REDUCTION OF AUDIBLE SWITCHING NOISE IN INDUCTION MOTOR DRIVES USING RANDOM POSITION PWM

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ABSTRACT

RPWM (Random Pulse Width Modulation) is a switching technique to spread the voltage and current harmonics on the wide frequency area. Using randomly changed 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 RPWM have been attracting an interest as an excellent method for the reduction of acoustic noise on the inverter drive system. In this paper a new RPPWM (Random Position PWM) is proposed and implemented. Each of three pulses is located randomly in each switching interval. Along with the randomization of PWM pulses, the space vector modulation is executed in the C167 microcontroller also. The experimental results show that the voltage and current harmonics were spread to wide band area and that the audible switching noise was reduced by 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 were mainly focused on the harmonic loss and efficiency of the drive system.[1] Recently, according to the increase of the concern for the improvement of working environment, many studies are attempted 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 constant switching frequency. According to the increase of the carrier frequency, the current harmonics shift to higher frequency area, and the magnitude of the harmonics is 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. It includes the ultrasonic PWM switching method[4],[5] and SHE (Selected Harmonic Elimination) PWM method[6], and so on.

Recently, as a new PWM method for the noise reduction, RPWM method is introduced which uses the broad band switching frequency to spread the noise spectrum instead of using a specific fixed switching frequency. RPWM method is operated with different carrier switching frequency at each switching time to spread the spectrum of the voltage, current and noise. RPWM method is attracting an interest as an excellent method for the 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.[11]

In this study a new RPWM is proposed. Each PWM pulse can be located in any place in each modulation intervals as far as they do not corrupt the switching sequences for the space vector modulation. For the implementation of proposed method, a 16 bit microcontroller C167 was used. The duty ratio is calculated based on the SVM 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 in wide frequency range and the audible switching noise is reduced effectively using the proposed RPWM.

2. RANDOM PWM

The power carried by the k-th harmonic P_k is propotional to the following function of the random variable 6_n and N:[14]

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

Where E{.} denotes statistical expectation, $\bar{a}_n$ is the duty ratio of the switching signal in the n-th switching interval, and 6_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 6_n is random variable, (1) is given by

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

3. RANDOM POSITION PWM

In this study, a new RPWM technique is proposed to randomize the pulse position. This is similar to LLPWM (Lead-Lag PWM) method. 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 intervals 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 LLPWM.
The switching functions of SVPWM (space vector PWM) is shown in fig. 1(a) and the proposed RPPWM 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.

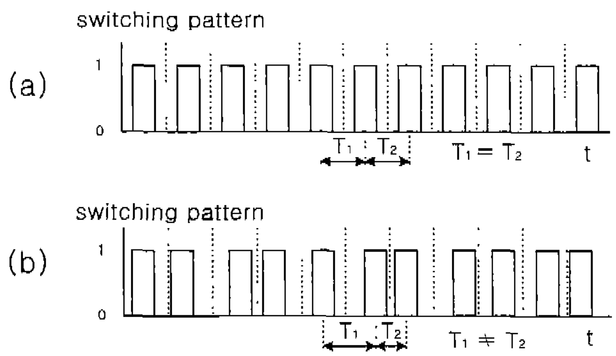

Fig. 1 Switching functions; (a)SVPWM, (b) RPPWM

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 microcontroller. By the way, a good random generator should be able to 1) generate random numbers with wide range, 2) generate uniformly distributed random numbers, 3) avoid the 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 ranged 0 to *im* can be generated by

$$jran = (jran * ia + ic)\%im . \quad (3)$$

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

$$ran = (float)\, jran / (float) im . \quad (4)$$

And a integer random number ranged *jlo* to *jhi* is generated by

$$j = jlo + ((jhi - jlo + 1) * jran) / im . \quad (5)$$

In (3)-(5), *ia*, *ic* and *im* are selected constant and called multiplier, increment and modulus respectively. And, *jlo* and *jhi* are minimum and maximum values of the generated random number respectively. Now this random number function can be used in any other processor and microcontroller. But *ia*, *ic*, *im* should be selected carefully.[12] And *ic* must be prime number and *ic* and *im* should satisfy the following relationship.

$$ic \approx \left(\frac{1}{2} - \frac{1}{6}\sqrt{3}\right) im \quad (6)$$

3.2. Space Vector Modulation

SVM (Space Vector Modulation) is used widely in inverter drive system. Reportedly, SVM is a excellent voltage modulation method, because it can use large available DC link voltage. In this study, space vector modulation method is the basis in implementation of the proposed RPPWM. In fig. 2, 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 for the vector U_1, the duration time T_2 for the vector U_2, and the duration time T_0 for the zero vector are expressed by

$$\begin{aligned} T_1 &= T \cdot M \cdot \frac{\sin(60° - \alpha)}{\sin 60°} \\ T_2 &= T \cdot M \cdot \frac{\sin \alpha}{\sin 60°} \\ T_0 &= T - T_2 - T_1 \end{aligned} \quad (7)$$

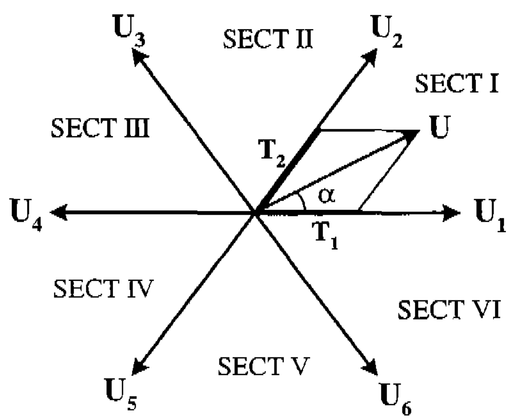

Fig. 2 Diagram for space vector modulation

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 which sector the voltage vector is located in. 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. 3 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 make this rule, inappropriate switching is happened.

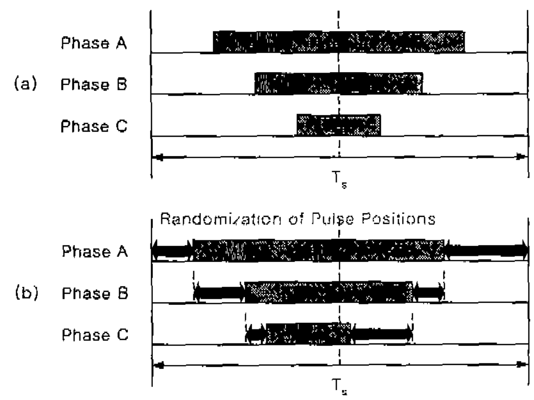

Fig. 3 PWM pulse position; (a)SVPWM, (b)RPPWM

4. SYSTEM CONFIGURATIONS

Implemented RPPWM system consists of C167 microcontroller board, IPM inverter, 1.5kw induction motor, control program, and host program. Fig. 4 shows the schematic diagram of the proposed RPPWM.

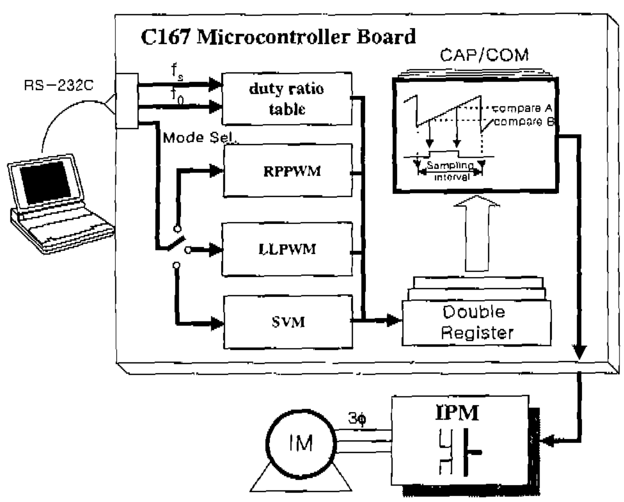

Fig. 4 System configurations

As a main controller, C167 microcontroller (Siemens co.) was used. The microcontroller C167 has a 16 bit RISC architecture and shows a good performance in controlling the DC motor, 3-phase brushless motor, and 3-phase induction motor, etc. The proposed algorithm for RPPWM is executed in the C167 controller and the pulse signals to gate the IPM are generated through the output port of the C167 microcontroller. That is, PLD(Programmable Logic Device) is not needed to implement the logic circuits for the pulse signals. C167 uses the internal CAP/COM (capture/compare) units to produce the pulse signal, which gives low cost implementation of the inverter drive system.

5. EXPERIMENTAL RESULTS

In measuring the noise, it is common that the system has to be operated under the condition of rated load and speed. This is proper to measure the total noise including the mechanical noise. In this study, however, we are interested in the electromagnetic switching noise generated by inverter switching device, not in the mechanical noise. So, experiment was done under the no load condition. 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 apart from the motor shaft.

5.1. Voltage and Current Spectrum

The spectrum of the voltage harmonics is shown in fig. 5 under the condition of no load, 40Hz reference speed, and 3kHz switching frequency. Fig. 5(a) is the case of center aligned SVPWM, (b) is the case of LLPWM, and (c) is the case of the proposed RPPWM. In fig. 5(a), dominant discrete components of harmonics appear around the integer multiple of switching frequency. From fig. 5(b), we find that the total amount of discrete components of harmonics is reduced while the continuous components are slightly increased with LLPWM. But the discrete component of the harmonics around the switching frequency is still dominant. Fig. 5(c) is in the case of the proposed RPPWM. The discrete components of the harmonics are considerably reduced. Fig. 6 shows the spectrum of the current harmonics under the condition of no load, 40Hz reference speed and 3kHz switching frequency in case of (a) SVPWM, (b)LLPWM and (c) RPPWM. The result of current spectrum shows a similar aspect to the voltage spectrum.

5.2. Noise Spectrum

Fig. 7 shows the spectrum of the noise with (a) center aligned SVPWM, (b) LLPWM and (c) proposed RRPWM. In the case of SVPWM shown in fig. 7(a), the most dominant component of the harmonics appears around the twice the switching frequency, and the secondary around the switching frequency. And there are noise components at 750Hz and 1800Hz independent of the switching frequency. In the case of LLPWM shown in fig. 7(b), the component of twice the switching frequency is considerably reduced, but the component around the switching frequency is a little increased. But noise component around 750Hz is considerably increased. In the case of RPPWM shown in fig. 7(c), when compared with (a), the magnitude of noise around the switching frequency is slightly reduced, and that of twice the switching frequency is considerably reduced. But the component around 750Hz is also increased.

Fig. 8 shows the spectrum of noise when the switching frequency is changed to 4kHz. Although the switching frequency was changed, the component of 750Hz frequency existed both at LLPWM and RPWM schemes independent of the switching frequency.

6. CONCLUSION

A new random position PWM is proposed and implemented in this study. By the reported lead-lag PWM, the frequency distribution of harmonics is spread in a wide range. However, becausc the position of the pulse is limited to two kinds of locations-lead or lag, the discrete components of harmonics are not sufficiently reduced.

In this proposed RPPWM, each 3 phase pulse can be located in any place in each modulation intervals 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 LLPWM.

The experimental results show that the spectrum of the voltage and current is spread in wide frequency range and the audible switching noise is reduced effectively using the proposed RPWM. Also it is proved that the RPWM can cause the mechanical resonance in case the natural frequency of the machine is superposed.

Acknowledgements

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7. REFERENCES

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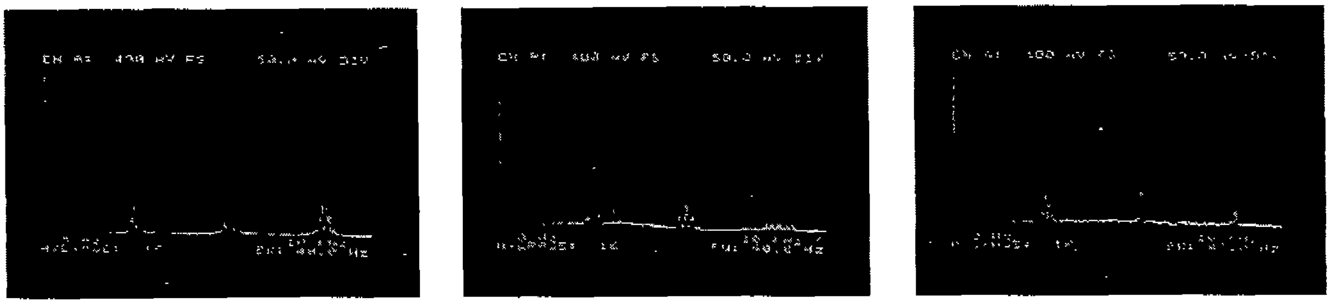
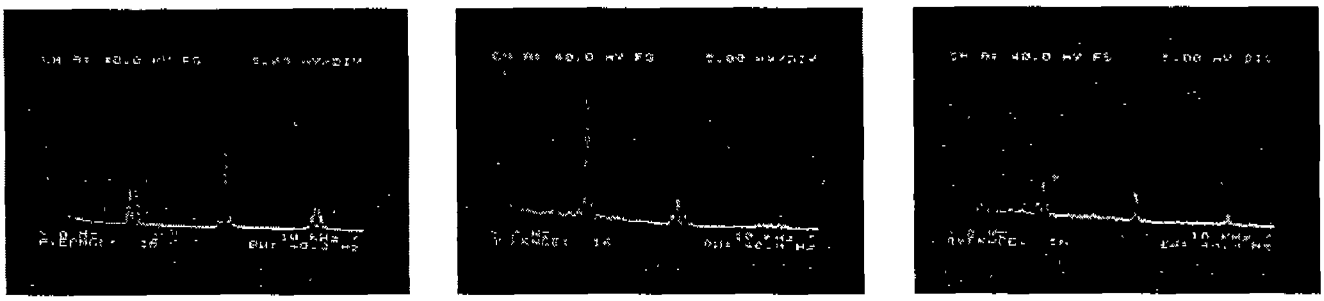


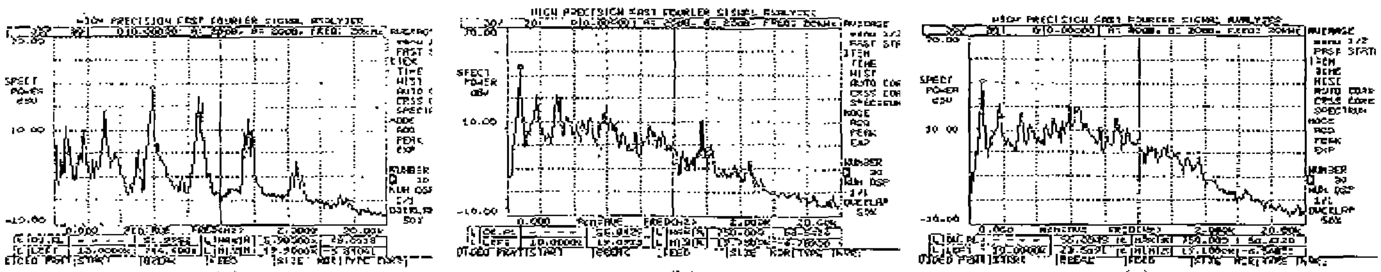
(a) (b) (c)

Fig. 5 Voltage spectra in case f_0=40Hz, f_{sw}=3kHz; (a) SVPWM, (b) LLPWM, (c) RPPWM



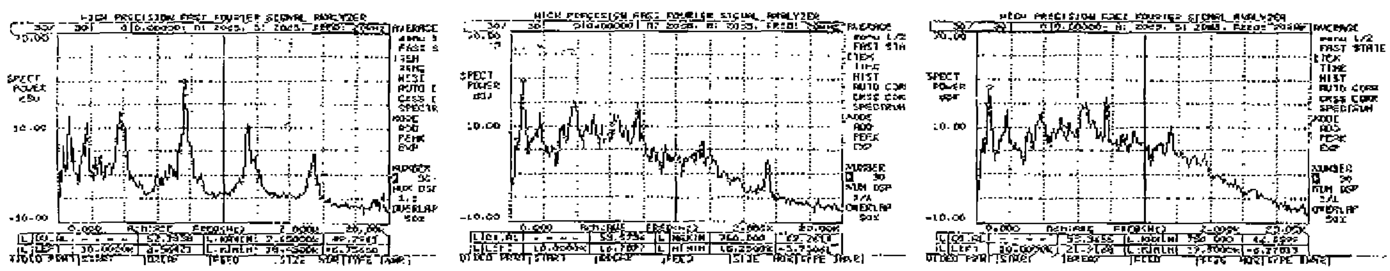
(a) (b) (c)

Fig. 6 Current spectra in case f_0=40Hz, f_{sw}=3kHz; (a) SVPWM, (b) LLPWM, (c) RPPWM



(a) (b) (c)

Fig. 7 Noise spectra in f_0=40Hz, f_{sw}=3kHz; (a) SVPWM, (b) LLPWM, (c) RPPWM



(a) (b) (c)

Fig. 8 Noise spectra in case f_0=40Hz, f_{sw}=4kHz; (a) SVPWM, (b) LLPWM, (c) RPPWM