Audible Noise in Speed-Controlled Inverter-Fed Medium-Sized Induction Motors

J. Muster, P. K. Budig, R. Belmans, W. Geysen, Ph. K. Sattler

Abstract

The audible noise produced by three-phase, squirrel-cage induction motors, is caused by the space harmonics of the flux-density distribution in the air gap of the machine. When the motor is supplied by a frequency inverter in order to control the speed, time harmonics in both current and voltage are present, yielding new components in the audible noise spectrum. In the paper, a number of motor-inverter combinations are compared for medium-sized induction motors (90 kW). As a reference case, the motors are supplied with a generator, delivering a variable frequency without harmonics. Theoretical explanations for the increase of the audible noise level and the additional frequency components are given.

1 Introduction

The increasing use of speed-controlled inverter-supplied induction motors has several advantages for the users. Especially when squirrel-cage speed induction motors are employed, an ideal matching of the speed required by the manufacturing process is obtained, without the inconvenience of brushes and commutator as found in the DC motor. However, some disadvantages have to be mentioned as increased motor losses, pulsating torques and increased audible noise levels when compared to a sinusoidal supply.

When the speed range is extended above the rated speed, the audible noise of the machine is dominated by the aerodynamic audible noise of the fan. This is definitely so when two- and four-pole machines are used. At low frequencies, the audible noise, induced by the inverter supply, may become predominant. The aerodynamic audible noise sources may be counteracted by using a separate fan or by optimizing the motor and fan construction. The audible noise due to the inverter supply depends on the operating principle of the inverter (Voltage-Source Inverter VSI or Current-Source Inverter CSI). In a voltage-source inverter a pulse-width modulation (PWM) scheme may be used, and high pulse frequencies may be beneficial for the audible noise [1].

In this paper, it will be shown how the inverter type influences the generated audible noise. Furthermore, the effect of the number of slots in the rotor of the motor will be discussed in order to find out whether an odd or even number of rotor slots has advantages in speed-variable induction motors with respect to the audible noise level.

2 Theoretical Considerations

2.1 Basic Quantities

The audible noise in induction machines has two major origins. The first one is the fan and the passing of the cooling air through the machine. The second one is the generation of electromagnetic vibrating forces in the machine air gap, acting on the mechanical structure, mainly the stator, and causing it to oscillate.

Even when a purely sinusoidal stator current is supplied, several – in theory an infinite number – of space harmonics are generated by the stator windings. These harmonics all induce voltages in the rotor, generating currents that again produce an infinite number of space harmonics.

When discussing the audible noise of induction motors, the following influences have to be taken into consideration:

- space harmonics due to the distribution of windings in individual slots;
- space harmonics of the stator and rotor caused by the changing reluctance due to slotting;
- space harmonics due to the non-centred position of the rotor with respect to the stator bore or due to an unbalance of the rotor, i. e. the eccentricity harmonics;
- space harmonics due to saturation.

When the machine is inverter supplied, the non-sinusoidal currents and voltages lead to supplementary time harmonics. With the same analysis as used for the fundamental time harmonic, they lead to a new set of space harmonics and supplementary components in the audible noise spectrum. Some of the tones are very pure and therefore, very annoying for the human ear.

2.2 Harmonic Number and Frequencies Due to the Machine Layout

In order to calculate the audible noise, the harmonic numbers and the frequencies of the various space harmonics of the flux-density distribution in the air gap have to be derived [2–4].

Due to the distribution of the stator windings into individual slots, space harmonics are generated with a number of pole pairs:

$$\nu = p(6g+1), \text{ with } g = 0, \pm 1, \pm 2, \ldots. \tag{1}$$

The so-called slot harmonics, these are those harmonics of which the amplitude is not decreased by the winding design, have a number of pole pairs:

$$\nu = p + gN_1, \text{ with } g = \pm 1, \pm 2, \ldots, \tag{2}$$

with N_1 the number of stator slots. This is also the number of pole pairs due to the reluctance change caused by slotting. Both slot and slotting harmonics have to be added accounting for the correct phase angle [5].

The harmonic numbers of the rotor harmonics in squirrel-cage induction motors are:

$$\lambda = p + g_2 N_2, \text{ with } g_2 = \pm 1, \pm 2, \ldots, \tag{3}$$

with N_2 the number of rotor slots. The combination of the rotor and stator harmonics lead to forces waves with a number of pole pairs

$$r = |\nu \pm \lambda| \quad \text{or} \quad 0 \quad \text{or} \quad |2\nu| \quad \text{or} \quad |2\lambda|. \tag{4}$$

In general, the influence of the uniformly distributed forces ($r = 0$) or the forces with a high number of pole pairs (e. g. $|2\nu|$ or $|2\lambda|$) may be neglected. Therefore, only the first term of eq. (4) has to be considered. The resulting frequencies are (+ in eq. (4)):

$$f = 2f_1\left[\frac{N_2}{2p}|g_2|(1-s) \pm 1\right] \tag{5}$$

and (– in eq. (4)):

$$f = 2f_1\left[\frac{N_2}{2p}|g_2|(1-s)\right]. \tag{6}$$

Space harmonics due to saturation have the harmonic numbers:

$$\mu = 3p \pm gN_2. \tag{7}$$

The resulting forces have the harmonic number:

$$r = |\mu \pm \nu| \tag{8}$$

and the frequencies (+ in eq. (7))

$$f = 2f_1\left[\left(\frac{N_2}{2p}|g_2|(1-s) \pm 1\right) \pm 1\right] \tag{9}$$

and (– in eq. (7)):

$$f = 2f_1\left[\frac{N_2}{2p}|g_2|(1-s) \pm 1\right]. \tag{10}$$

Eccentricity causes harmonics having a number of pole pairs:

$$\rho = (p \pm 1) \pm gN_2 \tag{11}$$

yielding forces with number of pole pairs:

$$r = |\lambda \pm \rho| \tag{12}$$

and frequencies (+ in eq. (12))

$$f = 2f_1\left[\frac{N_2}{2p}|g_2|(1-s) \pm 1\right] \pm \frac{f_1}{p}(1-s) \tag{13}$$

and (– in eq. (12))

$$f = 2f_1\left[\frac{N_2}{2p}|g_2|(1-s)\right] \pm \frac{f_1}{p}(1-s). \tag{14}$$

2.3 Influence of the Inverter Supply

If an induction motor is supplied by an inverter, the frequencies discussed above become a function of the speed. This leads to new components in the excitation. For a VSI with PWM inverter or a non-pulsed CSI, the current is approximately a square wave. Therefore, the amplitude of the time-harmonic components are inversely proportional to the harmonic number:

$$I_{1,n} = I_1/n \quad \text{with } n = 6g+1 \text{ and } g = 0, \pm 1, \pm 2. \tag{15}$$

The slip of the n-th time harmonic is:

$$s_n = 1 - 1/n \approx 1. \tag{16}$$

In other words: the rotor approximately stands still with respect to the higher time harmonics, rotating in space at high speeds. At no-load ($s = 0$), the stator time harmonics with frequency:

$$f_{1,n} = (6g \pm 1)f_1 \tag{17}$$

induce rotor currents, having the frequency:

$$f_{2,n} = 6\,g\,f_1\,. \tag{18}$$

This is caused by the fact that they have a different rotation sense.

When using PWM-VSI, often the distinction is made between a 180° pulsing scheme as frequently found when using sinus modulation, and a 120° pulsing scheme, generally used in triangular modulation.

In the sinus modulation, the spectrum is dominated by [4]:

$$f_{1,n} = 2f_1(G \pm 1)n, \tag{19}$$

with G the number of pulses per half period of the fundamental time harmonic. With the triangular modulation scheme, two kinds of time harmonics are found:

$$f_{1,n} = 3f_1(G \pm 1)n \tag{20}$$

and

$$f_{1,n} = f_1 n. \tag{21}$$

The latter one may have amplitudes up to 20 % of the fundamental.

From the voltage harmonics, the current harmonics may be derived, using the equivalent circuit parameters:

$$|\underline{I}_n| = \frac{U_n}{\sqrt{(R_1 + R'_{2,n})^2 + (X_{\sigma 1,n} + X'_{\sigma 2,n})^2}}. \tag{22}$$

The parameters depend on the frequency of the harmonic n under consideration, amongst others due to the skin effect in the rotor bars [4, 8 – 10].

2.4 Audible Noise Generation

The calculation of the individual permeance waves is treated in literature by various authors [2, 3, 6, 7, 11 – 15]. When calculating the amplitude of forces generated by a component of the field, the normal component flux density distribution is required:

$$b_n(\alpha,t) = \Lambda(\alpha,t)\cdot a(\alpha,t). \qquad (23)$$

$\Lambda(\alpha,t)$ is the permeance distribution and $a(\alpha,t)$ the m.m.f. The radial force-wave distribution is found from the Maxwell stress theorem:

$$\sigma(\alpha,t) = \frac{b_n^2(\alpha,t)}{2\mu_0}. \qquad (24)$$

These stresses yield dynamic deformations $Y_{2\mathrm{dyn}}$, that are functions of the stator geometry, the material characteristics and the machine casing including the mounting.

The audible noise calculation is a combination of these vibrations, the acoustic properties of the stator and the situation of the surroundings. When vibrations are found having a frequency equal to a bending or torsional natural frequency of the stator assembly, the resulting audible noise may become large.

In literature when analysing an infinite bus situation, it is found that machines with a rotor having an odd number of bars are noisy, due to harmonics in the air gap flux-density distribution with low number of pole pairs leading to bending vibrations.

2.5 Theoretical Results

Two motors are used to verify the analysis. The first motor is a three-phase, standard motor. The second motor is a specially designed heat-pipe-cooled machine [16, 17]. In this motor, two rotors are used, one having 27 rotor slots, the other 28 rotor slots. The rated power is 90 kW for both.

The theoretical natural frequencies of the three motors under consideration, are given in Tab. 1 of [6].

Using the analysis as discussed above, the calculation of the excitation frequencies and pole pairs is possible, as a large number of combinations is found and a computerized calculating scheme has to be used [5 – 7].

In CSI and non-pulsed VSI time harmonics having six, twelve and 18 times the fundamental frequency are generally very pronounced. The used PWM-VSI has a pulse frequency yielding harmonics having a large influence on the audible noise. The frequency of these time harmonics is in the range between 500 Hz and 2 200 Hz.

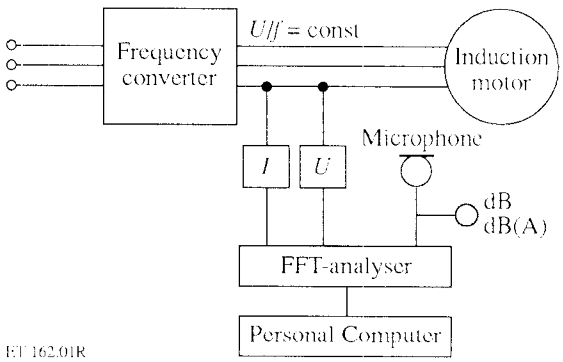

Fig. 1. Set up of the measurements

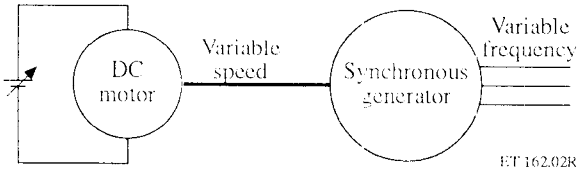

Fig. 2. Sinusoidal variable frequency supply

3 Experimental Results

Three motors and three supply types are combined. The fundamental frequency is varied from 5 Hz to 50 Hz. In order to limit the influence of the aerodynamic audible noise, the fan was removed. The motor was not loaded, the stator was Y-connected. In the above-mentioned frequency range, the overall value of the audible noise (both linear and dB(A)) is measured. The frequency spectra of the supplied voltage, current and audible noise are evaluated for specific values of the supply frequency. The voltage-to-frequency ratio is kept constant (**Fig. 1**). As a sinusoidal variable frequency supply, a synchronous generator, driven by a variable speed DC motor is used (**Fig. 2**).

4 Audible Noise in Speed-Controlled Operation

4.1 Overall Audible Noise Level

The combined results of all three motors and inverters are shown in **Fig. 3a**, **3b** and **3c**. As a general conclusion, it can be seen that the influence of the supply harmonics on the audible noise becomes more pronounced in the lower frequency range. The increase may be as high as 30 dB, the PWM-VSI being the least favourable in this respect.

In **Fig. 4a** it is shown that with a sinusoidal supply, the 28-slot motor has approximately the same emitted audible noise as the standard motor. The 27-slot motor may have either positive or negative deviations that may be as 10 dB(A). Therefore, a general conclusion with regard to the advantages of odd or even slot numbers is not possible when the supply frequency is controlled. Calculations [7] show that a slot ratio of 36-stator to 28-rotor slots yield torsional vibrations due to saturation; a ratio of 36 to 27 is sensitive to radial vibrations due to saturation. **Fig. 4b** and **4c** compare the three motors for the CSI, respectively the PWM-VSI.

With the 27-slot motor, resonances are found in the frequency range of 16 Hz to 20 Hz due to saturation harmonics and due to the stator fundamental and the second rotor slotting harmonic. The resonance is due to the specific number of slots. An increase of 13 dB(A) of the audible noise is found. This resonance causes with all supply types the high audible noise level and is the real disadvantage of the odd number of rotor slots, when a speed-controlled system is used. The increase of the audible

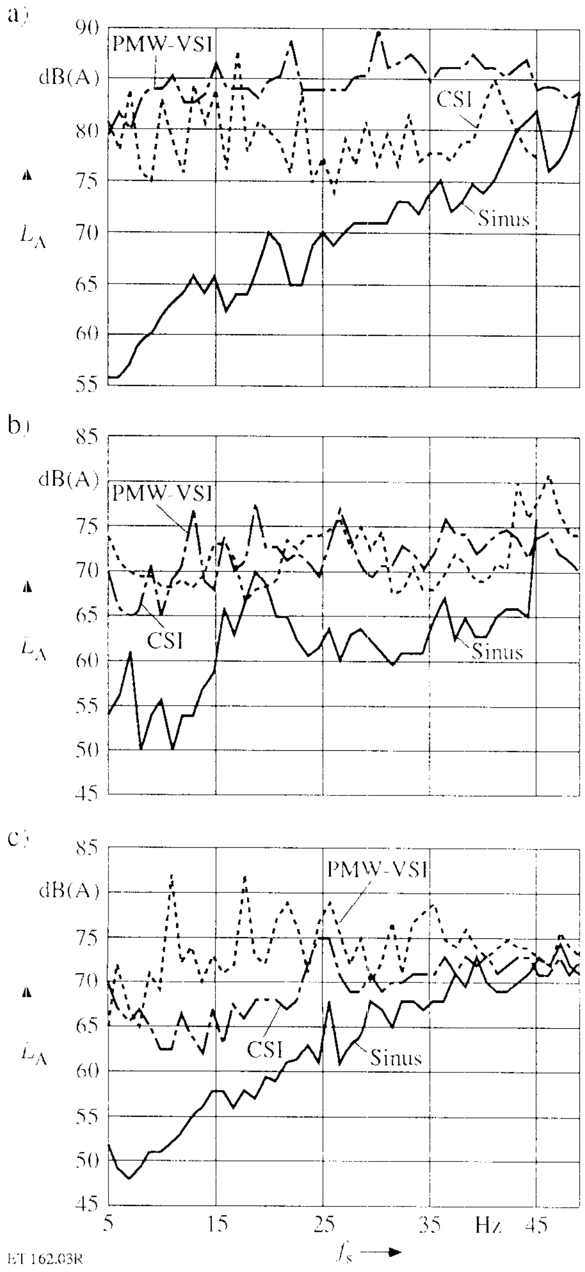

Fig. 3. Audible noise L_A for induction motors with sinusoidal supply, CSI and PWM-VSI (f_s supply frequency)
a) Standard induction motor
b) Heat-pipe-cooled induction motor with 27 rotor slots
c) Heat-pipe-cooled induction motor with 28 rotor slots

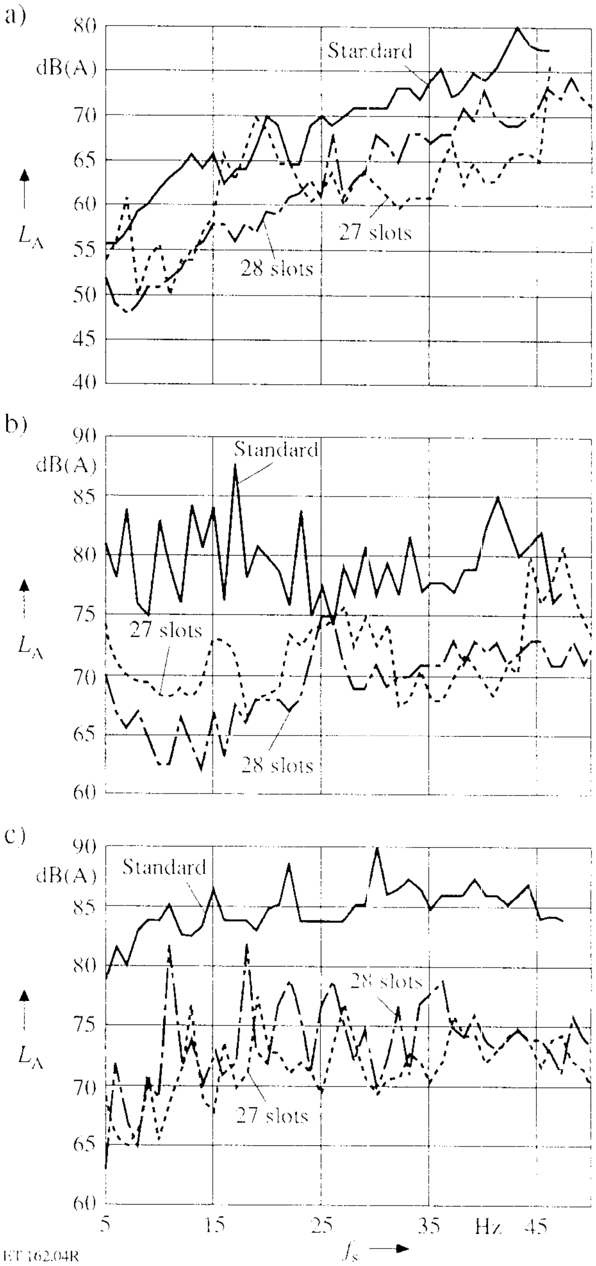

Fig. 4. Audible noise of the different motors
a) Sinusoidal supply
b) CSI supply
c) PWM-VSI supply

noise level at 37 Hz is caused by the resonance excited by the combination of the stator fundamental field and the third rotor slotting harmonic. The resonance problems are with inverter-supplied machines mystified due to the audible noise increase caused by the supply harmonics.

With the CSI, the audible noise is to a large extend independent of the motor type.

When analysing the audible noise differences in the PWM-VSI-supplied 28-slots motor, the inverse tendency is noted as this motor shows a large noise increase. This is partially due to the earthing of the neutral conductor during the tests, allowing a homopolar current due to saturation to flow, which is not accounted for in the analysis.

4.2 Current and Voltage Spectra

In order to find out what the causes of the audible noise increase due to inverter supply are, a number of spectra of the audible noise, the supplied voltage and current are analysed. In **Fig. 5a** to **8b**, an excerpt of the analysis is given.

When supplying the motor with a generator, the current and voltage is virtually free of time harmonics. Fig. 5a to 6b show the frequency spectra of the current and the voltage supplied to the heat-pipe-cooled motor with 27 rotor slots when the machine is supplied by a CSI and a PWM-VSI. Short-circuit currents are induced in the rotor squirrel cage, having a fixed frequency ratio

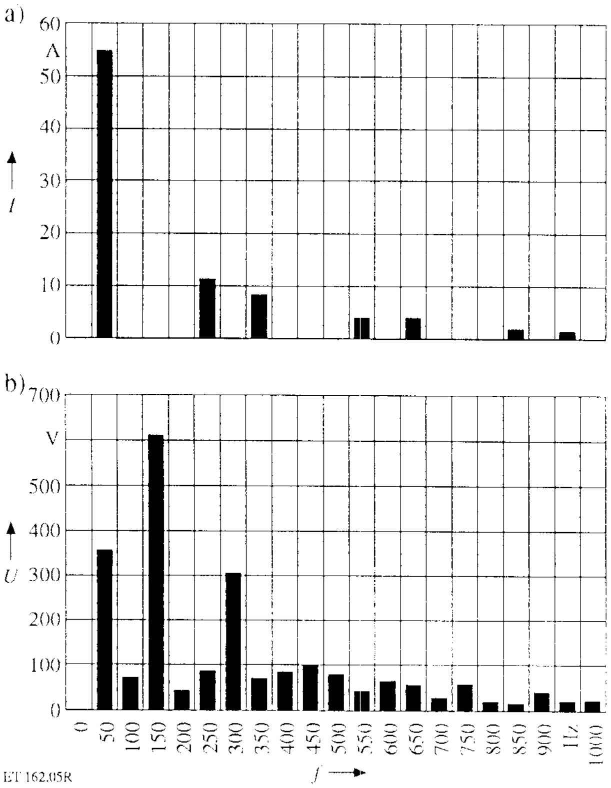

Fig. 5. CSI-supplied, 27 rotor slots heat-pipe-cooled motor at 50 Hz

a) Current spectrum

b) Voltage spectrum

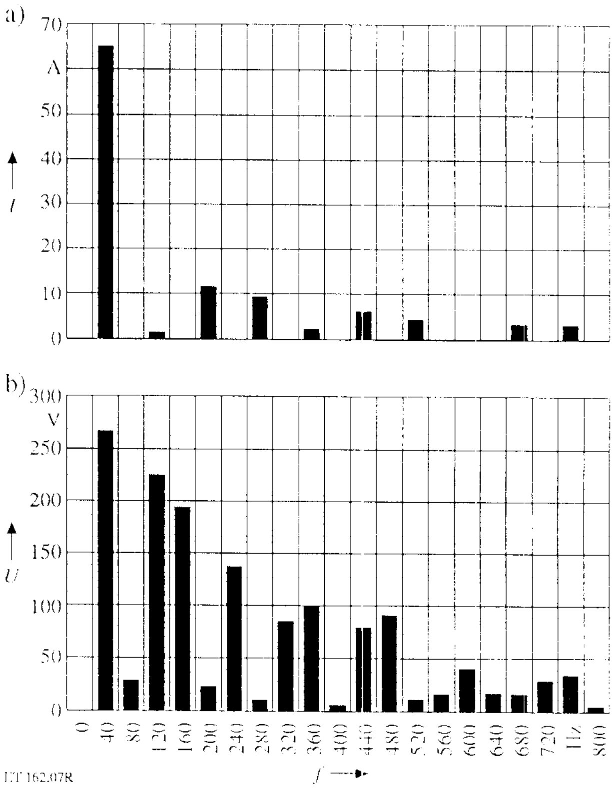

Fig. 7. CSI-supplied, standard squirrel-cage induction motor at 40 Hz

a) Current spectrum

b) Voltage spectrum

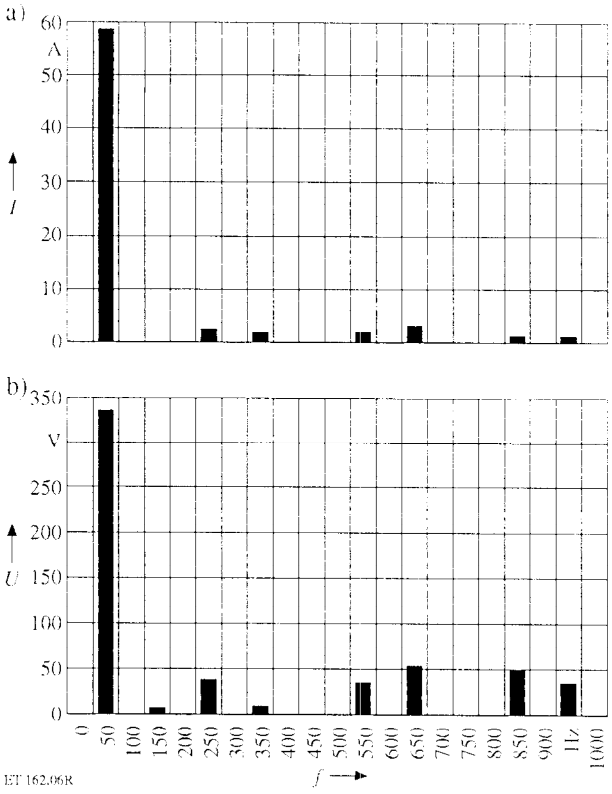

Fig. 6. PWM-VSI-supplied, 27 rotor slots heat-pipe-cooled motor at 50 Hz

a) Current spectrum

b) Voltage spectrum

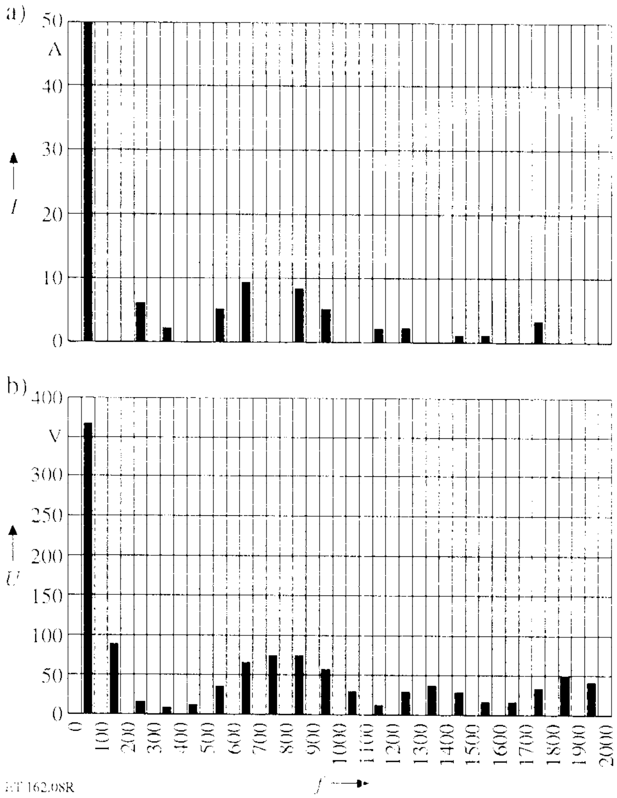

Fig. 8. PWM-VSI-supplied, standard squirrel-cage induction motor at 50 Hz

a) Current spectrum

b) Voltage spectrum

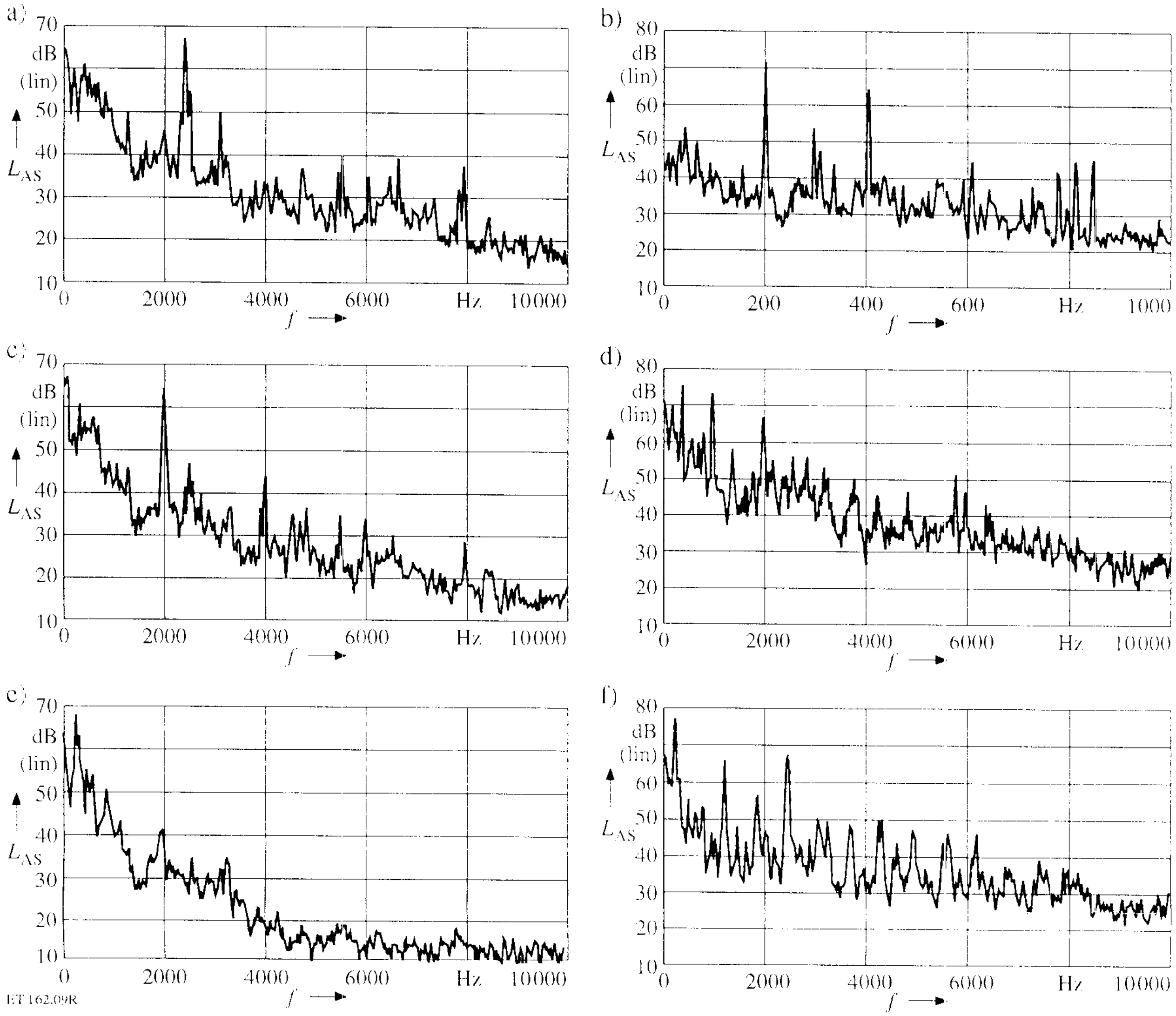

Fig. 9. Audible noise frequency spectrum L_{AS} of the heat-pipe-cooled motor with 27 rotor slots
a) Sinusoidal supply at 45 Hz
b) CSI supply at 34 Hz
c) Sinusoidal supply at 36 Hz
d) PWM-VSI supply at 34 Hz
e) Sinusoidal supply at 16 Hz
f) PWM-VSI supply at 15 Hz

with respect to the stator fundamental time harmonic (eqs. (15) and (18)). The spectrum of the current changes proportionally to the supply frequency (Fig. 7a to 8b). As the winding, slotting, eccentricity and saturation harmonics also change proportionally to the supply frequency, these interactions are virtually independent of the supply frequency, and the generated audible noise caused by the harmonics in the supplied current remains relatively constant as speed increases.

At f_1 = 5 Hz the current pattern is pulsed in order to decrease the influence of the current on torsional vibrations [12], yielding an increase of the audible noise level due to new harmonics.

When a PWM-VSI is used, the pulse frequency and its multiples and harmonics are pronounced. In the overall speed range, harmonics in both voltage and current are found. For a given pulse frequency, the amplitude and frequency spectra remain relatively constant. Therefore, when compared to the CSI, the number of coincidences between the frequency of the harmonics in the rotor and the frequency of the reluctance variation, which are a function of the speed, is much higher. This yields the necessary conditions to have large audible noise peaks, which increase the overall audible noise level when compared with other supply types. This kind of problems can only be counteracted by using a sufficiently high pulse frequency of several kHz. However, the other sources of audible noise are not counteracted using high switching frequencies.

4.3 Audible Noise Spectra

In **Fig. 9a**, the audible noise spectrum of the 27-slot heat-pipe-cooled motor is shown at a supply frequency of 45 Hz, with the sinusoidal supply. The audible noise due to the combination of the stator fundamental and the rotor slotting harmonics contains the following frequencies:

f = 505 Hz … 685 Hz:	1st rotor slotting harmonic,
f = 1 280 Hz:	2nd rotor slotting harmonic,

$f = 2\,500$ Hz: 3rd/4th rotor slotting harmonic-resonance,

$f = 3\,100$ Hz: (4th/5th rotor slotting harmonic).

The high audible noise peak at 2 500 Hz is due to the resonance as one of the mechanical natural frequencies is particularly close.

The frequency spectrum of the audible noise generated by the motor supplied by the CSI shows a low spectrum at low frequencies with high peaks in the low frequency range (**Fig. 9b**). The 200 Hz and 400 Hz noise components are caused by the 5th and 7th, respectively 11th and 13th current time harmonics, inducing currents in the rotor at six, respectively twelve times the fundamental frequency.

Fig. 9c shows the audible noise when using the sinusoidal supply at 36 Hz. The typical sound frequencies are again due to the rotor slotting harmonics.

$f = 636$ Hz ... 708 Hz: 1st rotor harmonic,

$f = 1\,345$ ... 1 489 Hz: 2nd rotor harmonic,

$f = 2\,054$ ... 2 198 Hz: 3rd rotor harmonic.

This spectrum may be compared to the one of the PWM-VSI-supplied motor (**Fig. 9d**). As resonance occurs at 1 788 Hz, a minor excitation, as, e. g. due to the 47nd and 49nd with an amplitude of approximately 4 % of the fundamental time harmonic of the current with the PWM-VSI supply may lead to high audible noise levels. The increase is here 30 dB. The same holds for the resonance frequency at 3 108 Hz. As the frequency spectrum of the current of a PWM-VSI only alters slightly as the supply frequency changes, these resonances dominate the audible noise frequency spectra at all speeds.

However, a resonance situation is not obligatory. **Fig. 9e** and **9f** show for a fundamental frequency of 15 Hz, sinusoidal, respectively 15 Hz PWM-VSI the audible noise spectrum emitted by the 27 rotor slots heat-pipe-cooled motor. The spectrum is dominated by a component at 272 Hz coming from the combination of the second rotor slotting harmonic and a component due to saturation. The supplementary time harmonics generate further frequencies, being multiples of the pulse frequency (1 260 Hz, 1 890 Hz, 2 520 Hz).

5 Conclusions

When the speed of an induction motor is controlled using static inverters, time-harmonic components in the current are generated. On top of the slot, slotting, saturation and eccentricity harmonics, this may lead to an increased audible noise level.

As the theoretical analysis of a standard motor and two heat-pipe-cooled machines shows (all 90 kW motors), these inverter-induced noise components dominate the audible noise spectrum beneath the rated speed. The supply using a sinusoidal voltage differs from the supply with an inverter (both CSI and PWM-VSI) due to the following aspects:

- Using a sinusoidal supply, the slot, slotting saturation and eccentricity harmonics yield audible noise components that may be particularly high when resonance occurs.
- Using a non-pulsed CSI, rotor currents are induced having frequencies and amplitudes with a fixed relation to the fundamental. The spectrum of the currents is proportional to the fundamental frequency. As the frequencies of the slot, slotting, saturation and eccentricity harmonics are also proportional to the fundamental frequency, their pattern is also speed independent. However, the relation between the harmonic components due to the time harmonics of the supplied current and the resonance frequencies of the induction motor, is not constant. The pulse pattern often used at low supply frequency to minimize pulsating torques, yields time-harmonic component with higher frequencies in the force spectrum generating the audible noise.
- Using a PWM-VSI, time harmonics are generated in the whole speed range. Their spectrum, both amplitude and frequency, is relatively constant for a given pulse frequency. Therefore, when compared to the non-pulsed CSI, the coincidence of the frequencies of reluctance waves in the machine, which are functions of the machine speed, and of the time harmonics of the inverter current, often lead to force components increasing the audible noise level. Therefore, this type of drive is often more noisy. This increase may be avoided by using high-pulse frequencies (several kHz). Using modern switching devices, this becomes feasible, even for medium-sized drives, as discussed here.

6 List of Symbols and Abbreviations

$a(\alpha, t)$	m.m.f. distribution
$b_n(\alpha, t)$	radial component of the flux-density distribution
f	frequency of the Maxwell stress distribution component
f_1	stator frequency
n	number of the stator time harmonic
p	number of pole pairs
r	harmonic number of the Maxwell stress distribution component
s	slip
t	time
G	number of pulses per half period of the fundamental time harmonic of a PWM inverter
$I_{1,n}$	r.m.s. value of the n-th time harmonic of the stator current
N_1	number of stator slots
N_2	number of rotor slots
R_1	stator resistance
$R_{2,n}$	rotor resistance of the n-th time harmonic
$U_{1,n}$	r.m.s. value of the n-th time harmonic of the stator voltage
$X_{\sigma 1,n}$	stator leakage reactance of the n-th time harmonic
$X_{\sigma 2,n}$	rotor leakage reactance of the n-th time harmonic
$Y_{2\mathrm{dyn}}$	dynamic deformation

α	angular coordinate in the air gap
λ	harmonic number of a rotor space harmonic
μ	harmonic number of a saturation harmonic
μ_0	permeability of free space
ν	harmonic number of a stator space harmonic
ρ	harmonic number of an eccentricity harmonic
$\sigma(\alpha, t)$	radial force-wave distribution (Maxwell stress)
$\Lambda(\alpha, t)$	permeance distribution
VSI	voltage-source inverter
CSI	current-source inverter
PWM	pulse-width modulation

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The Authors

Ronnie J. M. Belmans (1956) received the M.Sc. degree in Electrical Engineering from the Katholieke Universiteit Leuven/Belgium in 1979, the Ph.D. degree from the same university in 1984 and the Special Doctorate in 1989. From 1979 to 1985 he was a member of the staff of the Katholieke Universiteit Leuven. Currently, he is a Research Associate of the National Fund for Scientific Research (Belgium) at the same place. He is also part-time Associate Professor with the Katholieke Universiteit Leuven, teaching synchronous machines. His research interests include electrical machine design (permanent-magnet motors and induction motors), computer-aided engineering, and vibrations and audible noise in electrical machines. He was the Director for the NATO Advanced Research Workshop in Vibrations and Audible Noise in Alternating Current Machines (August, 1986). He worked at the Laboratory for Electrical Machines of the RWTH Aachen/Germany as a Von Humboldt Fellow (October 1988 until September 1989). From October 1989 till September 1990, he was a visiting Associate Professor at McMaster University, Hamilton/Canada. He is a member of the IEE (UK), a senior member of the IEEE (USA) and a member of the koninklijke Vlaamse Ingenieursvereniging (kVIV). Since November 1992 he is a member of the Editorial Board of ETEP. (Katholieke Universiteit Leuven, Dep. E.E. – Afd. V.I.T. – Lab. EMA, Kard. Mercierlaan 94, B-3001 Leuven-Heverlee/Belgium, T +32 16/22 09 31 / Fax +32 16/29 30 64)

Peter-Klaus Budig (1928) studied Electrical Engineering at the Technische Hochschule Dresden/Germany from 1948 till 1952. For two years he was Assistant at the chair of Electrical Machines and Drives. From 1954 he was with Sachsenwerk Dresden. He was involved in research and development of amplidyne, three-phase commutator-machines, DC and AC traction motors, thyristor-supplied traction motors. For some years he was Chief Technologist and finally Chief Engineer. At this time he is planning the production of new types of electrical machines like hermetic-motors, rolling-mill motors, hydrogenerators and fractional horsepower induction motors. 1966 he got a call as a Professor to the Technical University at Chemnitz/Germany. His research activities are three-phase linear motors, thyristor-supplied DC motors, electric cars, computation of magnetic fields, multi-motor AC drives, high precision drives for the submicrometer-range, magnetic bearing and high speed AC drives. (TU Chemnitz/Zwickau, Fachbereich Elektrotechnik, Carolastr. 8, D-09111 Chemnitz/Germany, T +49 3 71 / 5 61 33 23, Fax +49 3 71 / 5 61 33 61)

Willy J. D. Geysen (1939) received the M.Sc. degree in Electrical Engineering from the Katholieke Universiteit Leuven/Belgium in 1967 and the Ph.D. from the same university in 1970. He received the M.Sc. degree in Law from the State Commission. Since 1969 he has been a member of the staff of the Katholieke Universiteit Leuven, where he is currently Full Professor and Head of the Department of the Power Engineering Division. He served as Chairman of the Electrical Engineering Department from 1972 to 1975. He has been Visiting Professor at the Technical University Munich and at the University of Trier, both in Germany. His teaching and research interests include electrical machines, variable frequency drives and electrical safety. Since 1991 he is spokesman for the university. He is a member of IEEE, the IEE (UK), Verband Deutscher Elektrotechniker (VDE), Verband Deutscher Ingenieure (VDI) and koninklijke Vlaamse Ingenieursvereniging (kVIV). From January 1991 until October 1992 he was a member of the Editorial Board of ETEP. (Katholieke Universiteit Leuven, Dep. E.E. – Afd. V.I.T. – Lab. EMA, Kard. Mercierlaan 94, B-3001 Leuven-Heverlee/Belgium, T +32 16 / 22 09 31, Fax +32 16 / 29 30 64)

Jörg Muster (1955) studied Electrical Engineering at the Technische Hochschule Karl-Marx-Stadt/Germany from 1974 to 1978. Till 1985 he was Assistant at the chair of Electrical Machines and Drives, absolved with promotion about losses and torques of inverter-supplied AC machines. From 1985 until 1988 he worked for a tool-machine factory, developing high-speed AC drives. Since 1988 he is Scientific Assistant at the chair of Electrical Machines and Drives at the Technische Universität Chemnitz/Germany. (TU Chemnitz/Zwickau, Dezernat 5.0, Technologietransfer, Carolastr. 8, D-09111 Chemnitz/Germany, T +49 3 71 / 68 62 17, Fax +49 3 71 / 68 62 40)

Philipp K. Sattler (1923) received the Dipl.-Ing. and Dr.-Ing. degrees from the Technical University Munich/Germany in 1949 and 1957, respectively. In 1954 he joined Brown Boveri Company at Mannheim/Germany, where he was Chief of the Electrical Design Department of all Electrical Machines. In 1964 he became Professor of the RWTH (University) in Aachen/Germany and Director of the Institute of Electrical Machines. His interests in research and development are numerical calculation of electromagnetic field, forced cooling, linear motors, inverter-fed induction and synchronous motors, application of observers, and filters on electrical machines. He retired in 1988. (RWTH Aachen, Institut für Elektrische Maschinen, Schinkelstr. 4, D-52062 Aachen/Germany, T +49 241 / 80 76 38, Fax +49 241 / 40 45 97)