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ACOUSTIC STUDIES OF A 2.2 KW VARIABLE SPEED INDUCTION MOTOR

D Reyniers (1), J C S Lai (2) & D W J Pulle (3)

(1) Adelaide Logistic Company, Warradale 5046, Australia, (2) Acoustics & Vibration Centre, University College, Australia, (3) School of Electrical Engineering, University College, University of New South Wales, Australian Defence Force Academy, Canberra ACT 2600, Australia

1. INTRODUCTION

Adjustable speed drives are being used primarily because industrial applications demand variable speed operations such as in elevators and compressors. Furthermore the use of adjustable speed drives allow substantial energy savings, for example, in air conditioning systems. With the advent of power electronics, the speed of induction motors can now be controlled by inverters. However, as pointed out by many researchers (see for example, Timar & Hallinen [1], Belmans & Geysen [2]), inverter driven induction motors generally cause an increase in the supplementary losses and the noise and vibration levels emitted from the motors. While the harmonics in the supply are a major source in producing acoustic noise in inverter driven induction motors, even purely sinusoidal inverters (Belmans & Geysen [2] and Timar & Lai [3]) would give rise to a substantial increase in noise and vibration levels when the supply frequency coincides with the mechanical resonance frequency of the motor. Until recently most research into inverter driven induction motors has been focussed on the design of inverters without placing much emphasis on the vibro-acoustic behaviour of the motor itself.

The electrical performance characteristics of an inverter power conversion scheme largely depends on the choice of a particular PWM (pulse width modulation) scheme employed, Enjenti et al [4]. There are many types of PWM inverters available for use in variable speed drives, for example, carrier-modulated sine PWM and programmed PWM schemes. The programmed PWM techniques optimise the production of harmonics to minimise losses by reducing torque pulsations or by selective harmonic elimination. Enjenti et al [4] found that there was little or no difference between each of the programmed PWM techniques when significant numbers of low-order harmonics are removed.

Taniguchi et al [5] suggested that a solution to the audible noise problems from a PWM inverter would be to raise the switching frequency above the audible range. The switching frequency however, is limited by the storage time of the bipolar junction transistors (BJT's) and insulated gate bipolar transistors (IGBT's) employed in inverters. The problem with the storage time is only of concern during their switch off time which affects the overall switching signal. As a result of this storage time, faster switching leads to increased switching losses and hence less efficient inverters.

Habetler & Divan [6] suggested that the noise from an inverter driven electrical (induction) machine can be reduced by avoiding a concentration of harmonic energy at distinct tones. This can be achieved by employing a random switching pattern whilst preserving all of the advantages of the traditional PWM inverter. Random modulation is a relatively new method of PWM which has the potential to reduce the noise levels from the motor. Stemmler & Eilinger [7] proposed to use PFM (pulse frequency modulation) to spread the harmonics of a PWM inverter more evenly over the whole spectrum in order to avoid mechanical resonance and reduce acoustic noise.

In this paper, the effects of various controller strategies on the radiated acoustic noise of a 2.2 kW induction motor will be quantified by the overall A-weighted sound power level. Three configurations of frequency converter have been studied, namely an almost sinusoidal supply, PWM control and random modulation control. The relative contribution to the overall A-weighted sound power level due to aerodynamic/mechanical noise and electromagnetic noise for a range of motor operating speeds will be documented. Based on the measured sound power spectra and the supply voltage spectra, the differences in acoustical performance of the motor due to different frequency converters will be given.

2. EXPERIMENTAL SET-UP AND INSTRUMENTATION

The test motor was a Brook Crompton Betts three-phase, 4-pole 415V, 50Hz, 2.2kW induction motor with 44 rotor slots and 36 stator slots. Three drive configurations with the following characteristics were used:

1. an almost sinusoidal supply, hereafter referred to as the Benchmark, comprising a General electric 6.6 kW DC motor connected in shunt and mechanically coupled to drive a 3 phase 400V 5kVA synchronous generator, as shown schematically in Fig. 1. By adjusting the voltage from the variac, the magnitude of the DC voltage fed to the DC motor's armature and field windings varies. As the variac voltage increases, the speed of rotation of the DC motor increases and so does the speed of the synchronous generator. As the speed of the synchronous generator increases, its output frequency increases. The magnitude of the three phase output voltage from the synchronous generator is controlled by the variable DC power supply which controls the generator's field current. As a result the benchmark configuration provides a variable frequency, variable voltage three phase output, with very small harmonics.

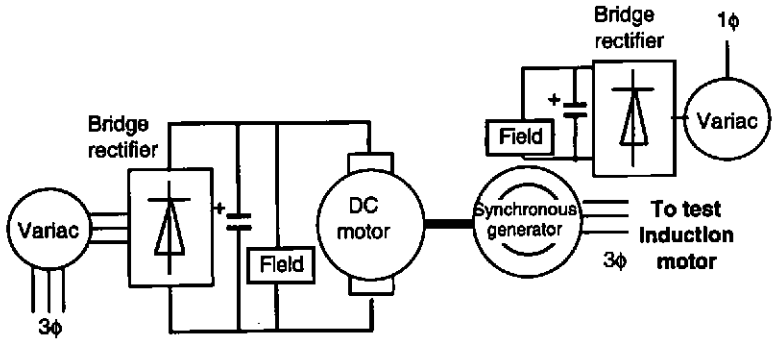


Fig. 1 Schematic diagram of Benchmark controller.

2. a PWM inverter with adjustable switching frequency. In the frequency range 22.3 - 32.5 Hz, the switching frequency varies from 669 Hz to 975 Hz while in the frequency range 32.6 Hz - 50 Hz, it varies from 685 Hz to 1050 Hz.

3. a random modulation inverter type VSC2000, manufactured by Zener Electric, in which the carrier frequency is modulated in pseudo-random manner with a spread of 20% about a selectable mean frequency of up to 16 kHz (16 kHz chosen in this study).

The three controllers were run by maintaining the same voltage-frequency (V/f) ratio. The output frequencies for the Benchmark controller, PWM and random modulation inverters remained stable to within $\pm$1-2 Hz, $\pm$1.5 Hz and $\pm$0.05 Hz respectively. Sound power measurements were made in an anechoic chamber using the sound intensity technique in accordance with the International Standard ISO 9614/2 [8]. The sound intensity measuring system comprised a Bruel & Kjaer (B&K) 2032 dual channel FFT analyser and a B&K sound intensity probe with two phase matched B&K 4135 (1/2 inch) condenser microphones mounted face to face and separated by 12 mm. The sound intensity measurements were controlled and processed by a Hewlett Packard (HP) series 300 microcomputer. Spectra of the supply voltage were obtained using a HP35665A dynamic spectrum analyser. All the results reported here were conducted under no-load conditions.

3. RESULTS

Overall Sound Power Levels

In order to determine the aerodynamic and mechanical noise from the induction motor, the motor was driven by a DC motor in the motor mode. All connections from the induction motor were removed and the noise from the DC motor was shielded using loaded vinyl. The DC motor was then powered up at various speeds and sound intensity measurements made. A plot of the A-weighted sound power level due to aerodynamic and mechanical noise is shown in Fig 2. As expected, the sound power level (due to aerodynamic & mechanical origin) increases with speed; it is very low at low speeds (approx. 41 dB(A) at 700 rpm) but increases to almost 62 dB(A) at 1500 rpm.

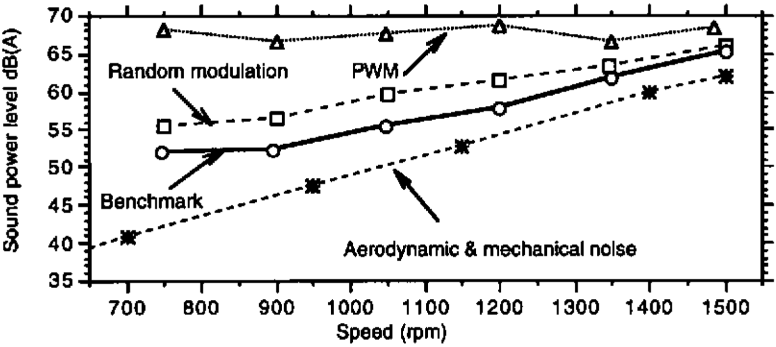
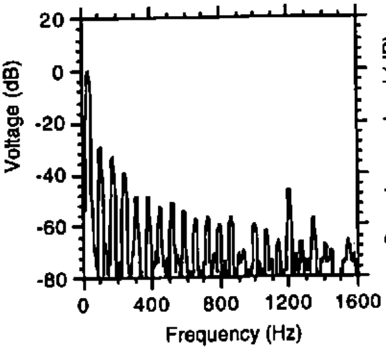


Fig. 2 Variation of A-weighted sound power level with speed.

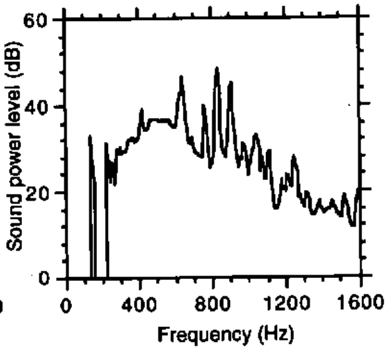
The overall A-weighted sound power levels (due to noise of aerodynamic, mechanical and electromagnetic origin) for the three different controlled drives are shown in Fig. 2. It can be seen that the Benchmark controller produces the lowest radiated sound power while the PWM inverter produces the highest radiated sound power. For all three controllers, the contribution by the aerodynamic and mechanical noise to the overall sound power is negligible at speeds below 900 rpm. As the speed increases, the aerodynamic and mechanical noise becomes more and more important especially for the Benchmark controller and the random modulation inverter. By 1500 rpm (the rated speed for the motor), the contribution of the aerodynamic and mechanical noise to the overall sound power is almost equal to that of electromagnetic origin for the Benchmark controller and the random modulation inverter. However, even at 1500 rpm, the contribution of the aerodynamic and mechanical noise to the overall sound power for the PWM inverter is still almost negligible compared with electromagnetic noise. In fact, Fig. 2 indicates that for the PWM inverter, the variation of the overall sound power level with speed is within 2 dB and that the electromagnetic noise dominates throughout the speed range from 700 - 1500 rpm. These results indicate that for a given motor, the noise at low speeds is dominated by electromagnetic noise which could be exacerbated when using a PWM inverter with low switching frequencies.

Supply voltage and Sound power Spectra

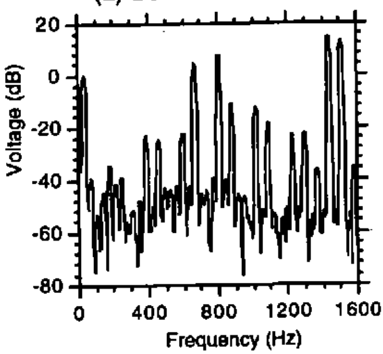
The voltage spectra of the three controllers producing a fundamental frequency of 35 Hz are shown in Fig. 3. Although the supply voltage of the Benchmark controller contains some harmonics, these harmonics are at least 30 dB below the fundamental (Fig.3(a)). Thus the Benchmark controller can be considered to produce an almost purely sinusoidal supply. On the other hand, the voltage spectrum of the PWM inverter in Fig. 3(b) shows the 19th, 23rd, 41st and 43rd harmonics are almost 10 dB higher than the fundamental. According to Yang [9], it is not unusual for the amplitude of some of the higher order harmonics to be considerably higher than the fundamental.



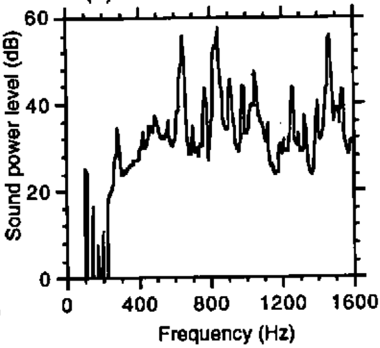
(a) Benchmark



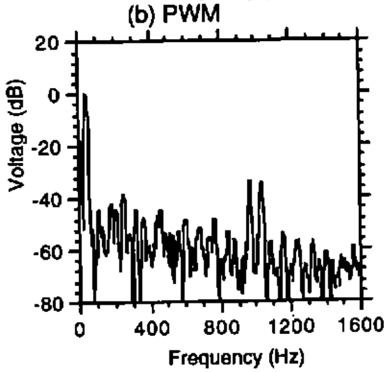
(a) Benchmark



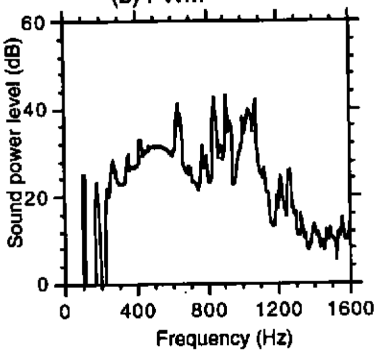
(b) PWM



(b) PWM



(c) random modulation



(c) random modulation

Fig.3 Supply voltage spectra.

Fig. 4 Sound power spectra.

Fig. 3(c) shows that the random modulation technique has been quite successful in reducing the harmonics to levels almost comparable with those of the Benchmark controller, thus resulting in similar radiated sound power levels as have already been observed in Fig. 2. Fig. 4 for the three different controllers confirm the adverse effects of the harmonics on the radiated sound power spectra. Though not presented here, the peaks in the sound power spectra were found to coincide with the resonant frequencies of the motor structure. The large amplitude harmonics in the supply voltage of the PWM inverter excited these resonances and thus produced substantially higher radiated acoustic sound power levels.

4. CONCLUSIONS

The radiated sound power level of an induction motor driven by an almost purely sinusoidal supply, a PWM inverter and a random modulation inverter for a range of speeds have been measured separately by the sound intensity technique. Results indicate that generally electromagnetic noise dominates at low speeds while aerodynamic and mechanical noise become more important at high speeds. The large amplitude harmonics present in the PWM inverter excite the resonance frequencies of the motor structure, thus causing sound power levels higher than those of the other two controllers by at least 10 dB. On the other hand, the random modulation technique has been successful in reducing the harmonic content in the voltage supply, thus resulting in overall radiated sound power level less than 5 dB higher than that controlled by an almost purely sinusoidal supply.

ACKNOWLEDGMENT

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