A Low-Cost System for Measurement and Spectral Analysis of Motor Acoustic Noise

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***Abstract*—Workplace noise has become one of the major issues in industry not only because of workers' health but also due to safety. Electric motors, particularly, inverter fed induction motors emit objectionably high levels of noise. This has led to the emergence of a research area, concerned with measurement and mitigation of the acoustic noise. This paper presents a low-cost option for measurement and spectral analysis of acoustic noise emitted by electric motors. The system consists of an electret microphone, amplifier and filter. It makes use of the windows sound card and associated software for data acquisition and analysis. The measurement system is calibrated using a professional sound level meter. Acoustic noise measurements are made on an induction motor drive using the proposed system as per relevant international standards. These measurements are seen to match closely with those of a professional meter.**

***Index Terms*—Acoustic noise, conventional space vector pulse-width modulation (CSVPWM), discrete fourier transform, induction motor drive, noise measurement, sound pressure level, spectral analysis.**

I. Introduction

Electric motors, especially induction motors, are a major source of noise in industry because of its widespread application. Evolution of solid state devices and development of variable speed motor drives unveiled new challenges to engineers from the acoustic noise perspective. For example, voltage source inverter (VSI) fed induction motors, shown in Fig. 1, cause unpleasant acoustic noise due to the harmonics in the inverter output voltage [1]–[3]. These harmonics cause narrow-band components around integral multiples of switching frequency in the frequency spectrum of the acoustic noise [3].

International standards recommend acoustic noise measurement and test procedures for rotating electrical machinery [4]. On account of health and safety, noise control rules are becoming increasingly stringent. Noise has to be kept below certain safe level. This has to be checked by noise measurement at regular intervals, which may not be economically feasible due to high cost of sound level meters. Research domain also demands a low-cost noise measurement system for frequent use in laboratory. Literature survey shows that many researchers are working on electromagnetic noise mitigation techniques for motor drives, especially using pulse width modulation (PWM) techniques [1], [5]–[8]. Recently, experimental investigation on the effect of inverter switching sequence on motor acoustic noise has been reported [9]. Such research activity would benefit from the proposed low-cost noise measurement system. This is capable of spectral analysis of the noise and has an accuracy comparable to that of a professional sound level meter.

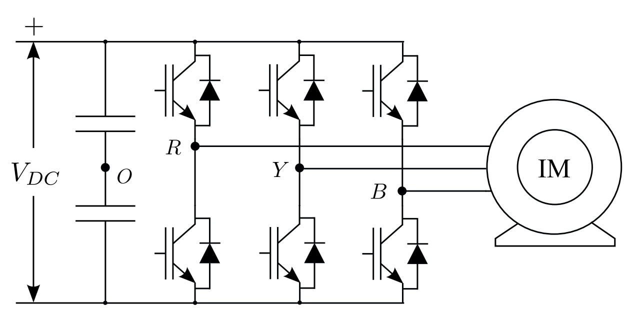


Fig. 1. Three phase voltage source inverter feeding an induction motor.

II. Noise Quantification and Evaluation

A source of sound can be generally represented by the radiated sound power measured in watts. Conversely, sound power relates to the rate at which a sound source radiates energy, i.e. energy per unit time. Theoretically, sound power can be calculated as the surface integral of sound intensities over the area of a hypothetical surface surrounding the source [10]. The sound intensity is defined as the energy transmitted through a unit area perpendicular to the wave propagation direction per unit time [11]. Since such measurements are not possible in practice, sound can be expressed in sound pressure level (SPL), which is defined as [10], [12]

$$L_p(t) = 20\ log_{10}\left(\frac{p(t)}{p_0}\right) \quad in\ dB \tag{1}$$

where $p(t)$ is the instantaneous sound pressure expressed in Pascal ($1Pa = 1N/m^2$) and p_0 is the reference sound pressure, 20 μ Pa. The static pressure at a point in the medium is the pressure that would exist at that point with no sound waves present. The instantaneous sound pressure at a point is the incremental change from the static pressure at a given instant caused by the presence of a sound wave [13].

Effective Sound Pressure (p) at a point is the root-mean-square (rms) value of the instantaneous sound pressure at that point over certain time interval [12]. In the case of periodic sound pressures, the interval should comprise an integral number of periods. In the case of non-periodic sound pressures, the interval should be long enough to make the value obtained essentially independent of small changes in the length of the interval [13].

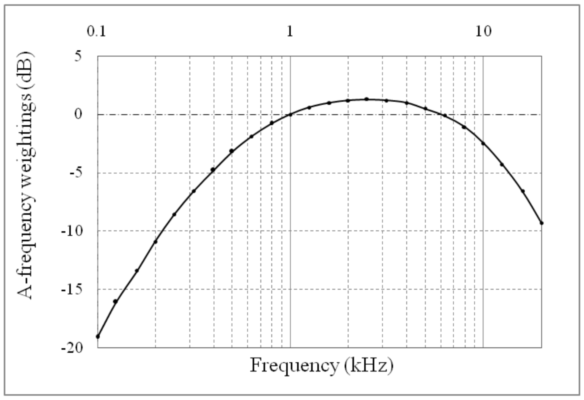


Fig. 2. A-weighting curve for sound level meter as per IEC 61672-1/2002.

The minimum sound intensity for a given frequency at which the human ear can perceive the sound, is defined as *threshold of hearing* [10], [14]. It is known that the threshold of hearing varies with the frequency of sound. In essence, it shows that noise with the same sound pressure level but at a different tonal frequency produces different impact on human ear because of the hearing mechanism. This peculiarity of human ear can be modeled using appropriate weighting functions or weighting curves. International standards suggest weighting curves such as A, B, C, D, E, Z or SI for SPL meters [10], [15]. The A-weightage curve, as exhibited in Fig. 2, is widely used in standard SPL meters.

III. Standards and Test Procedures for Acoustic Noise Measurement of Rotating Electrical Machinery

IEEE Std. 85-1973 [4] and ISO 1680 Part 1 and Part 2 [16] recommend standards for sound measurement and test procedures on rotating electrical machinery.

A. International Standards

IEEE Std. 85-1973 classifies the machines based on their maximum linear dimension [4].
Small machine - A machine having a maximum linear dimension of less than 250 mm.
Medium machine - A machine having a maximum linear dimension from 250 mm to 1 m.
Large machine - A machine having a maximum linear dimension in excess of 1 m.
For each machine type, a hypothetical surface surrounding the machine is assumed and sound measurements are taken on the prescribed points on this surface. The machine used in this work falls under the medium machine category. The preferred microphone positions for medium machines shall be in accordance with Fig. 3. Machine vibration can cause vibration of the base, floor or surrounding structure. Hence the machine under test should be vibration isolated from the test floor using resilient mounts [4].

Sound level meters shall comply with IEC 61672/2002, Class II or better. Class I sound level meters are precision grade instruments with higher accuracy where the data shall be stated in a tabular form at nominal one-third-octave intervals for frequencies from 63 Hz to 1 kHz and then at nominal one-twelfth-octave intervals for frequencies greater than 1 kHz to at least 16 kHz. Class II sound level meters are general purpose instruments where the data shall be stated in tabular form at nominal one-third-octave intervals for frequencies from 63 Hz to at least 8 kHz. A-weighting is mandatory for all classes of sound level meters. IEC standard provides various frequency weighting functions in equation form which enables weightage calculation at any frequency [15].

A microphone conforming to laboratory standard specifications shall be used as per IEC 61094-1/2000. A laboratory standard microphone is a condenser microphone with high accuracy, meeting certain mechanical dimensional requirements and electro-acoustical characteristics such as sensitivity. The microphone shall have an effective diameter of 25 mm or less. The electrical characteristics of the microphone signal amplifier shall satisfy the electrical requirements of IEC 60268-3/2000. Interconnecting cable shall not introduce cable noise interference with the signal when flexed, moved or subjected to environmental conditions encountered during testing. Individual components as well as the measurement system as a whole should be properly calibrated.

B. Test Procedure

International standards recommend the following test procedure for airborne sound measurements on rotating electric machinery:

Background sound measurement shall be made at the beginning and end of each major test series. Sound measurement shall be started only after running the motor for a sufficiently long period so as to stabilize the sound. If the sound pressure level with the machine running is greater than the background level by at least 10 dB, then preferred conditions exist and the sound is essentially that produced by the test machine. In other words, the background noise is negligible.
No-load test: The machine should be tested at rated voltage, rated speed and at no-load. An ac motor shall be sound tested at each of the speeds indicated on the nameplate. *Full-load test*: Type of motor mounting, loading method, power input

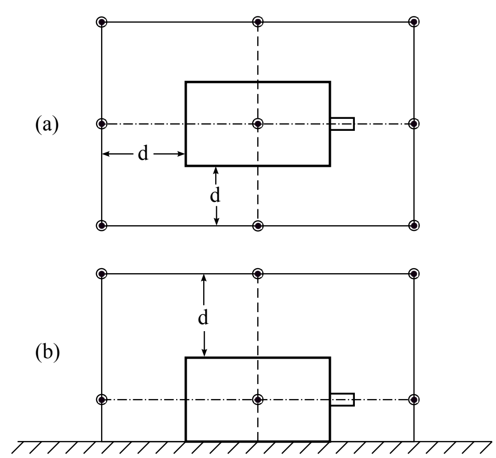


Fig. 3. The preferred microphone positions (marked as dots) for medium machines as per IEEE Std. 85-1973 - (a) plan and (b) elevation , where d = 1 m or greater.

requirements and accuracy of measurement should be agreed upon by parties concerned [4].

The A-weighted sound pressure level shall be measured at each microphone position on the measurement surface. The measurements shall be carried out after the machine has reached a steady condition of the defined operating mode.

C. Measurement of Acoustic Noise

The usual method of motor noise intensity measurement is done in an anechoic or semi-anechoic chamber at the distance of 1 meter for medium machines. An anechoic chamber is a test chamber where the room surfaces absorb essentially all the incident sound energy over the frequency range of interest, thereby providing free field conditions. Free field is a sound field in a homogeneous medium free of boundaries. A semi-anechoic chamber is a test chamber with a hard reflecting floor and other surfaces absorb essentially all the incident sound energy over the frequency range of interest [17]. The measurement of this noise is expressed in dBA, which is the weighted noise intensity as sensed by the human ear.

IV. Proposed Measurement System

A. Measurement Set-up

Analogue noise is captured using a hardware arrangement which consists of a microphone, an amplifier and an anti-aliasing filter. The overall block diagram is shown in Fig. 4 and a photograph of the hardware is shown in Fig. 5.

1) Microphone: An electret condenser microphone is used as it is very sensitive, compact in size (effective diameter < 25 mm) and has low power requirements. Let ‘s’ be the sensitivity of the microphone as defined below:

$$s = \frac{Output\ voltage, v(t)\ in\ Volts}{Sound\ pressure, p(t)\ in\ Pascal} \tag{2}$$

The sensitivity is usually defined with p_0 at a frequency of 1 kHz. In terms of s, eqn. (1) can be rewritten as,

$$\begin{aligned} L_p(t) &= 20\ log_{10}\left(\frac{v(t)/s}{v_0/s}\right) \\ &= 20\ log_{10}\left(\frac{v(t)}{v_0}\right) \end{aligned} \tag{3}$$

If the variation in the sensitivity of the microphone with frequency can be neglected, then acoustic noise can be measured in terms of the output voltage of the microphone as indicated by eqn. (3).

2) Amplifier: A non-inverting amplifier circuit is built using TL084 Opamp and the amplifier gain can be varied based on requirement. The measured frequency response of the amplifier is shown in Fig. 6. as it is evident from the figure, the amplifier has flat characteristics between 20 Hz and 200 kHz.

3) Anti-aliasing Filter: A fourth order Butter-worth low-pass filter is used as an anti-aliasing filter to allow only the audio frequency signals. This filter is designed with a cut-off frequency of 20 kHz and a high frequency attenuation of approximately -80 dB/decade. The measured frequency response of the amplifier with anti-aliasing filter is presented in Fig. 6. The filtered signal is passed to a personal computer (PC) for sampling, data acquisition and analysis through a co-axial cable which minimizes noise interference.

The total component cost is less than one thousand rupees (INR) whereas the professional sound level meter (Brüel & Kjær type 2260) costs around rupees 2.5 lakhs. A PC/laptop is inevitable for any research activity dealing with digital controllers. The same can be used along with the hardware to analyze the acoustic noise. Even with professional SPL meters, a PC/laptop is necessary to load the noise analysis software [18].

B. Noise Sampling and Storing

The analog signal from the anti-aliasing filter is sampled using windows sound card and data acquisition toolbox of MATLAB [19].

1) Windows sound-card: The sound card is an internal expansion card attached to the computer motherboard that facilitates to acquire, process and deliver audio signals under the control of computer programs. Its main functions are:
Synthesize (generate sounds), act as an interface to communicate and synchronize with electronic musical instruments, analog to digital conversion and digital to analog conversion. In windows sound card, a maximum sampling frequency of 44.1 kHz is possible. This is sufficient for accurate results

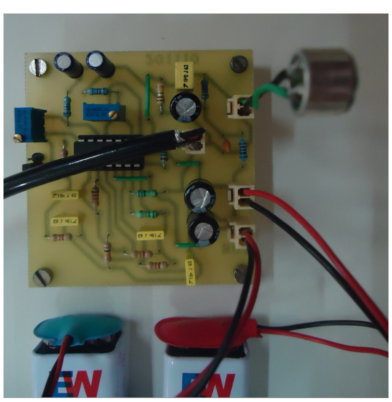


Fig. 5. Photograph of the acoustic noise capturing board consisting of a microphone, amplifier and a filter.

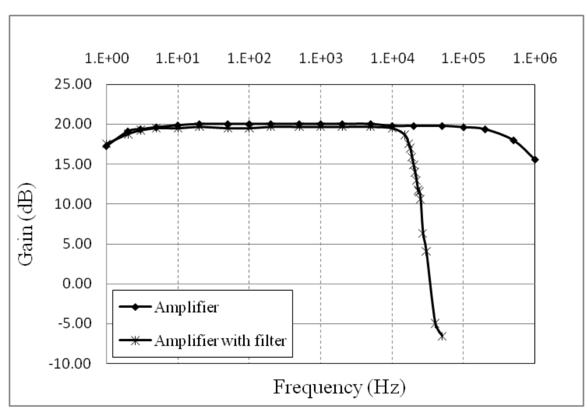


Fig. 6. Frequency response of amplifier with and without filter.

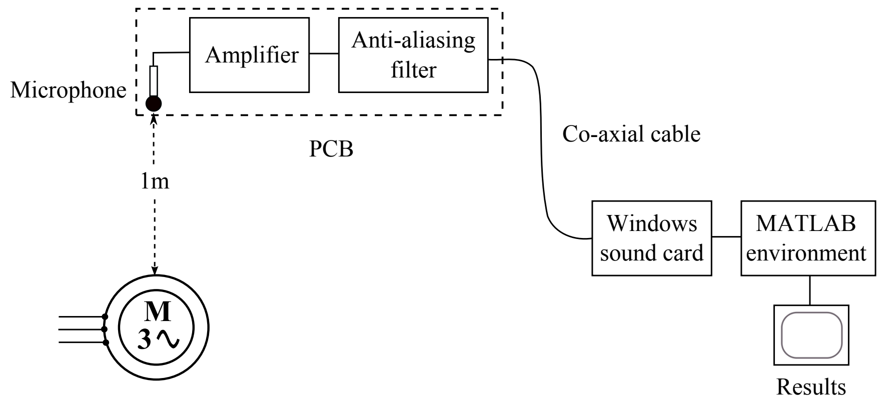


Fig. 4. Block diagram of the noise measurement system.

as the maximum audio frequency is only 20 kHz and hence Nyquist sampling criterion is satisfied.

2) Data Acquisition Toolbox: The data acquisition toolbox provides a complete set of tools for analog and digital input/output operations from various PC compatible data acquisition devices such as Windows sound card. It supports analog input (AI), analog output(AO) and digital input/output (DIO) subsystems. It allows users to easily acquire sound directly from sound cards into MATLAB, or to generate live sound from MATLAB to sound cards. The data acquisition consists of the following steps [20]:
1. Create a device object using the *analoginput*, *analogoutput*, or *digitalio* creation function which are used to access the hardware device.
2. Add channels to analog input and analog output objects and add lines to digital I/O objects to receive or send data.
3. Configure properties using the functions that depend on user's requirement and available hardware settings. For example, any desired sampling rate less than or equal to 44.1 kHz can be chosen for the sound card.
4. Acquire or output data with the *start* and *getdata* function.
5. Remove the device object from memory using the *delete* function, and remove it from the MATLAB workspace using the *clear* command.

Duration of data acquisition can be fixed based on the nature of noise to be measured, ie, whether the noise is fast varying or slow varying. The sampled data in time domain can be stored as a data array for further analysis. Other softwares or C programming can also be used to implement the data acquisition and analysis part.

V. Spectral Analysis of Noise using Discrete Fourier Transform

The spectral analysis of the stored data is done using discrete fourier transform (DFT) implemented in MATLAB. Assume *fs* is the sampling frequency and N is the data length. The steps followed are:
1. Take the stored data samples as mentioned in section IV-B. These samples represent the data samples in time domain denoted by v[n]. Transform them into frequency domain using DFT and is implemented in MATLAB by *fft* function. The DFT of the length-N time-domain sequence v[n] is given by V[k] and is defined by [21]

$$V[k] = \sum_{n=0}^{N-1} v[n] e^{-j2\pi kn/N}, \quad 0 \leq k \leq N-1 \tag{4}$$

2. Multiply V[k] with corresponding A-weightage values. Since both V[k] and A-weightage value are in frequency domain, direct multiplication is possible in linear scale. To find the A-weightage value corresponding to V[k] denoted as A[k], compute the frequency corresponding to k:

$$f[k] = k\,\Delta f = k\left(\frac{fs}{N}\right)$$

where $\Delta f = \frac{fs}{N}$ represents the frequency difference between two adjacent frequency bins. A-weightage curve is a function of frequency [15] and hence A[k] can be found out. Now, the A-weightage value of V[k] is A[k]V[k].
3. Calculate the total energy over the data window in frequency domain. The total energy of a length-N sequence can be computed by summing the squares of the absolute values of A[k]V[k] and then dividing by N (Parseval's relation); ie,

$$\varepsilon_g = \frac{1}{N} \sum_{k=0}^{N-1} |A[k]V[k]|^2 \tag{5}$$

These samples are having complex-conjugate symmetry for real valued inputs. So only half of the samples are required for energy computation. ie,

$$\varepsilon_g \approx \frac{2}{N} \sum_{k=0}^{(\frac{N}{2})-1} |A[k]V[k]|^2 \tag{6}$$

4. Sampling frequency and data window duration might vary depending on the nature of the noise to be measured. So the mean energy over a data window of T seconds or signal power can be used.

$$\varepsilon_m \approx \frac{2}{T.N} \sum_{k=0}^{(\frac{N}{2})-1} |A[k]V[k]|^2 \tag{7}$$

The A-weighted rms value of the voltage signal is

$$v_{rms} = \sqrt{\varepsilon_m} \tag{8}$$

Now, the average sound pressure level, L_{av} can be expressed as [12]

$$L_{av} = 20\ log_{10}\left(\frac{v_{rms}}{v_0}\right) = 10\ log_{10}(\varepsilon_m) + C \quad in\ \ dBA \qquad (9)$$

where C is the calibration constant which depends on reference voltage v_0.

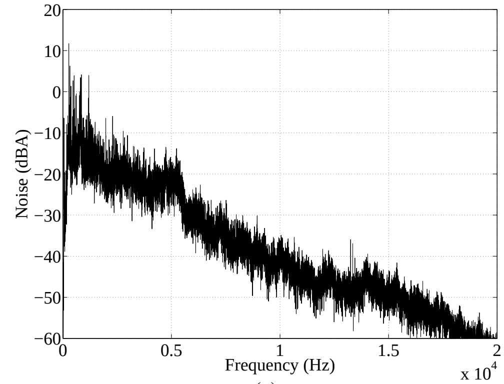
4. To determine the calibration constant C, place the microphone and the professional SPL meter close to each other and at a particular distance from a sound source. A sound with frequency between 160 Hz and 1250 Hz of the sinusoidal pattern shall be used for calibration of sound level meter according to IEC standards [15]. Sounds of sinusoidal shape of frequency 500 Hz and 1 kHz are generated using MATLAB, sound card and speaker. Different amplitudes are also applied at these frequencies as shown in Table I, where K is a parameter. The readings in dB as well as dBA of the professional meter and the proposed system are tabulated in Table I. The difference between the two set of readings (X-Y) is almost constant as seen from Table I. The average value of (X-Y) can be taken as the calibration constant 'C'.

VI. Experimental Verification of Sound Measurement

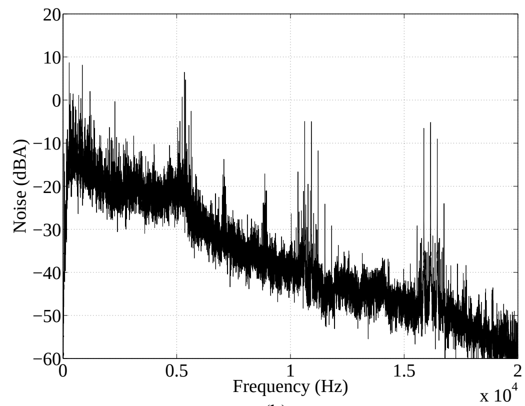
In order to verify the accuracy of measurement of the proposed system, various noises are generated. These are measured using the suggested system and a Brüel & Kjær type 2260 Sound level meter. Brüel & Kjær 2260 SPL meter is a fast and precise type 1 sound analyzer which conforms to IEC and ANSI standards [18]. The sounds applied are of sinusoidal pattern with frequency 2 kHz and 4 kHz. For various values of K, the dB and dBA results of Brüel & Kjær SPL meter and the proposed measurement system are found to match closely as indicated by Table II.

VII. Experimental Results on Spectrum analysis of Motor Acoustic Noise

For spectral analysis, the acoustic noise radiated by a 6 kW, 400 V, 10.5 A, 50 Hz, 4-pole, three-phase squirrel cage induction motor is captured and sampled. A 10 kVA IGBT-based voltage source inverter is used to feed the motor drive. The digital platform used is based on TMS 320LF2407 DSP processor. The induction motor is run with inverter using conventional space vector PWM (CSVPWM) technique [9] and under constant volts per hertz (V/f) control. All measurements are taken under no-load [4] with V_{DC}= 566 V. The audible noise is measured 1m away from the motor and perpendicular to the shaft at the shaft height [4]. The acoustic noise emitted by the voltage source inverter-fed induction motor is measured at various operating conditions. The weighted frequency spectrum of the acoustic noise is presented in Fig. 7(a) with a 400 V, 50 Hz mains supply. Fig. 7(b) shows the weighted acoustic noise spectrum when the motor drive is operated using CSVPWM at a fundamental frequency (f_m) of 50 Hz, switching frequency (f_c) [22] of 5.4 kHz with rated voltage



(a)



(b)

Fig. 7. Weighted frequency spectrum of motor acoustic noise in dBA with (a) 400 V, 50 Hz mains supply, (b) conventional space vector PWM at f_m= 50 Hz, f_c= 5.4 kHz.

TABLE I
Experimental results to get calibration constant, C

Signal		B&K meter (X)		Proposed system (Y)		Difference (X-Y)	
Nature	Magnitude	dB	dBA	dB	dBA	dB	dBA
Sinusoidal with f=500 Hz	K=0.25	81.1	77.8	9.4	6.1	71.7	71.7
	K=0.5	86.4	83.2	15.3	12	71.1	71.2
	K=1	87.6	84.4	15.8	12.5	71.8	71.9
Sinusoidal with f=1 kHz	K=0.25	73.7	73.5	1.3	1.1	72.4	72.4
	K=0.5	78.5	78.4	7	6.9	71.5	71.5
	K=1	80	80	8.8	8.6	71.2	71.4
Calibration constant, C =						71.62	71.68

TABLE II
Comparison table for various sounds

Signal		B&K meter		Proposed system with C=71.6		Difference	
Nature	Magnitude	dB	dBA	dB	dBA	dB	dBA
Sinusoidal with f=2 kHz	K=0.25	69.4	70.2	70.8	71.5	-1.4	-1.3
	K=0.5	76.1	77.2	76.1	77.2	0	0
	K=1	79.6	80.7	80.1	81.2	-0.5	-0.5
Sinusoidal with f=4 kHz	K=0.25	67.9	68.3	67.1	67.3	0.8	1
	K=0.5	71.9	72.6	72.2	73	-0.3	-0.4
	K=1	78.8	79.6	77.9	78.7	0.9	0.9
Mean =						-0.08	-0.05

applied on the motor. Narrow band frequency components can be seen around integral multiples of the switching frequency in Fig. 7(b). These are due to the voltage harmonics around integral multiples of the switching frequency.

VIII. Conclusion

The paper presents the design, fabrication, calibration and testing of a low-cost noise measurement system for measurement and spectral analysis of acoustic noise radiated by induction motor drives. Experimental results show that the proposed noise measurement system has an accuracy comparable to professional SPL meters. Frequency spectrum of the acoustic noise radiated by the motor drive, when it is fed from an inverter using CSVPWM technique, is presented to demonstrate the capability of the proposed system in terms of spectral analysis.

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