A New Space Vector Random PWM Scheme for Induction Motor Drives

°*Hoe-Geun Kim *Seok-Hwan Na *Young-Cheol Lim **Young-Gook Jung

*Dept. of Electrical Engrg. (RRC-HECS) Chonnam National University, Yong Bong Dong, Buk- Gu, Kwang-Ju, REPUBLIC OF KOREA

**Dept. of Electrical Engrg. Daebul University, 72-1,Sanho-ri, Samho-myen,Youngam-Kun, Chonnam, REPUBLIC OF KOREA (e-mail:jyg@mail.daebul.ac.kr)

Abstract - The RPWM (Random Pulse Width Modulation) is a switching technique to spread the voltage and current harmonics over a wide frequency area. By using randomly changing switching frequency of the inverter, the power spectrum of the electromagnetic acoustic noise can be spread to the wide-band area. The wide-band noise is much more comfortable and less annoying than the narrow-band one. So, the RPWM has been attracting interest as an excellent method for the reduction of acoustic noise on the inverter drive system. In this paper a new RPPWM (Random Position Space Vector PWM) is proposed and implemented. Each of three phase pulses is located randomly in each switching interval. Along with the randomization of PWM pulses, the space vector modulation is also executed in the C167 micro-controller. The experimental results show that the voltage and current harmonics are spread to a wide band area and that the audible switching noise is reduced by the proposed RPPWM method.

1.INTRODUCTION

The PWM (Pulse Width Modulation) method is one of the most important factors that increase the performance of the inverter drive system. Up to now, studies on PWM have been mainly focused on the harmonic loss and efficiency of the drive system[1]. Recently, due to the increase of the interest in the improvement of work environment, many attempts have been made to reduce the noise emitted from the motor. The mechanical noise is mainly from the cooling fan in the motor and it is relatively broad band low frequency components associated with motor speed[2]. In contrast, the electromagnetic noise due to the PWM switching is generated with narrow band high frequency, which causes communication obstacle and unpleasant high frequency audible noise. In general, the PWM inverter is operated with a constant switching frequency. As the carrier frequency increases, the current harmonics shift to a higher frequency and the magnitude of the harmonics are reduced.

As a result of psychological study, it is known that the narrow band noise is more unpleasant than the broad band one[3]. Several studies related to the technique for reducing this audible noise have been reported. They include ultrasonic PWM switching method[4],[5] and SHE (Selected Harmonic Elimination) PWM method[6].

Recently, a new PWM method for noise reduction, RPWM method has been introduced, which uses broad band switching frequency to spread the noise spectrum instead of using a specific fixed switching frequency. The RPWM method is operated with different carrier switching frequencies at each switching time to spread the spectrum of the voltage, current and noise. The RPWM method is attracting interest as an excellent method for noise reduction because of its simple algorithm. There are several ways to implement the RPWM; 1) randomizing the triangular carrier frequency[7],[8], 2) randomizing the period of modulation intervals[9], 3) leading or lagging the pulse position randomly in each modulation interval[10].

In this study a new RPWM is proposed. Each of PWM pulses can be located in any place in each modulation interval as long as they do not corrupt the switching sequences for the space vector modulation. For the implementation of the proposed method, a 16-bit micro-controller C167 was used. The duty ratio is calculated based on the SVM (Space Vector Modulation) method and then, each pulse is located in a randomly selected position. The experimental results show that the spectrum of the voltage and current is spread over a wide frequency range and the audible switching noise is reduced effectively by using the proposed RPWM.

2.RANDOM PWM

The power[11] carried by the k-th harmonic P_k is propotional to the following function of the random variable θ_n and N:

$$P_k \propto \left| E\left\{ \sum_{n=1}^{N} \bar{a}_n \frac{\sin\left(\pi \frac{k}{N} \bar{a}_n\right)}{\pi \frac{k}{N} \bar{a}_n} \cdot e^{-j2\pi k/Nn} e^{-j2\pi k/N\theta_n} \right\} \right|^2$$

(1)

Where E{.} denotes statistical expectation, $\bar{a}_n$ is the duty ratio of the switching signal in the n-th switching interval, and θ_n is a random variable representing the position of the switching pulse in the n-th interval, and N is the number of switchings in a cycle.

If θ_n is random variable, (1) is given by

$$P_k \propto \left| \sum_{n=1}^{N} \bar{a}_n \frac{\sin\left(\pi \frac{k}{N} \bar{a}_n\right)}{\pi \frac{k}{N} \bar{a}_n} \cdot e^{-j2\pi k/Nn} \cos\left[\pi \frac{k}{N}\left(1 - \bar{a}_n\right)\right] \right|^2$$

(2)

3.RANDOM POSITION SPACE VECTOR PWM

In this study, a new RPWM technique is proposed to randomize the pulse position. This is similar to LLPWM (Lead-Lag PWM) method[10]. LLPWM places the pulses on the lead position or lag position alternatively. But in the proposed RPPWM, each three phase pulse can be located in any place in each modulation interval as far as they do not corrupt the switching sequences for the space vector modulation. Due to the high degree of freedom in locating the pulse position, the spectrum of the harmonics can be shaped flatter compared to that of the conventional method.

The switching functions of conventional SVPWM and the proposed RPPWM are shown in Fig. 1(a) and in Fig. 1(b). In SVPWM, pulses are placed in the center of switching interval, but in RPPWM, pulses are placed at a random position at each modulation interval.

3.1 Random Number Generation

To randomize the pulse position, a random function may be used which is shipped with the compiler dependent upon a micro-controller. A good random generator should be able to 1) generate random numbers over a wide range, 2) generate uniformly distributed random numbers, and 3) avoid periodicity. In some cases, however, these requirements are not satisfied. Therefore, a user defined portable random number generator is useful.

A positive integer random number j_{ran} ranged 0 to i_m can be generated by

$$j_{ran} = (j_{ran} \cdot i_a + i_c)\%i_m \qquad (3)$$

And a floating point random number r ranged 0 to 1 is generated by

$$r = (float)j_{ran}/(float)i_m \qquad (4)$$

And an integer random number ranged j_{lo} to j_{hi} is generated by

$$j = j_{lo} + ((j_{hi} - j_{lo} + 1) \cdot j_{ran})/i_m \qquad (5)$$

In (3)-(5), i_a, i_c and i_m are the selected coefficients and called the multiplier, increment and modulus, respectively. j_{lo} and j_{hi} are minimum and maximum values of the generated random number, respectively. Now this random number function can be used in any other processor and micro-controller. But i_a, i_c, i_m should be selected carefully[11]. i_c must be a prime number, and i_c and i_m should satisfy the following relationship[13]. Also, table 1 shows the coefficients i_a, i_c, i_m as examples for generating the random numbers.

$$i_c \approx (\frac{1}{2} - \frac{1}{6}\sqrt{3})i_m \qquad (6)$$

The random distributions are considered to be improper or proper as shown in Fig.2. Fig.2 (a) shows random distributions by choosing the proper coefficients. Each generated random number is approximately five hundred. It means that each random number is generated evenly, if the coefficients i_a, i_c, i_m are properly selected.

3.2 Space Vector Modulation

SVM(Space Vector Modulation) is used widely in inverter drive systems. Reportedly, SVM is an excellent voltage modulation method, because it can use large available d.c link voltage. In this study, space vector modulation method is the basis of implementation of the proposed RPPWM. In Fig. 3, the reference voltage vector U can be decomposed into U_1 and U_2. If the angle of vector U is α, the duration time T_1, T_2 and T_0 are expressed by

$$T_1 = T \cdot M \cdot \frac{\sin(60° - \alpha)}{\sin 60°}$$
$$T_2 = T \cdot M \cdot \frac{\sin \alpha}{\sin 60°} \qquad (7)$$
$$T_0 = T - T_2 - T_1$$

Where T_1 = the duration time of the vector U_1,

T_2 = the duration time for the vector U_2 , T_0 = the duration time for the zero vector.

3.3 Randomizing the Pulse Position

Based on the SVM, the duty ratio of each pulse can be calculated and then the pulse position is determined by the random number. Each range of pulse position is different according to sector of the voltage vector. In case that the reference voltage vector is in sector 1, it is implemented by the composition of the vector U_1 and U_2. Fig. 4 shows the relative position of pulses associated with each phase. In this case, phase A pulse can be located in any place in a modulation interval. But phase B pulse must be in the range of the phase A pulse position, and phase C pulse must be in the range of phase B pulse position. If any pulse does not obey this rule, inappropriate switching occurs.

3.4 Pulse generation using CAP/COM (Capture/Compare) timer

PWM generator is required to gate the power switching devices at the accurate time according to pulse position and duty ratio calculated by space vector modulation. In this paper, the pulse positions can be determined by double register compare mode of CAP/COM units built in micro-controller. For the purpose of determining the pulse positions, CAP/COM units built in micro-controller writes down the ON time and OFF time of pulse in register X and Register Y. Fig.5 shows the generation method of PWM pulse position using double register compare mode of CAP/COM timer built in micro-controller

4.SYSTEM CONFIGURATION

The implemented RPPWM system is consist of C167 micro-controller board including the control program and host program, IPM (Intelligent Power Module) inverter, 1.5kw three phase squirrel cage induction motor. Fig. 6 shows the schematic diagram of the proposed RPPWM based inverter system and table 2 shows the parameters used in experimental system.

As a main controller, C167 micro-controller (Siemens co.) was used. The micro-controller C167 has a 16-bit RISC architecture and shows good performance in controlling d.c motors, 3-phase brushless motors, or 3-phase induction motors. The proposed algorithm for the RPPWM is executed in the C167 controller and the pulse signals to gate the IPM are generated through the output port of the C167 micro-controller. It means that PLD(Programmable Logic Device) is not needed to implement the logic circuits for the pulse signals. The C167 uses the internal CAP/COM (capture/compare) units to produce the pulse signal, which gives low cost implementation of the inverter drive system. The software is burned on the flash ROM for the standalone operation. However, the C167 controller can be connected to the host computer via RS-232 serial communication for the final control of the system or for the monitoring of the system. Table 3 shows parameters transferring between host PC and C167 micro-controller. The host program is operated in Windows 98/NT and MS-Visual BASIC 5.0 is used as a program complier. User interface of the developed host program is shown in Fig.7. The host program controls not only running/ stopping of motor but also parameters for serial communication. Fig. 8(a) and Fig. 8(b) show the experimental SVM pattern and RPPWM pattern , respectively, which are measured by using logic analyzer (Pod-A-Lyzer8020).

5.EXPERIMENTAL RESULTS

In measuring the total noise including the mechanical noise generated by motor drives, it is common that the system has to be operated under the condition of rated load and speed. However, in this study, we are interested in the electromagnetic switching noise generated by inverter switching device, not in the mechanical noise. So, experiment was done under the condition of no load. The noise is measured in the anechoic chamber that is designed for the measurement of motor noise. The noise spectra are measured from the two points, 1m above the motor, and 1m in front of the motor shaft.

5.1 Voltage and Current Spectrum

By using the symmetrical SVM in Fig. 4(a) and the RPPWM method in Fig. 4(b), Fig. 9(a) and Fig. 9(b) show the experimental waveforms of inverter output voltage and current under the condition of no load, 40Hz reference speed and 3kHz switching frequency. Under the same condition as Fig. 9, Fig. 10 and Fig.12 show the simulation results for spectrum analysis of inverter output voltage and current. And, Fig. 11, Fig.13 and Fig.14 show experimental spectrum results for voltage, current and audible switching noise. First of all, voltage and current spectrum of the symmetrical SVM as shown in Fig.10(a), Fig.11(a) and Fig.12(a), Fig.13(a), the most dominant discrete components of harmonics appear around twice the switching frequency range. The second dominant discrete components of harmonics exist around the switching frequency range.

In case of Fig.10(b), Fig.11(b) and Fig.12(b), Fig.13(b), voltage and current spectrum of the proposed RPPWM, it shows that the discrete components of the harmonics are considerably reduced around all the switching frequency range, twice the switching frequency range and the triple switching frequency ranges.

5.2 Noise Spectrum

Fig. 14 shows the spectrum of the audible switching noise with (a)symmetrical SVM and (b)RPPWM under the condition of no load, 40Hz reference speed and 3kHz switching frequency. In the case Fig.14(a), the most dominant components of noise appear in twice the switching frequency, while second dominant components of noise exist around the switching frequency. Especially, there are discontinuous spectrum for switching noise causing unpleasant and uncomfortable feeling. Also there are noise components at 750Hz and 1.8KHz which are not concerned about the switching frequency.

Compared with Fig.14(a), the case Fig.14(b) shows that a specific fixed switching frequency is spread into wide band area. It means that the audible switching noise is reduced by the proposed RPPWM. Also the magnitude of noise around the switching frequency is slightly reduced, and that of the switching frequency is considerably reduced. However, noise component of 750Hz is quite increased because the RPPWM can cause the mechanical resonance in case the natural frequency of machine is superposed.

Fig.15 shows noise spectrum in case of f_0=40Hz, f_{sw}=4kHz. Although the RPPWM is accomplished, the total sound energy generated by the machine is not reduced. But the spectrum of the noise is now spread to create a more appealing, less annoying sound. Fig.16 and Fig.17 show the spectrum of the noise in case of f_0=60Hz, f_{sw}=3kHz and f_0=70Hz, f_{sw}=3kHz, respectively.

6.CONCLUSIONS

A new random position space vector PWM is proposed and implemented in this study. In this proposed RPPWM, each of 3 phase pulse can be located in any place in each modulation interval as far as they do not corrupt the switching sequences for the space vector modulation. Along with the randomization of PWM pulses, the space vector modulation is also executed in the C167 micro-controller. Due to the high degree of freedom in locating the pulse position, the spectrum of the harmonics can be shaped flatter compared with the SVPWM. The experimental results show that the spectrum of the voltage is spread over a wide frequency range and the audible switching noise is reduced effectively by using the proposed RPPWM.

This work was supported by the RRC-HECS, CNN under grant 98-01

REFERENCES

[1] MURPHY, J.M.D., and EGAN, M.G. :'A Comparison of PWM strategies for inverter-fed induction motors', IEEE Trans. Industry Applications,1983, 19(3), pp.363-369.

[2] YANG, S. J.: 'Low-noise electrical motors'(Clarendon Press, Oxford, 1981)

[3] KRYTER, K. D.: 'The effects of noise on man'(Academic Press, 1985)

[4] GRNAT, D. A.: 'PWM AC motor drive employing ultrasonic carrier', IEE Power Electronics and Variable Speed Drives Conference,PEVD'95, 1984, pp. 237-240.

[5] Holtz, J., LAMMERT, P., and LOTZKAT,W.: 'High-speed drive system with ultrasonic MOSFET PWM inverter and single-chip microprocessor control', IEEE Trans. Industry Applications, 1987,23(6), pp. 1010-1015.

[6] TAKAHACHI, I., and MOCHIKAWA.H.: 'Optimum PWM waveforms of an inverter for decreasing acoustic noise of an induction motor', IEEE Trans. Industry Applications,1986, 22(5), pp.828-834.

[7] HABETLER, T. G., and DIVIAN, D. M.: 'Acoustic noise reduction in sinusoidal PWM drives using a randomly modulated carrier', IEEE Trans. Power Electronics, 1991,6(3), pp. 356-363.

[8] NA, S. H., LIM, Y. C., PARK, J. K., and YANG, S. H. :'Triangular carrier frequency modulated random PWM', The International Conference on Electrical Engineering, ICEE'98,1998, pp. 315-318.

[9] PEDERSEN, J. K., and BLAABJERG,F.: 'Digital quasi-random modulated SFAVM PWM in an AC-drive system', IEEE Trans. Industry Applications, 1994,41(5), pp518-525.

[10] KIRLIN, R. I., KWOK, S., LEGOWSKI, S., and TRZYNADLWSKI, A. M.: 'Power spectra of a PWM inverter with randomized pulse position', IEEE Power Electronics Specialist Conference, PESC'93, pp. 1041-1047.

[11] TRZYNADLOWSKI, A. M., BLAABJERG, F., PEDERSEN, J. K., KIRLIN, R. L., and LEGOWSKI S.: 'Random pulse width modulation techniques for converter-fed drive systems- A Review,' IEEE Trans. Industry Applications, 1994,30(5), pp.1166-1174

[12] PRESS, W. H., FLANNERY, B. P., TEUKOLSKY, S. A., and VETTERLING, W. T. :'Numerical Recipes in C: The Art of Scientific Computing'(New York: Cambridge University Press, 1988).

[13] KNUTH, D. E.: 'Semi-numerical Algorithms' (Addison Wesley, 1981 2nd edn.)

Table 1 Constants for portable random number generators

Overflow at	i_m	i_a	i_c
2^{20}	6075	106	1283
2^{21}	7875	211	1663
2^{22}	7875	421	1663
2^{23}	11979	430	2531
	6655	936	1399
	6075	1366	1283
2^{24}	53125	171	11213
	11979	859	2531
	14406	967	3041

Table 2 Experimental parameters

Micro-controller	C167-20MHz(Siemence)
IPM	PMC20U060 600V/20A
PWM	SVPWM / RPPWM(3KHz~4KHz)
Motor	Three phase squirrel cage Induction Motor
Motor parameters	Rating : 2hp 200V/60Hz Stator resistance : 3.35 ohm Rotor resistance : 1.99 ohm Inductance : 163.73mH Leakage inductance : 6.94mH Inertia factor : 0.1kgm^2

Table 3 Parameters transferring between host PC and C167

From host PC to C167	From C167 to Host PC
1.Motor reference speed 2.Switching frequency 3.PWM method (SVPWM,RPPWM)	1.Rotation speed of reference vector 2.Position of reference vector 3.Switching frequency 4.Operating PWM method

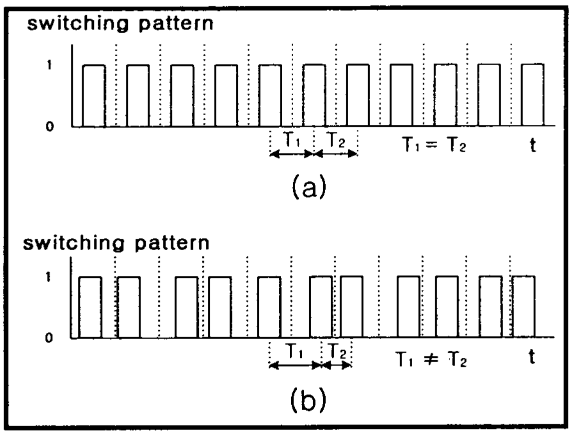
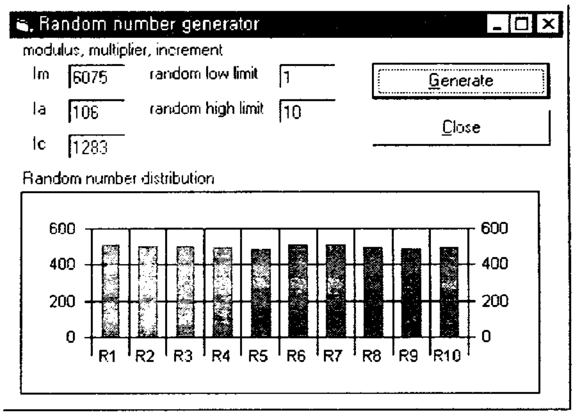
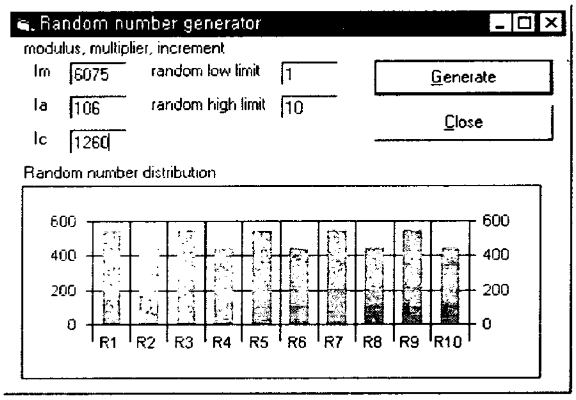


Fig. 1 Switching functions

(a) Conventional SVPWM (b) Proposed RPPWM



(a)



(b)

Fig. 2 Random distributions along with chosen coefficients for the random number generators

(a) Properly chosen coefficients (I_m= 6075, I_a= 106, I_c= 1283)

(b) Improperly chosen coefficients (I_m= 6075, I_a= 106, I_c= 1260)

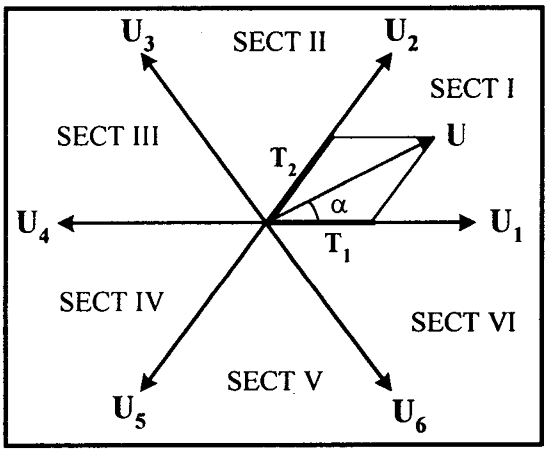


Fig. 3 Diagram for space vector modulation

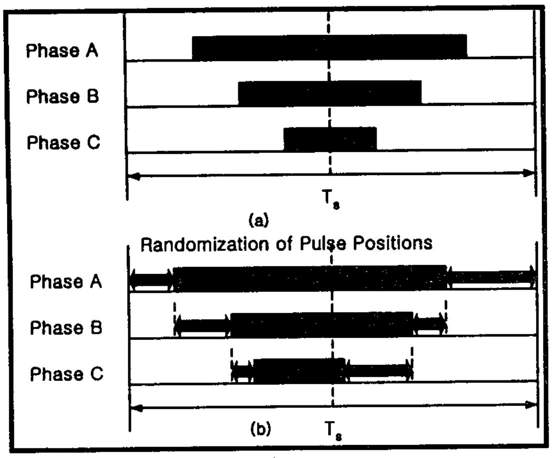


Fig. 4 PWM pulse positions

(a) Conventional SVPWM (b) Proposed RPPWM

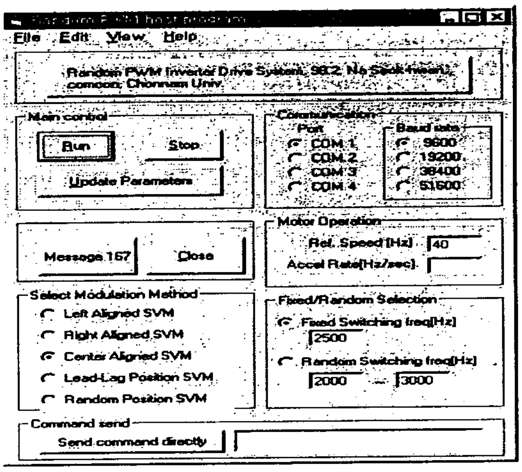


Fig. 7 User interface of host program

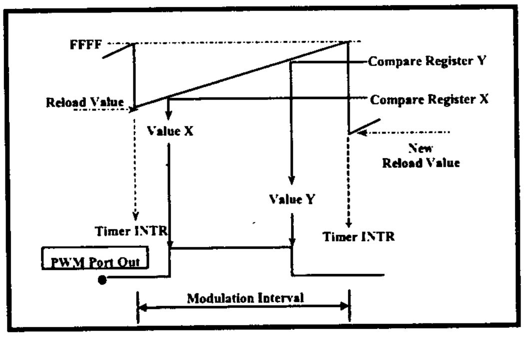
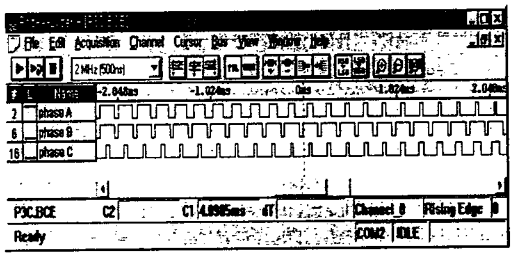
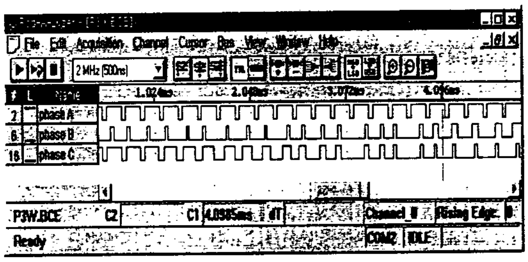


Fig. 5 Generation of PWM by CAP/COM units built in micro-controller



(a)



(b)

Fig. 8 Experimental PWM patterns Measured by logic analyzer

(a) Conventional SVPWM (b) Proposed RPPWM

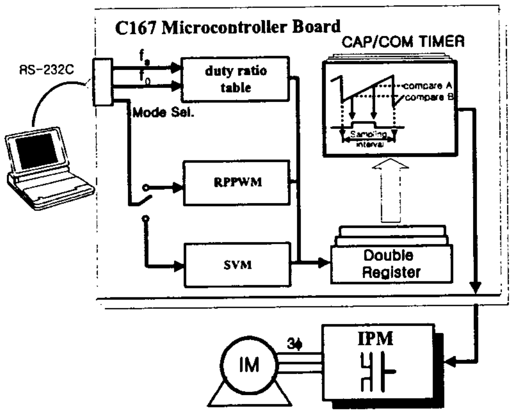
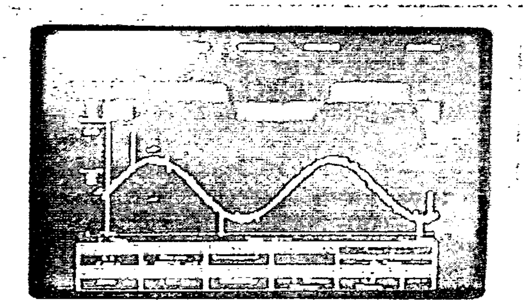
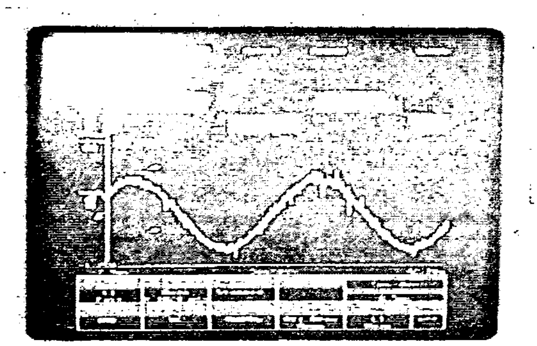


Fig. 6 Configuration of the proposed system



(a)



(b)

Fig. 9 Experimental voltage and current waveforms (f_0=40Hz, f_{sw}=3kHz, modulation index = 0.7)
(a) Conventional SVPWM (b) Proposed RPPWM
(Upper part : Waveform of inverter output voltage Lower part: Waveform of inverter output current)

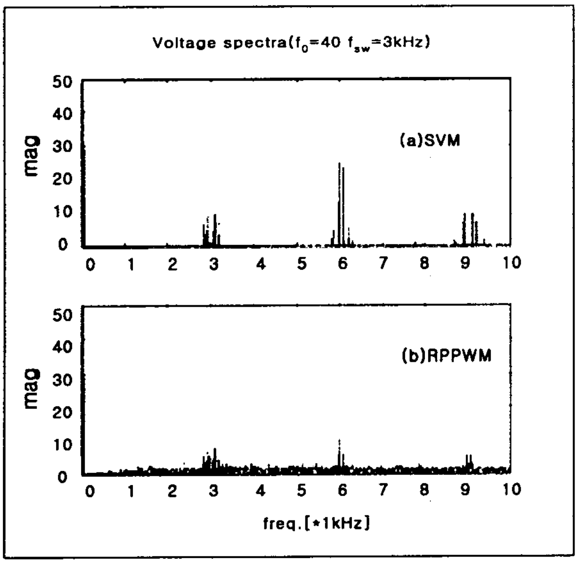
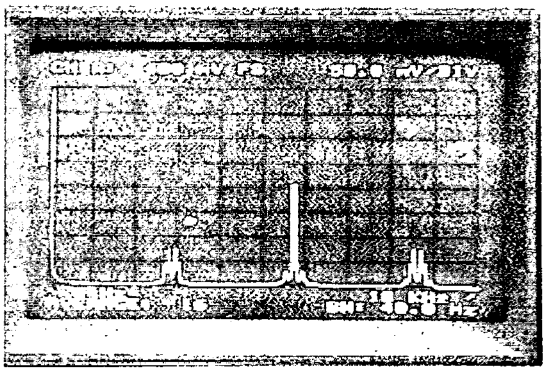
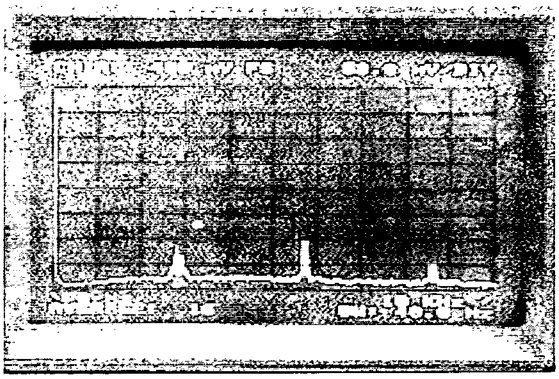


Fig. 10 Simulation result of voltage spectra (f_0=40Hz, f_{sw}=3kHz)
(a) Conventional SVPWM (b) Proposed RPPWM



(a)



(b)

Fig. 11 Experimental voltage spectra (f_0=40Hz, f_{sw}=3kHz)
(a) Conventional SVPWM (b) Proposed RPPWM

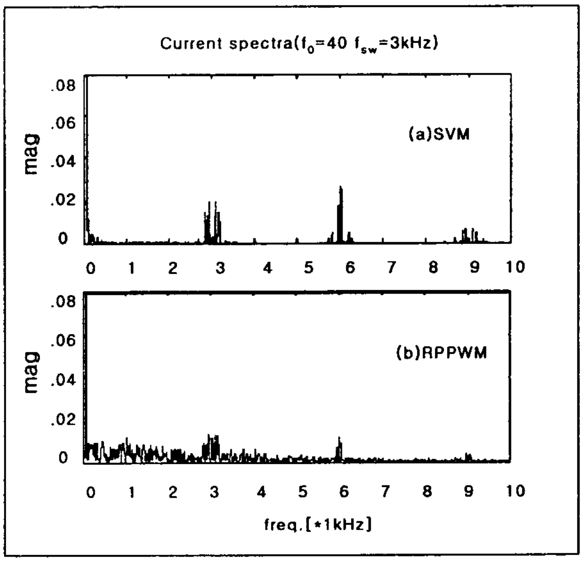
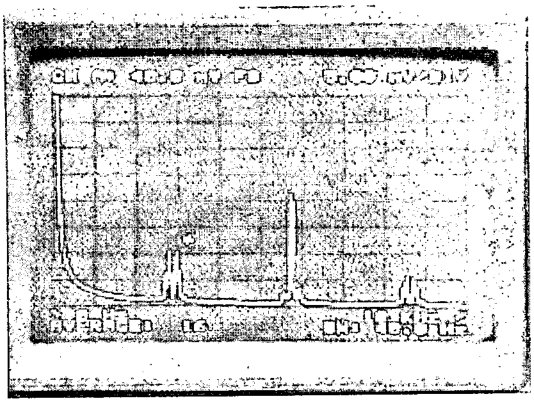
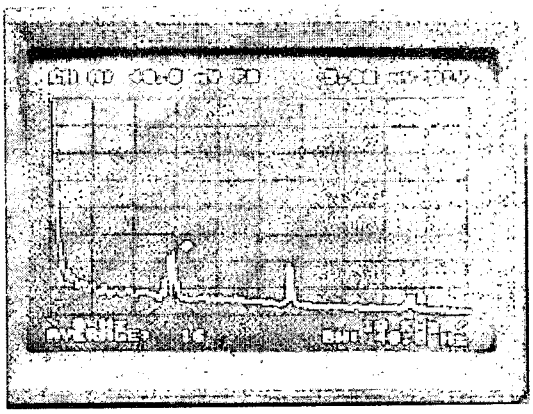


Fig. 12 Simulation result of current spectra (f_0=40Hz, f_{sw}=3kHz)
(a) Conventional SVPWM (b) Proposed RPPWM



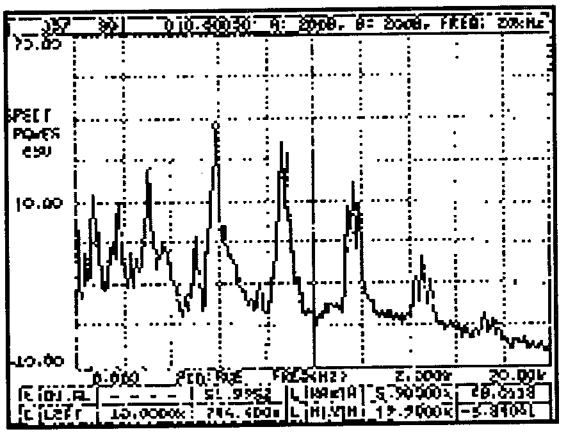
(a)



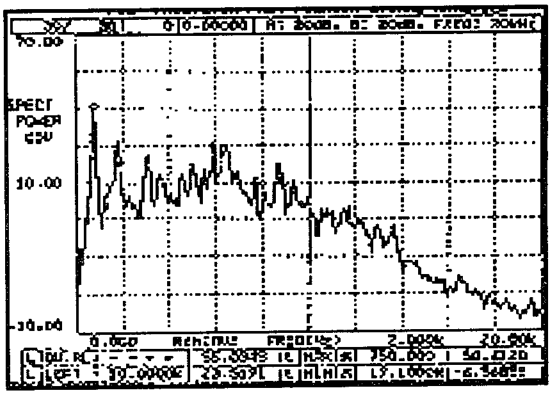
(b)

Fig. 13 Experimental current spectra (f_0=40Hz, f_{sw}=3kHz)

(a) Conventional SVPWM (b) Proposed RPPWM



(a)

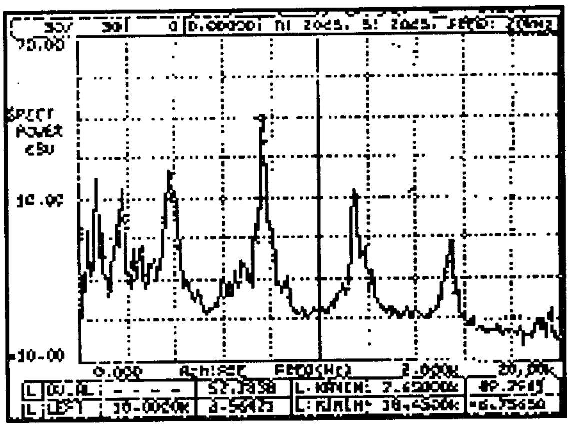


(b)

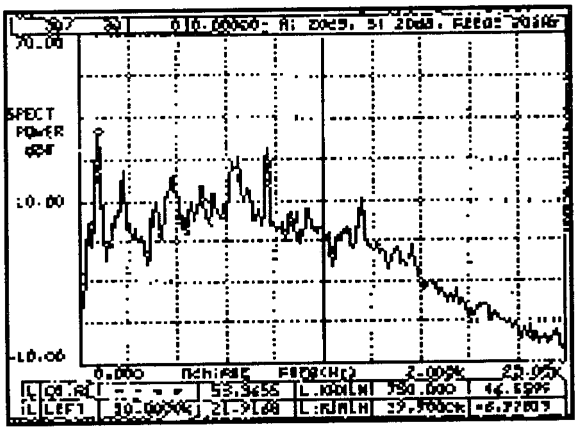
Fig. 14 Experimental noise spectra (f_0=40Hz, f_{sw}=3kHz)

(a) Conventional SVPWM (b) Proposed RPPWM

(Y-axis: 10 db/div., X-axis: 2kHz/div.)



(a)

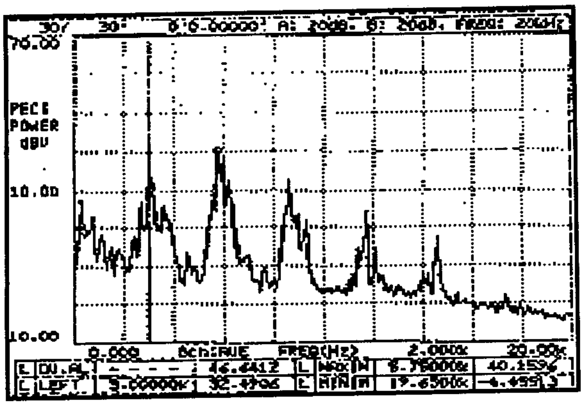


(b)

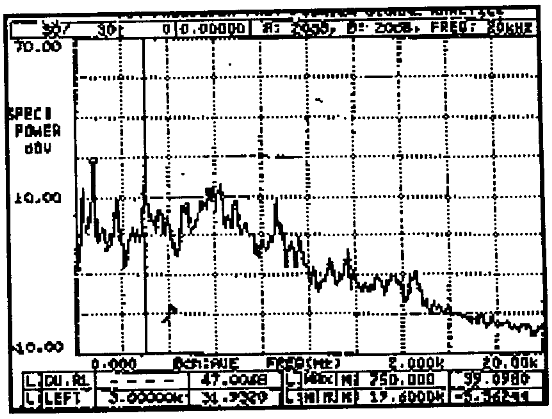
Fig. 15 Experimental noise spectra (f_0=40Hz, f_{sw}=4kHz)

(a) Conventional SVPWM (b) Proposed RPPWM

(Y-axis: 10 db/div., X-axis: 2kHz/div.)



(a)

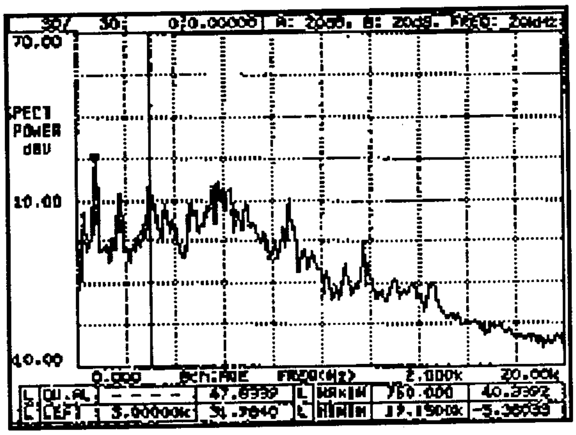


(b)

Fig. 17 Experimental noise spectra (f_0=70Hz, f_{sw}=3kHz)

(a) Conventional SVPWM (b) Proposed RPPWM

(Y-axis: 10 db/div., X-axis : 2kHz/div.)

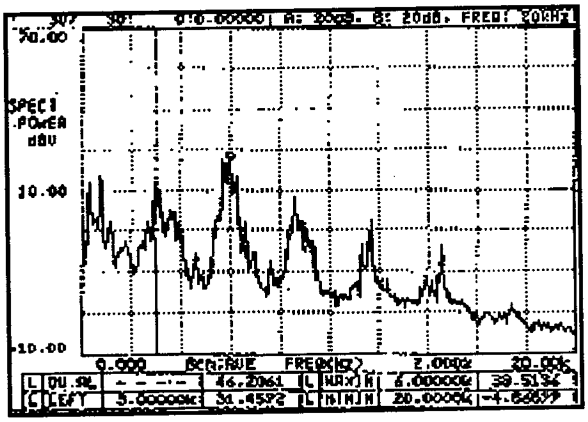


(b)

Fig. 16 Experimental noise spectra (f_0=60Hz, f_{sw}=3kHz)

(a) Conventional SVPWM (b) Proposed RPPWM

(Y-axis: 10 db/div., X-axis : 2kHz/div.)



(a)