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High Frequency Switching Operation of PWM Inverter for Direct Torque Control of Induction Motor

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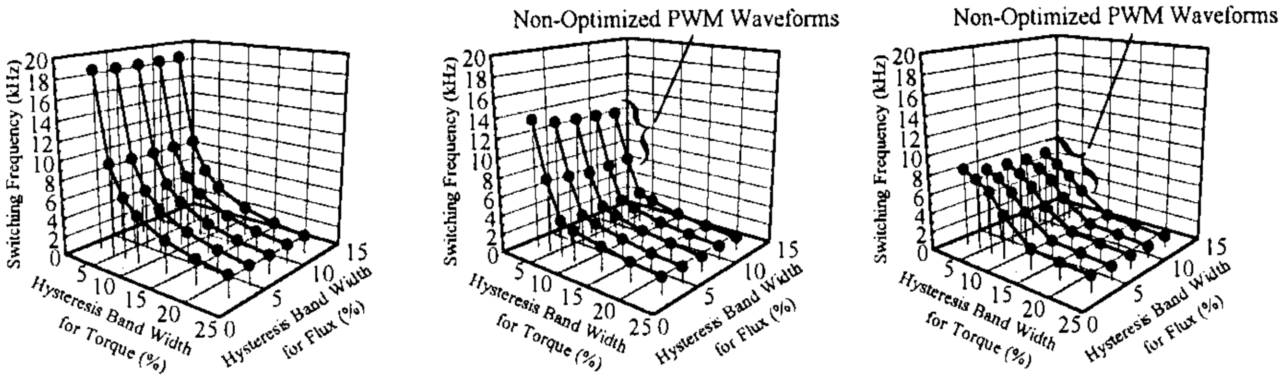
Abstract — ***The paper presents a novel simple method for high frequency switching operation of a PWM inverter for direct torque control of an induction motor, which makes an acoustically silent drive possible. The conventional method can not actually raise the switching frequency of the inverter even though hysteresis band widths for flux and torque control are reduced because of delay time in the feedback signals. In order to overcome the problem, the proposed method introduces dither signal injection into the conventional system by superposing a high-frequency and small-amplitude triangular wave on the flux and torque errors respectively. According to the simulation and experimental results, the stator flux ripple and torque ripple were reduced to 30 (%) compared with those of the conventional operation, and the acoustic noise level was decreased to less than 56 (dBA) over the operating speed range from 100 to 1500 (rpm).***

I. Introduction

This paper focuses on high frequency switching operation of a PWM inverter for direct torque control of an induction motor. The controller is inherently based on relay control of both stator flux and developed torque of the motor, and outputs optimum switching signals to the inverter so that the flux and torque errors can be restricted within specified hysteresis bands of the comparators [1]-[3]. In principle, the switching frequency of the inverter depends on the hysteresis band width, and an acoustically silent motor operation can be realized by reducing the band width and using high speed power devices, for example IGBTs, MOSFETs and so forth, in the inverter. However, the switching frequency can not practically be increased even though the band width is sufficiently reduced because of delay time in detecting stator voltages and currents and in estimating the stator flux and torque feedback signals. In order to overcome the above problem, the paper proposes a novel method introducing a dither signal into the conventional system, which enables the controller to raise the switching frequency regardless of the delay time and also makes acoustically silent drive possible. In what follows, basic principle of the method is briefly discussed, and several simulation and experimental results are presented, which prove feasibility of the proposed method.

II. Characteristics and Problems of Conventional Direct Torque Control

Since direct torque control of an induction motor is based on relay control of the stator flux and developed torque, it is desirable to have feedback of their instantaneous values to the controller without any delay. If the delay exists in obtaining the feedback signals, the control errors of the flux and torque can not be restricted within hysteresis bands of the relay elements. In other words, if a high frequency switching operation of the inverter is necessary to realize an acoustically silent drive by reducing the hysteresis band widths, it is essential to design carefully the feedback circuits employing high speed components with broad frequency characteristics. However, it is probably difficult to avoid the problem, because even a minute delay of micro seconds detrimentally affects the switching operation of the relay control.
Fig.1(a)-(c) are computer simulation results which have been



(a) No delay in feedback signals. (b) 10 (μs) delay in feedback signals. (c) 20 (μs) delay in feedback signals.

Fig. 1. Characteristics of switching frequency of conventional direct torque control (simulation results).

TABLE I

RATED VALUES AND NOMINAL PARAMETERS OF TEST MOTOR

Squirrel Cage Induction Motor		R_1	0.542 (Ω)
Rated Power	1.5 (kW)	R_2	0.536 (Ω)
Rated Speed	1650 (rpm)	L_{11}	54.1 (mH)
Rated Torque	8.64 (Nm)	L_{22}	51.0 (mH)
Number of Poles	4	M	51.0 (mH)

obtained by operating a test motor of TABLE I at 700 (rpm) under no load condition. The figures show characteristics of the averaged switching frequency of the inverter against the hysteresis band widths for the flux and torque control which have been normalized with respect to the rated stator flux amplitude and the rated torque per pole pair. It is clear from Fig. 1(a) that the switching frequency almost entirely depends on the hysteresis band width of torque control and is inversely proportional to that. According to the result, when the switching frequency is wanted to be more than 10 (kHz), the band width must be reduced to less than 4 (%). Assuming the delay time of 10 (μs) and 20 (μs) in obtaining the feedback signals of the stator flux and torque, the switching frequency can not be raised with ease as shown in Fig. 1(b) and (c) even though the hysteresis band width is sufficiently reduced. When the delay time is 10 (μs), the upper limit of the switching frequency is approximately 14 (kHz), and is only 8 (kHz) in case of 20 (μs). To make matters worse, the PWM waveforms of the stator voltages can not be optimized as the hysteresis band widths are reduced. Fig. 2 shows stator current and voltage waveforms which have been obtained by the computer simulation. The simulation tests were conducted under the same conditions as those of Fig. 1, and the hysteresis band widths were adjusted to be 4.6 (%) for flux and torque control respectively. As shown in the figure, the PWM waveform is detrimentally degraded even when the delay time of only 10 (μs) is in the feedback signals. Therefore, it is proper to consider that the upper limit of the switching frequency is practically from 3 to 4 (kHz) at most in case that the delay time exists.

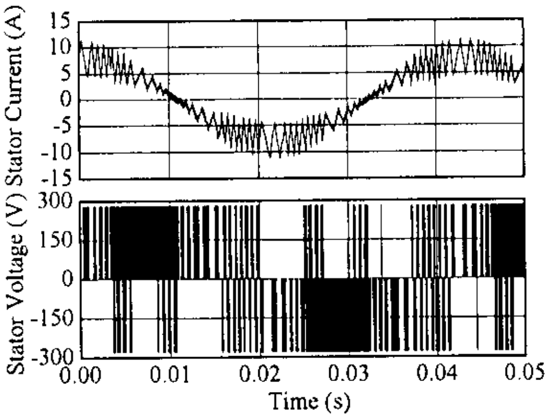


Fig. 2. Stator current and non-optimized PWM waveform with reduced hysteresis band width (simulation result).

III. HIGH FREQUENCY OPERATION OF PWM INVERTER FOR DIRECT TORQUE CONTROL

The proposed method introduces dither signal injection into the conventional direct torque control system by superposing a high-frequency and small-amplitude triangular wave on the flux and torque errors. The hysteresis comparators for the flux and torque control are non-linear elements, while the dither signal has an effect to make their non-linearity linear in a sense [4][5]. Fig. 3 shows a schematic diagram of the whole system where the triangular wave is employed as the dither signal. The frequency of the signal should be more than 30

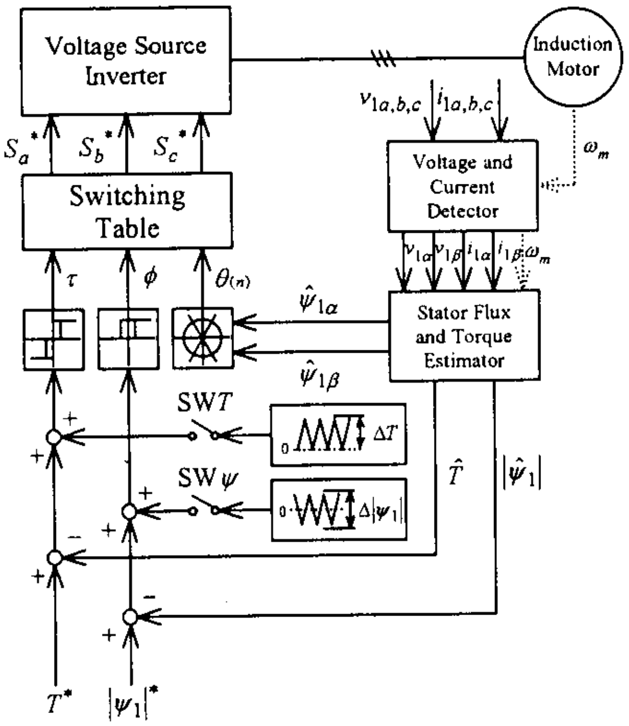
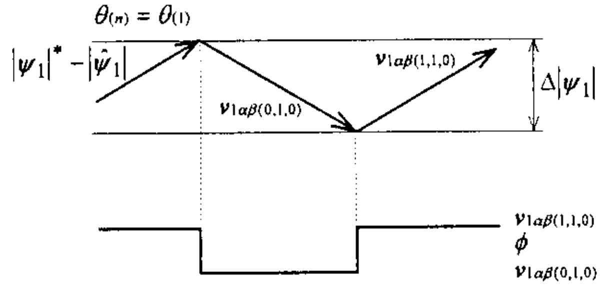


Fig. 3. Direct torque control system with dither signal injection.

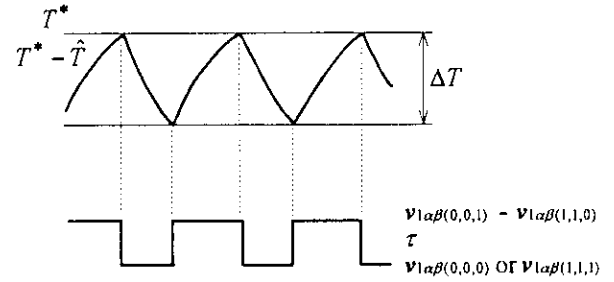
(kHz) to make the switching frequency of the inverter more than 15 (kHz), and its amplitude should be as small as that of hysteresis band widths for the flux and torque control. The hysteresis band inherently acts as a non-sensitive band, but the switching operation in hysteresis elements can be performed by superposing the triangular wave even though minute variations of the errors occur.

Fig. 4 illustrates the switching operation for the flux and torque control of the conventional direct torque control. According to the original principle of the control, the switching operation of the inverter is performed so that the flux and torque errors can be restricted within the corresponding hysteresis bands; hence the flux and torque ripples of the motor and switching frequency of the inverter are determined by the hysteresis band widths.

On the other hand, Fig. 5 illustrates the switching operation for the flux and torque control to which the dither signal has been applied. As shown in the figure, the ripples of the flux and torque can be simultaneously reduced less than the hysteresis band widths, and the switching frequency can be raised obviously. It should be noted that quick torque response of the original method has not been withered even though the dither signal is injected, because the dither signal effectively works only when the torque error is within the hysteresis band. When the torque error on which the dither signal is superposed gets big enough to be much more than hysteresis band width, conventional switching operation is carried out as usual by the hysteresis element, which does not degrade an inherent advantage of quick torque response of the direct torque control.

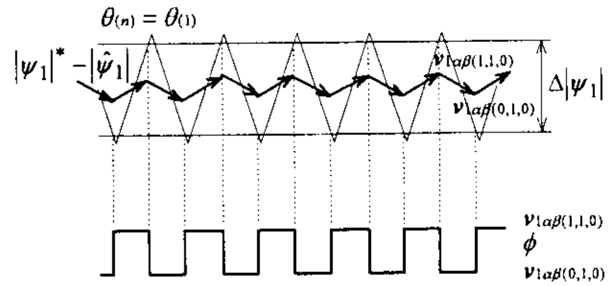


(a) Switching operation for stator flux control.

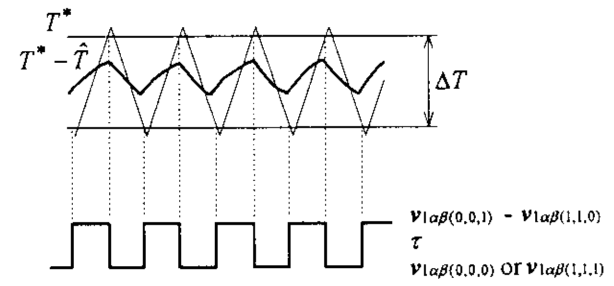


(b) Switching operation for torque control.

Fig. 4. Conventional switching operation for flux and torque control.

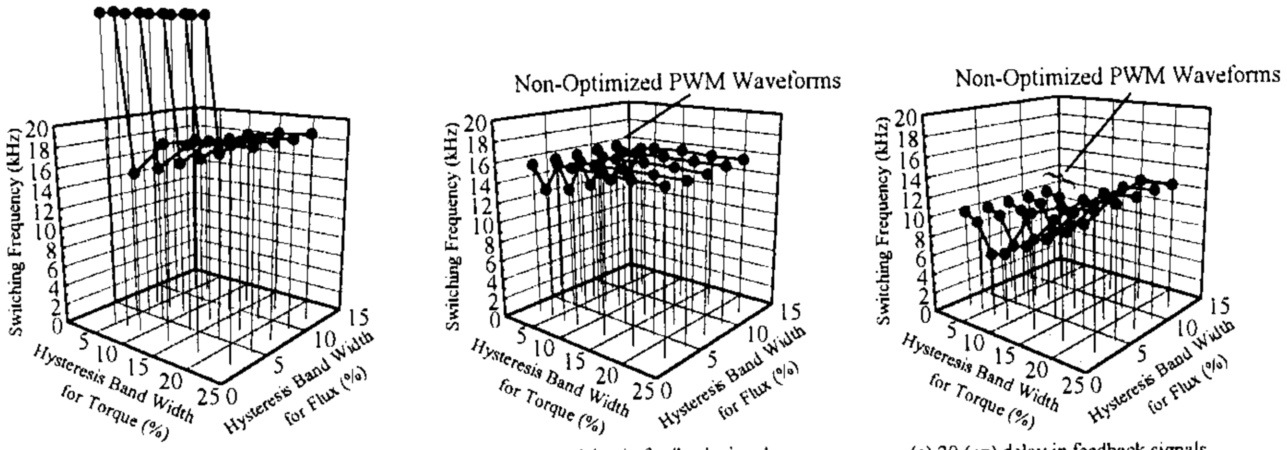


(a) Switching operation for stator flux control with dither signal.



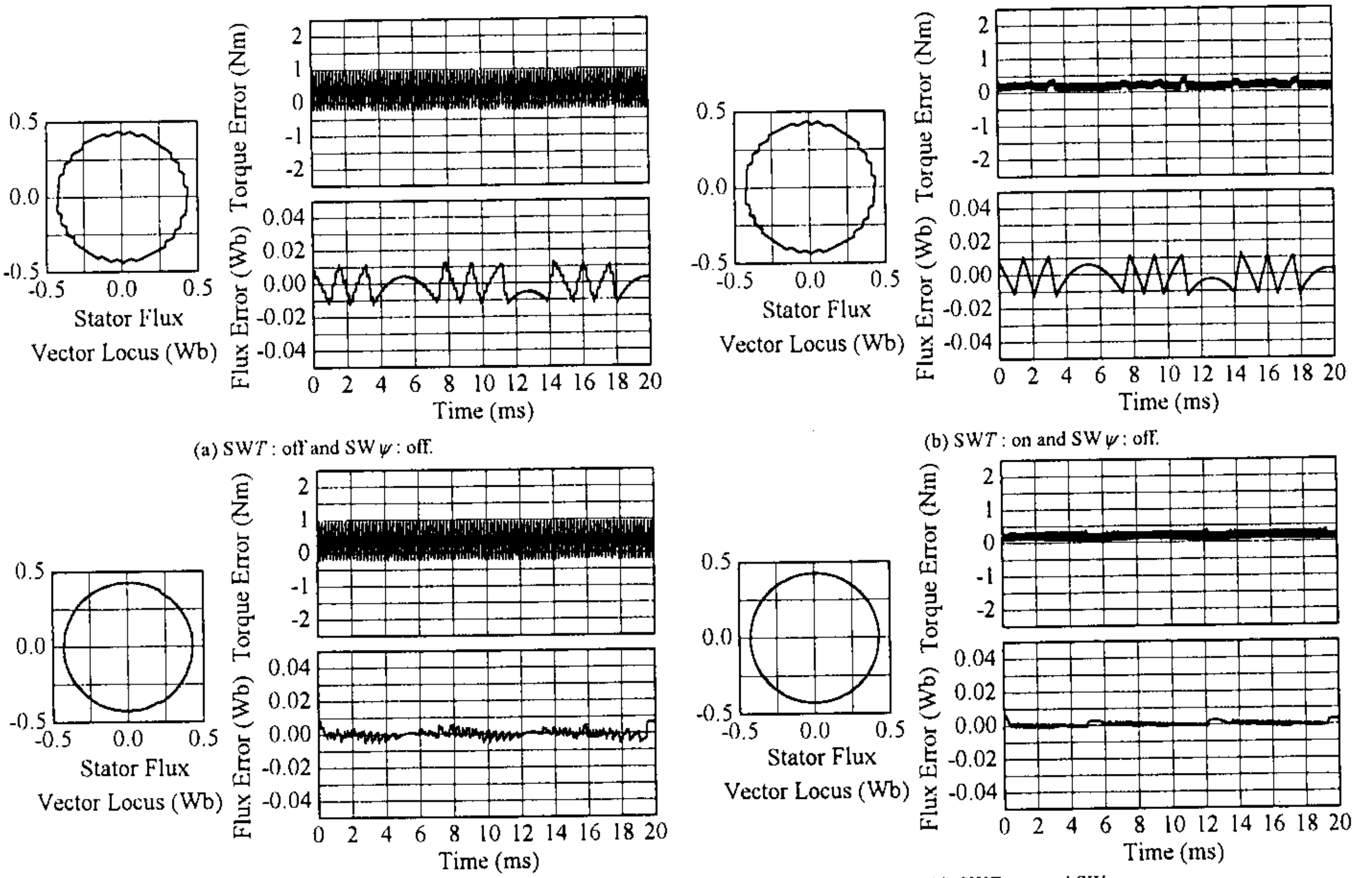
(b) Switching operation for torque control with dither signal.

Fig. 5. Switching operation for flux and torque control with dither signal.



(a) No delay in feedback signals. (b) 10 (μs) delay in feedback signals. (c) 20 (μs) delay in feedback signals.

Fig. 6. Characteristics of switching frequency of direct torque control with dither signal injection (simulation results).



(a) SWT : off and SWψ : off.

(b) SWT : on and SWψ : off.

(c) SWT : off and SWψ : on.

(d) SWT : on and SWψ : on.

Fig. 7. Waveforms of stator flux and torque errors (simulation results).

IV. Operating Characteristics of Proposed Dither Signal Injection Method

A. Computer Simulation Tests and Their Results

Simulation tests have been performed to verify effects of the dither signal injection on the control characteristics assuming the following four conditions:

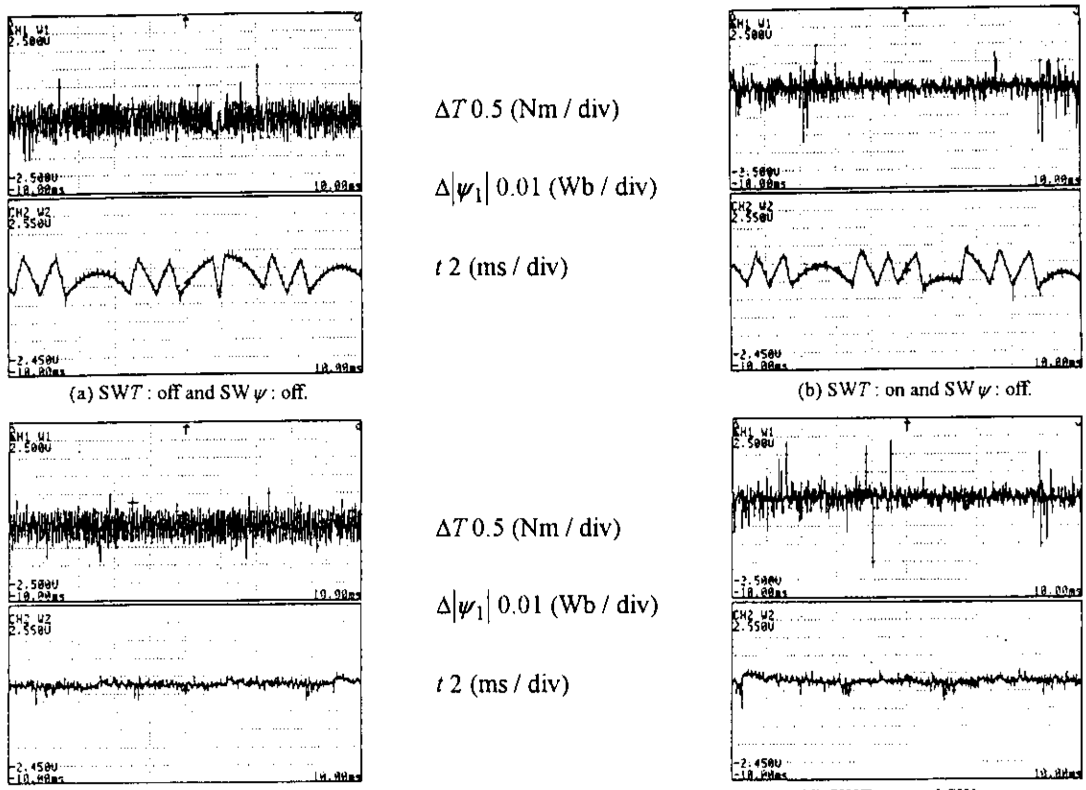
(i) no dither signals to the flux error nor the torque error,

(ii) dither signal only to the torque error,

(iii) dither signal only to the flux error, and

(iv) dither signals to both the flux error and the torque error.

Fig. 6(a)-(c) show the simulation results corresponding to



(a) SWT : off and SWψ : off. (b) SWT : on and SWψ : off.

(c) SWT : off and SWψ : on. (d) SWT : on and SWψ : on.

Fig. 8. Waveforms of stator flux and torque errors (experimental results).

those of Fig. 1 under the condition of (iv). It is known from Fig. 6(a) that the switching frequency can be raised to more than 18 (kHz) when no delay time is in obtaining the feedback signals of the flux and torque. As long as the hysteresis band width is not so small, the switching frequency can be kept almost constant. On the other hand, the switching frequency can be raised more than 15 or 12 (kHz) in spite of the delay time as shown in Fig. 6(b) and (c) respectively. However, the switching frequency is rather decreased than increased when the hysteresis band widths are too small. This is probably because of abnormal resonant oscillations between the ripples of the flux and torque errors and the dither signal.

Fig. 7(a)-(d) show the simulation results of the stator flux and torque error waveforms. According to the figures, the errors can be effectively reduced to approximately 30 (%) of the hysteresis band widths when the dither signal is applied to the system, which means that more smooth locus and rotation of the stator flux is possible. Also, although averaged offset of the developed torque against its command is in principle half of the hysteresis band width, it can be found that the proposed method is quite effective as well to reduce the offset as shown in Fig. 7(b) and (d).

B. Experimental Tests and Their Results

In order to verify the improvement of operating characteristics by the proposed method, an experimental system has been built up to drive a test motor described in TABLE I. The controller of the system has been made of analog circuits including the dither signal injecting function, and IGBT modules have been employed as switching devices in the power circuit of the PWM inverter. Test conditions of the experiments were exactly same as those of computer simulations, and several advanced tests with respect to the acoustic sound of the motor were also conducted.

Fig. 8(a)-(d) show the experimental results which correspond to the results of Fig. 7. It is known from these figures that all of the waveforms conform to the simulation results very well, and amplitude of the errors can be reduced as much as the simulation results by applying the dither signal to the system. Also, It should be stated that the quick torque response of the motor was experimentally confirmed without any degradation factors, that is overshoot nor undershoot, even though the dither signal is injected to the errors of the flux and torque.

Fig. 9 shows the experimental results of acoustic noise level when the test motor was operated at no load condition from

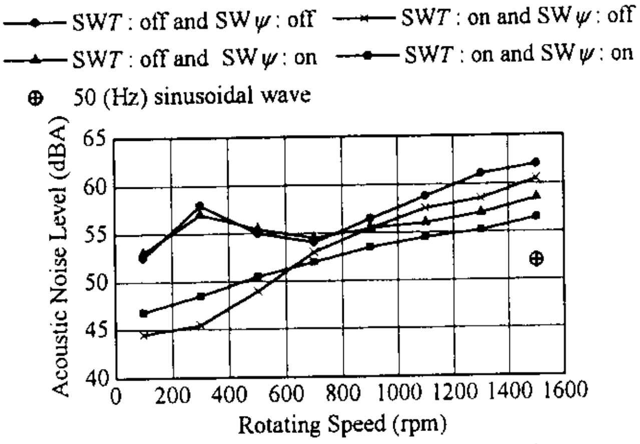


Fig. 9. Acoustic noise level of motor (experimental results).

100 to 1500 (rpm). From this figure, the noise level can be improved to less than 56 (dBA) over the whole speed range in case of (iv). The proposed method is very effective to reduce the acoustic noise compared with the characteristic of pure sinusoidal operation of which level was 52 (dBA). Fig. 10 (a)-(c) show frequency spectra of the acoustic noise when the motor was operated at 1500 (rpm). It can be found that the spectra of the conventional method is rather remarkable in low frequency region, while the spectra which was obtained in case of (iv) by the proposed method is effectively dispersed like a white noise. This characteristic is very essential to reduce the sound level which is sensed by a human being.

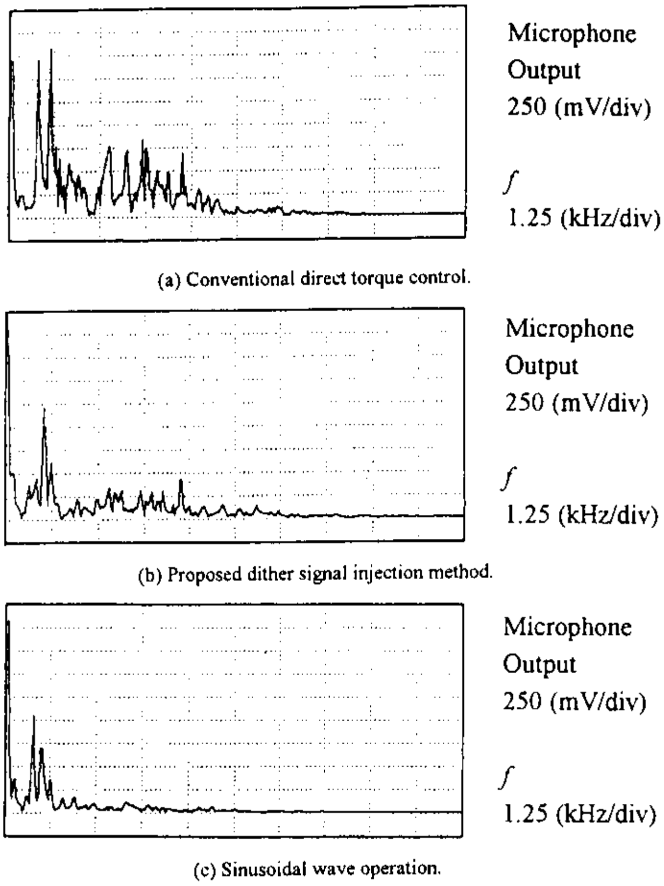


Fig. 10. Frequency spectra of acoustic noise (experimental results).

V. Conclusion

The paper has presented a novel simple method for high frequency switching operation of a PWM inverter for direct torque control of an induction motor, which aims at realizing an acoustically silent drive. The method introduces dither signal injection into the conventional system by superposing a high-frequency and small-amplitude triangular wave on the flux and torque errors. The frequency of the dither signal should be more than 30 (kHz) to make the switching frequency of the inverter more than 15 (kHz), and its amplitude should be as small as hysteresis band widths for the flux and torque control. According to the simulation and experimental results of a 1 (kW) test motor, amplitude of the stator flux ripple and developed torque ripple are reduced to approximately 30 (%) of those of the conventional operation, and the acoustic noise level was decreased to less than 56 (dBA) over the whole operating speed range, which is much closer to the noise level of pure sinusoidal operation than that of the conventional operation.

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