

Magnetic Noise Reduction Method of Inverter Driven Induction Motors Using Non-uniform Slots Pitched Core

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Abstract

Induction motors are designed so that the air gap length is reduced as small as possible to restrict the exciting current. Reduction of the air gap length inevitably causes the magnetic noise to increase. The induction motor presently put in practical use is so designed that the vibromotive frequency (slot ripple frequency) may not approach the mechanical resonance frequency caused by the motor slot ripple, for the power supply frequency is fixed.

However, this principle is not applicable to the variable frequency drive by means of inverter drive, that is, a condition that no mechanical resonance should be taken place for any arbitrary frequency is required. This requirement is practically impossible to be achieved. This requirement is practically impossible to be achieved. This paper therefore presents the motor of a new principle which enables the countermeasure against the magnetic noise for the variable speed drive, that is, the proposal and the results of experiments in relation to the magnetic noise restricting motor in which a rotor core with non-uniform pitched slots structure is employed.

1. Introduction

Magnetic noise problem of rotating machines is an eternal issue to be solved. Particularly, induction motors having a small gap size are demanded to have their noises reduced substantially. Recently, because of the addition of a PWM carrier wave and a variable speed control by inverter driving, such noises cannot be solved by a conventional design technique for merely avoiding a resonance point of structures. This is because, in the variable speed control in this case, a slot ripple which is a major cause of magnetic noise has the possibility of generating at all frequency bands.

Therefore, when a skew is fitted to a rotor or a slot combination, which is a conventional magnetic noise suppressing method, is selected, a design technique of a level to avoid a resonance point with a structure is not sufficient to deal with the noise. This paper aims to solve such problems by quite a new technique, or by means of an irregular slot pitch, without sticking to the basic concept of a conventional design. Ever since the beginning of the history of rotating machines, the stator and the rotor are basically designed to have a regular slot pitch. As a result, a slot ripple frequency of the machine being operated is substantially constant, readily inducing a resonance phenomenon with the structure of a rotating machine.

To prove the above fact, magnetic noise and vibration theory of conventional rotating

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machines (particularly, induction motors having a small gap size) have been therotically developed as a periodic function due to a force wave with an equal pitch produced in gaps. The theory is constituted as the composition of many sine waves containing high harmonic waves due to the presence of slot pitch at equal intervals.

Namely, as long as a conventional design method is adopted, the radical reduction of magnetic noise when speed-change controlling of inverter is conducted cannot be expected. The principle of irregular slots according to this method, resulting effects to be expected, and test results will be described to verify the effectiveness of the prototype irregular slot pitched rotor of this paper.

2. Present Magnetic Noise-related Problems

Rotating machines are considered to include induction machines, synchronous machines, d.c. machines and other special machines. And, the rotating machines with the structure having at least a slot have the possibility of generating magnetic noise due to a slot ripple phenomenon. But, since the slot ripple is caused mainly due to a zigzag leakage flux generated on a gap surface, its possibility of inducing a problem varies depending on the gap size.

Generally, the synchronous machine has less possibility of causing a problem because its gap size is large. The induction motor is designed to have a gap size as small as possible to suppress an exciting current. Therefore, a zingzag leakage flux is increased, resulting in causing a large problem of magnetic noise (particularly, large magnetic noise due to slot ripple). The d.c. machine is just positioned between the synchronous machine and the induction motor.

Magnetic noise is also related to output capacity. For example, small to intermediate capacity models are greatly influenced by an unbalanced magnetic attraction force generated on the shaft due to a big factor of the vibration of the rotor containing a shaft system. On the other hand, large capacity models have a low characteristic frequency of the shaft system (rotor), so that the vibration of the rotor does not cause a problem in particular. But, resonance between the polygonal deformation vibration resonance phenomenon of the stator core and the frame sheet metal construction does not constitute a problem.

〈2-1〉 Production of irregular-spaced slot rotor and vibration characteristics of standard induction motor construction

This paper reviews the suppression of magnetic noise of squirrel cage induction motors which have an aluminum die-cast rotor for which an irregular-spaced slot structure is easily adopted and which are of small to intermediate capacity models largely influenced by the vibration of the rotor. Fig. 1 to Fig. 3 show the results of analyzing frequencies of noises of standard three-phase squirrel cage induction motors under no load. These motors have an aluminum die-cast squirrel cage rotor to which a one-slot pitch skew is applied.

Fig. 1 is of a 4-pole 2.2 kW induction motor (IM), Fig. 2 a 4-pole 5.5 kW IM, and Fig. 3

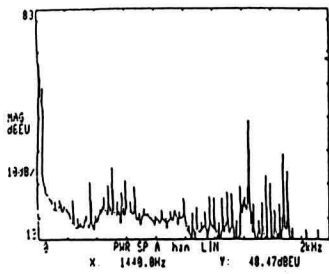


Fig. 1. 4 pole 2.2 kW IM, 200 V-60 Hz noise spectrum by FFT analyzer

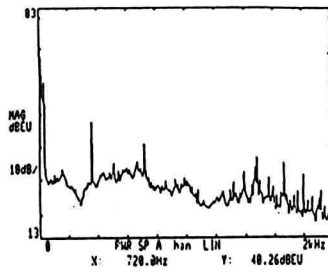


Fig. 2. 4 pole 5.5 kW IM, 200 V-60 Hz noise spectrum by FFT analyzer

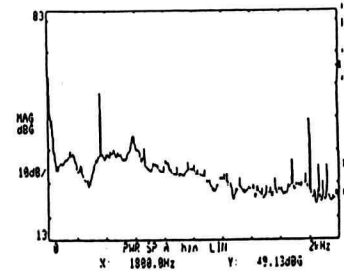
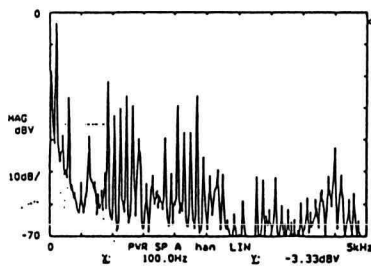
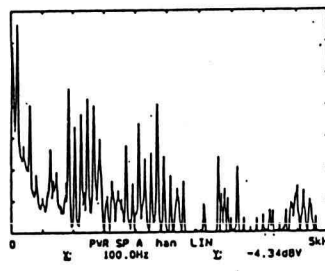


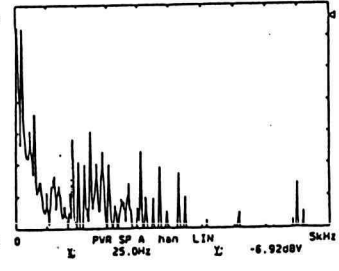
Fig. 3. 4 pole 11 kW IM, 200 V-60 Hz noise spectrum by FFT analyzer



(A) No Skew



(B) 0.3 Slot Pitch Skew



(C) 1.0 Slot Pitch Skew

Fig. 4. 4 pole 1.5 kW IM (200 V-50 Hz) relationship between rotor slot skew and acoustic noise

a 4-pole 11 kW IM. It is seen from the drawings that a major noise is a magnetic noise caused by a slit ripple in a range of 500-2,000 Hz.

Fig. 4 (A, B, C) also shows an example of 4-pole 1.5 kW IMs with different types of rotor slot skew. It is seen from Fig. 4 that skew has quite a large influence on magnetic noise and is effective to deal with magnetic noises. But, it is also true that mere adjustment of skew cannot remove magnetic noise completely.

〈2-2〉 Analysis of magnetic noise due to slot ripple

The equation shown below is one example of analysis equation for vibration and magnetic noise caused by slot ripple and phase belt harmonic frequency which are extensively used in the industry these days. In the equation, f designates a vibromotive frequency with respect to the stator, and f' a vibromotive frequency with respect to the rotor.

The equation (1) is a vibromotive frequency f_s due to slot ripple when rotating, N_1 and N_2 are slot numbers of the stator and the rotor, k is a given positive integer (1, 2, 3, ...), p is the number of poles, s is a slip, and f_0 is a power source frequency (Hz). Here, it is conditioned that N_1 and N_2 are disposed at equal intervals. The equation (1) is generally for N_2 , but may be for N_1 depending on the motor structure and its mounting conditions. In this

case, the stator mainly produces vibration and magnetic noise.

$$f_s = \left\{ \frac{N_2 k}{p} (1-s) \right\} f_0 \quad (1)$$

$$f'_s = \left\{ \frac{N_1 k}{p} (1-s) \right\} f_0$$

$$P_g = P_0 \left(1 + \frac{P_R P_S}{2 P_0^2} \{ \cos[(R-S)x - RNt] \right. \quad (2)$$

$$\left. + \cos[(R+S)x - RNt] \} + \frac{R_S}{P_0} \cos Sx + \frac{P_R}{P_0} \cos R(x - Nt) \right).$$

$$M = A \cos(Px - \omega t) + B \cos[(2q-1)Px + \omega t] \quad (3)$$

$$+ C \cos[(2q+1)Px - \omega t]$$

$$+ D \cos \left[\left(\frac{S}{P} - 1 \right) Px + \omega t \right] + E \cos \left[\left(\frac{S}{P} + 1 \right) Px - \omega t \right]$$

$$+ F \cos \left[\left(\frac{S}{P} - 1 \right) P(x - Nt) + \omega st \right] + G \cos \left[\left(\frac{R}{P} + 1 \right) P(x - Nt) - \omega st \right].$$

In the above equation, P designates permeance, and subscripts G , R , S and O designate a gap, a rotor, a stator and an average value, respectively. R , S and N designate the number of rotor slots, the number of stator slots, and a rotor speed (Rad/s), respectively. And, x and t designate a rotational position and time. In the equation (3), A to G designate a coefficient, P_g and M a gap permeance and a gap magnetomotive force. And, P and q designate a pole logarithm and a phase belt number per pole.

The equations (2) and (3) are extractions from the theoretical equations shown in a book written by Mr. P.L. Alger⁽²⁾ well known, which are representative magnetic vibration calculation equations being used worldwide.

It is known that magnetic noise actually causes a problem only when a vibromotive frequency such as a slot ripple and a number of vibration inherent in a structure core closer to cause a resonance phenomenon.

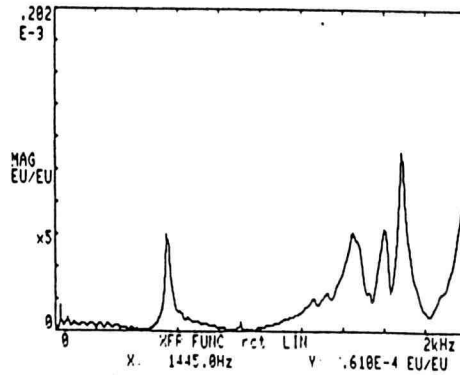


Fig. 5. 4-pole 1.5 kW IM, motor vibration characteristics of 4-pole 1.5 kW IM

〈2-3〉 Relation between speed-change control and magnetic noise

Fig. 5 shows vibration frequency characteristics (impact response) of a structure containing a rotor of a representative motor (4-pole 1.5 kW IM). This figure was obtained by analyzing a frequency of output of a vibration (over-speed) pickup mounted on a motor frame by means of an FFT analyzer according to a tapping method. It is seen from the figure that rotating machines always have several points where a frequency easily resonates, and it is believed to be theoretically and economically impossible to remove such resonating point. Fig. 5 apparently shows a resonance characteristic of 500 Hz of a shaft system, and annulus ring vibrations of 1,500 Hz and 1,700 Hz of a stator core.

These resonance points can be moved to some extent by modifying the structure's design, but cannot be removed completely.

When speed-change controlling is made under such conditions, the slot ripple indicated by the equation (1) has the possibility of occurring in all frequency zone, so that it is theoretically proved that the resonance phenomenon cannot be avoided completely. Therefore, conventional techniques for dealing with magnetic sound are insufficient. One of methods for thoroughly remedying this problem is to provide conditions to prevent or to make it hard to occur the resonance phenomenon with a structure than under the above conditions.

3. Concept of Irregular-spaced Slots

A method to be considered is to avoid the agreement (deviating from the center frequency) with the resonating points of a structure by arranging the rotor slots at irregular intervals in order to suppress magnetic noise. According to a vibration theory, the resonance phenomenon is a phenomenon of accumulating vibration energy into a tank circuit, and vibration of several cycles is not sufficient to accumulate vibration energy into the tank circuit. Its one example is shown in Fig. 6, which shows an oscilloscopic relation between time and increase of amplitude by vibration of the rotor system which is the major cause of

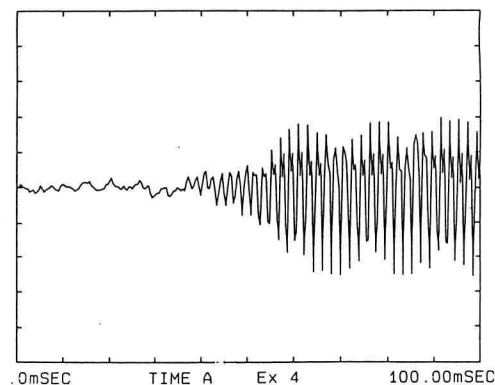


Fig. 6. relationship between acceleration time and growing amplitude of tank circuit (1.5 kW IM motor)

magnetic noise of small to intermediate capacity models.

Fig. 6 shows changes in a vibration acceleration of a motor frame when a number of inherent vibration of 495 Hz of a shaft system (rotor) and an oscillator frequency are combined and a sinusoidal a.c. voltage of 5V is applied to the input terminal (between terminals) of a 4P-1.5 kW IM.

As shown in Fig. 6, a certain degree of time (excitation cycle) is required for the increase of amplitude by vibration due to the resonance phenomenon of a machine system. When it is assumed that a start-up time for the increase of amplitude is a time constant of the tank circuit, it relates to a mass of the system, and the start-up time constant of amplitude by vibration of a resonance system increases as the mass increases.

It can be said here that the start up to resonance amplitude of the rotor (shaft system) of a representative squirrel cage induction motor, a 4-pole 1.5 kW IM, needs time of about 20 ms. Conversely, a value of amplitude by vibration of the resonance system can be suppressed by changing a vibration cycle within the start-up time to shift the resonance conditions.

One of the method to enable the above concept is to adopt "irregular spaced arrangement of rotor slots", or irregular-spaced slots.

<3-1> Basic design conditions for irregular-spaced slots

The irregular-spaced slots can be adopted for both the stator and the rotor, but it is considered to be more practical to adopt for the rotor in view of workability and economy. And, the basic effects of adopting the irregular-spaced slots will be summarized as follows.

(1) Opposite phase excitation within the time constant of amplitude by vibration (utilization of 180-degree phase difference hand).

(2) Oscillation of the produced frequency into the form of, e.g., a sine wave, to make the growth of amplitude difficult due to resonance. (Rotor slot pitch is divided into dense and non-dense portions.)

(3) Slots are random-pitched to disperse a vibromotive frequency component

Basic conditions for the production of the rotor according to this method will be described below. This paper relates to magnetic noise of small to intermediate capacity models and basically aims to avoid a resonance phenomenon of the rotor, and aims to avoid an unbalanced magnetic pull (UMP) due to asymmetry which acts on the rotor. Therefore, an axial symmetry structure is required to be designed. And, care must be taken to avoid saturated gear teeth so that a face width is no excessively narrow, in order to enhance the irregular-spaced effect.

<3-2> Prototype irregular slot pitched rotor core

Three types of prototype irregular slot pitched rotor core were made for a 4-pole 1.5 kW squirrel cage induction motor based on the above concept of irregular slot (Fig. 7).

These rotor cores were produced according to the conditions (2) and (3) of <3-2> and the UMP removal principle based on axial symmetry. The slots have the same shape, and the

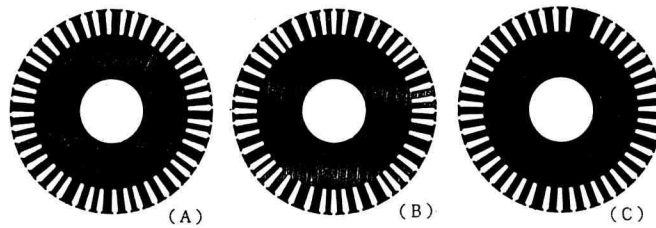


Fig. 7. examples of inequality slot pitched rotor cores (A, B, C)

irregular-spaced effect is achieved by a positional change only.

(Note) If the slot shape is selected as desired and the slot intervals are close, designing of the slot cross section to be small relieves the conditions for limiting the saturation of gear teeth and should be able to effectively design irregular slots. But, its effect on electrical and operating characteristics cannot be disregarded. Therefore, these prototypes were designed to have the same slot shape with different arrangements.

A method for designing the irregular slots will be reported in another paper.

4. Test Results

Fig. 7 shows the results of analyzed frequencies of vibration and noise of 4-pole 1.5 kW induction motors with prototype rotors (irregular slots A, B and C) at 50 Hz under no load. It is seen by comparing Fig. 7 and Figs. 1 and 4 (operation results of standard squirrel cage rotor) that vibration frequency distributions of vibration (noise) are different to some extent. The standard rotor has less vibration (noise) when operated with commercial 50 Hz power because it is designed to be out of a resonance point.

Fig. 7(A) shows irregular slots, which have a remarkable effect of suppressing a resonance phenomenon and the effect is particularly conspicuous in a frequency zone of 500 Hz or more. But, magnetic noise is high at low frequencies of 50 Hz and 100 Hz. This is considered owing to the effect of (2) of <3-1>.

Fig. 7(B) disperses the frequency component to a high frequency zone. This can be said that because designing was made under the condition of (3) of <3-1>, excitation energy was dispersed into a broad frequency range so that it is not concentrated on to the frequency component of the equation (1).

Fig. 7(C) is designed with the slot positions shifted by a 1/4 slot pitch to equally arrange at 90 degrees based on the principle of equal slots. This design provides better effects than the irregular slots of (B) but is inferior to (A). But, (C) was recognized to have effects similar to those of the standard equal slots.

Fig. 7(C) was miss produced rotor cores, in this case one slot portion was remained (i.e. blind slot), then it becomes inbalance in electric and magnetically.

The irregular slot pitched rotors (A), (B) and (C) and the standard rotor ($N/N=36/45$) shown in Fig. 8 are provided with one slot skew, and their noises were measured under the

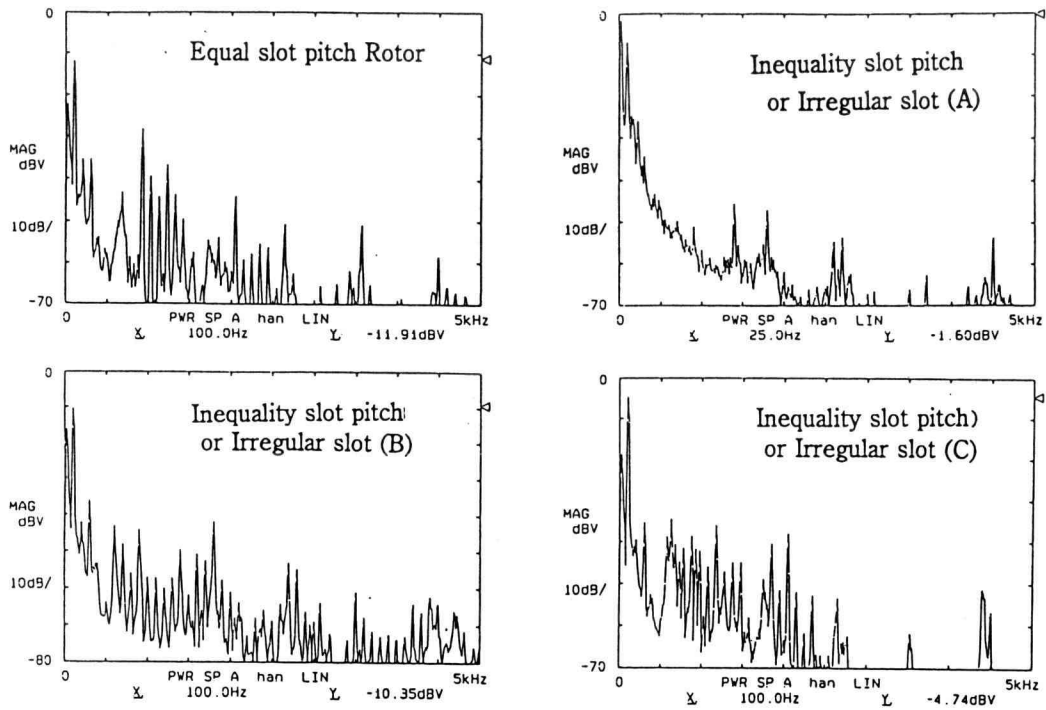


Fig. 8. noise comparison of normal rotor (same slot pitch) and test rotors (inequality slot pitch A, B, C)

same conditions. It is seen from the results that the irregular slot pitched rotor (A) has a high effect of preventing resonance. A reason, that low frequencies (50 Hz, 100 Hz) have a high level, might be that the prototype had a high UMP. This is not a significant problem and can be solved with high possibility.

5. Conclusion

Equal pitched stator and rotor slots which are basically used to design conventional motors produce a gap face (force wave) of a powerful specific frequency component as shown by the equation (1).

Therefore, a resonance phenomenon with the motor structure is a cause of producing a magnetic noise problem. As countermeasure, a resonance point with a structure was avoided, and a vibromotive force was reduced by the skewed slots of a rotor. But, such measures were limited, and the limitation was conspicuously observed when driven at variable speed by an inverter. In this case, there was a possibility of operating at a resonance point, and a solution could not be attained by conventional magnetic noise countermeasures. But, this paper has proved that such problems can be solved by disposing irregular slots on a rotor. This principle can be theoretically proved to be effective in

preventing a resonance phenomenon of a rotor and also in preventing a polygonal deformation annuls ring vibration resonance phenomenon of a stator core. Although a prototype irregular slot pitched rotor according to the design method of (1) of <3-1> was not produced this time, its effect can be highly expected theoretically.

This study was continuously made from the time when the author was till with Toshiba Corporation. And, special thanks go to the relevant personal of Toshiba Mie Factory and Engineering Department of the head office for kindly assisting me for this study.

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