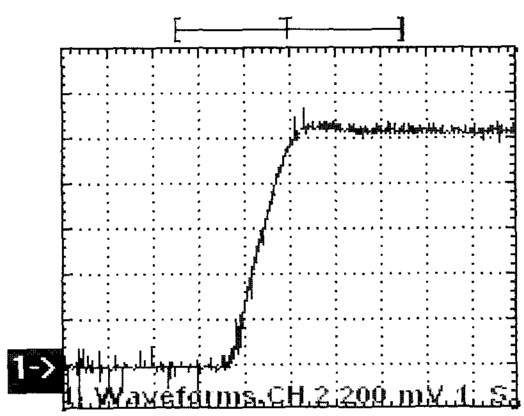
The turn-on and the turn-off angle of the main switches in the power converter are fixed at the optimized value shown in Table 1, while the prototype could be operated at the condition of traction and at the condition of braking.

Table 1 Turn-on angle and turn-off angle

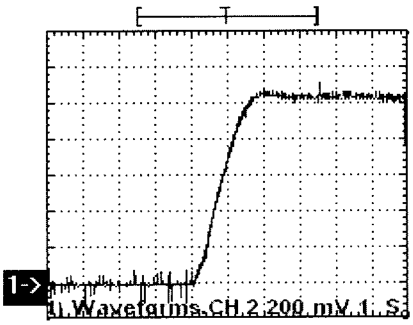
Condition	Turn-on angle	Turn-off angle
Traction	-7.5^0	37.5^0
Braking	22.5^0	67.5^0

Fig.9 gives the rotor speed curves at the condition of starting of the prototype based on the Intel 80C196KB and the 80C31 single-chip microprocessor control, respectively, while the given rotor speed is 1200 r/min. Fig.10 gives the rotor speed curves of the prototype based on the 2 control strategies, while the given rotor speed is 1200 r/min and the load, 55.7 N.m, is removed. Fig.11 gives the phase current waveform of the prototype based on the 2 control strategies, while the condition of the prototype could be changed from the rated traction (55.7 N.m, 1200r/min) to braking with the braking torque being 20.0 N.m.

The prototype based on the 2 control strategies are shown to have well dynamic performance.



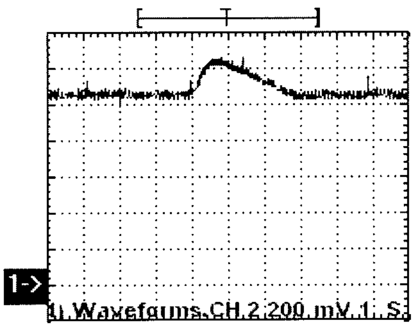
a) Based on the Intel 80C196KB single-chip microprocessor



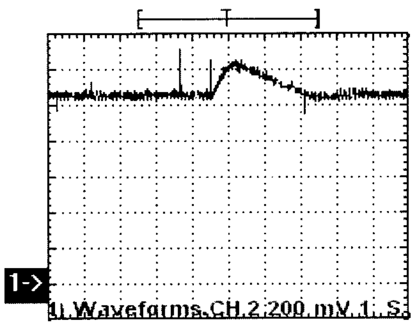
b) Based on the 80C31 single-chip microprocessor

Scale: Abscissa: 1.0 s/div. Ordinate: 230 r/min/div.

Fig. 9 Rotor speed curves at the condition of starting



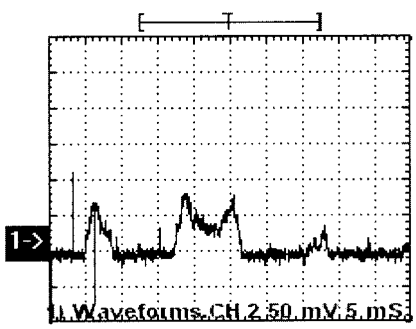
a) Based on the Intel 80C196KB single-chip microprocessor



b) Based on the 80C31 single-chip microprocessor

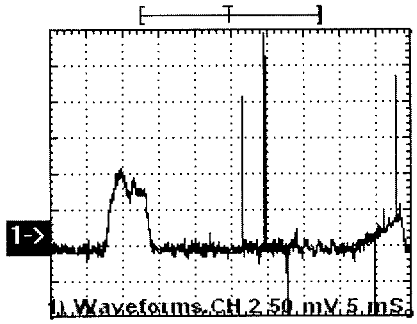
Scale: Abscissa: 1.0 s/div. Ordinate: 230 r/min/div.

Fig. 10 Rotor speed curves while the load is removed



Scale: Abscissa: 5.0 ms/div. Ordinate: 110.0 A/div.

a) Based on the Intel 80C196KB single-chip microprocessor



b) Based on the 80C31 single-chip microprocessor

Scale: Abscissa: 5.0 ms/div. Ordinate: 90.0 A/div.

Fig.11 Phase current waveform

6. Conclusions

Results of the prototype test indicate that the electric vehicle drive application is an ideal use of switched reluctance motor based on the Intel 80C196KB or the Intel 80C31 single-chip microprocessor. Advantages include reliability and a high performance-to-cost ratio. Not only this system could be applied to the drive system of the whole series of electric vehicles, but it could also be spread over the switched reluctance motor drive system in other applications, such as conveyors, mining machines and so on.

Acknowledgments

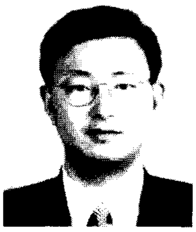
The authors would like to thank the following sponsors for their support of this work: Korea Science and Engineering Foundation, grant No. R01-2001- 000300-0; Brain Busan 21 Project in 2002; National Natural Science Foundation of China, contributing sponsor of grant No. 60004008; and Natural Science Foundation of Jiangsu Province of China, sponsor of the 2001 Youth Science & Technology Creative Talent Foundation under Grant No. BK2001411.

References

[1] P. Jiang, H. Zhang, and Y. Jin, "A control system of switched reluctance drives based on MCS-8089 microprocessor," *Journal of Nanjing University of Aeronautics & Astronautics*, vol. 26, no. 2, April 1994, pp.160-167.

[2] H. Chen, J. Jiang, D. Liu, and X. Zhu, "Commutation of switched reluctance motor drives," in *Proceedings of the 7th International Power Electronics & Motion Control Conference*, vol.2, 1996, pp.443-446.

[3] H. Chen and G. Xie, "Adjustable-speed control of switched reluctance motor drive," in *Proceedings of the 8th International Power Electronics & Motion Control Conference*, vol.5, 1998, pp.56-59.
[4] H. Chen and G. Xie, "Theory and practice of PWM control for switched reluctance motors," *Journal of China University of Mining & Technology*, vol.26, no.3, 1997, pp.23-27.
[5] H. Chen and G. Xie, "The hardware controller of switched reluctance motor drive," *Proceedings of 3rd International Symposium on Advanced Electromechanical Motion Systems*, vol.1, 1999, pp.561-566.
[6] H. Chen and C. Zhang, "A new braking control strategy for switched reluctance motor drive," in *Proceedings of the 9th International Power Electronics & Motion Control Conference*, vol.5, 2000, pp.182-185.



Hao Chen

He was born in Nanjing, China, in 1969. He received the B.S. and Ph.D. degrees from the Dept. of Automatic Control, Nanjing University of Aeronautics & Astronautics, Nanjing, China, in 1991, and 1996, respectively. He joined China University of Mining & Technology, Xuzhou, China, as an associate professor in the Department of Automation in 1998, and as a Professor since 2001. He was a visiting professor at the Department of Electrical & Computer Engineering, College of Engineering, Kyungsung University, Busan Korea from Feb. 2002 to May 2002. He is the author of one book and more than 70 papers. His current research interests are motor control, switched reluctance drives, electric vehicles, electric traction, servo drives, power converters, and DSP control .

Professor Chen is a Member of the International Compumag Society and a Member of the Chinese Automation Society.

Tel: +86-516-3884587

Jin-Woo Ahn

He was born in Busan, Korea, in 1958. He received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from Pusan National University, Busan, Korea, in 1984, 1986, and 1992, respectively.

He has been with Kyungsung University, Busan, Korea, as an associate professor in the Department of Electrical and Computer Engineering since 1992. He was a visiting researcher in the Dept. of EE, Glasgow University, U.K, in 1995, and of the University of Wisconsin-Madison, USA, in 1998. He is the author of five books and more than 100 papers. His current research interests are motor drives and electric vehicle drives.

Dr. Ahn is a lifetime member of the Korean Institute of Electrical Engineers, a member of the Korean Institute of Power Electronics, and a senior member of the IEEE.

Tel: +82-51-620-4773