Noise and Vibration Monitoring for Premium Efficiency IE 3 Three-Phase Induction Motors

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***Abstract*—The paper presents the original SV-100 platform that enables low-cost and very high accuracy determinations of noise and vibration levels. The aim of the proposed platform is to achieve an effective integration of the two topics of this analysis: vibrations and noises. To the best of our knowledge, no low price, dedicated compact platform with embedded measuring instruments exists. For proving the practical utility of the proposed platform, two induction motors of 7.5 kW and 11 kW, respectively, in single-layer winding, at 1000 rpm, with IE3 premium efficiency were analyzed. This analysis is required because, according to IEC60034-30 standard, the IE3 efficiency standard has become mandatory for induction motors of rated power greater than 7.5 kW. Therefore, in order to improve the motor operating efficiency, the power losses caused by noises and vibrations have to be reduced. Several variants of supply were studied, i.e., by the three-phase 50 Hz network and by a three-phase inverter at 40, 50 and 60 Hz, respectively. The experimental determinations of noises are presented comparatively, by using a Bruel&Kjaer sonometer and by using the new platform SV-100. The results are compared with the IEC60034 standard.**

***Index Terms*—acoustic noise, energy efficiency, induction motors, noise measurement, vibration measurement.**

I. INTRODUCTION

The sources of the noise produced by three phase induction motors with squirrel-cage rotor are of electromagnetic, mechanical, and aerodynamic nature, respectively [1-13]. The total amount of these noises is the overall noise of the motor, generated in the acoustic spectrum.

The irregular distribution of the armature slots, the eccentricity of the rotor, magnetostriction, commutations processes and magnetic saturation cause electromagnetic noise, which emerges by the interaction of the higher harmonics of the magnetic field of the stator and rotor [14-21].

From a practical viewpoint, the value of mechanical noise produced by the bearings depends mainly on several qualitative factors of bearings, which must be taken into consideration when designing the motor:

- lubrication of the bearings;
- globosity and road rolling of the bearing balls;
- maximum operating temperature, without creating deformation of the balls;
- maximum operating speed.

The most important source of aerodynamic noise of induction motors is the fan. The number of blades, their thickness, as well as the inclination angle depends, greatly, on the correct sizing of the fan, particularly with the purpose to reduce noise, as well as to ensure an efficient cooling. A precise analysis of the various noise sources of electrical machines requires a suitable measurement system in accordance with international standards [22-27].

Accurate noise measurements are helpful in many ways, including the motor optimization.

II. MEASUREMENT OF NOISE GENERATED BY ELECTRIC MOTORS

According to ISO 1680/1 standard, which regulates the measurement methods of noise in electric motors, the measuring equipment must be designed such as to measure weighted acoustic power levels, as square mean in octave band (or 1/3 octave averaged over time on measuring surface) [28-36]. Increased total noise in electric motors causes low efficiency, thus higher operating costs and higher maintenance costs, as well as low reliability [37-40]. In order to perform the analysis of acoustic noise in an induction motor, it is essential and necessary to define the basic terms involved in this case.

Vibration [30] is the oscillatory motion of an elastic body of mass *m* caused by an external force initially applied to the elastic body.

The vibration frequency of an electric machine in vibration mode is given by [31-36]:

$$f_m = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} = \frac{1}{2\pi} \cdot \sqrt{\frac{k \cdot g}{m \cdot g}} = \frac{1}{2\pi} \cdot \sqrt{\frac{g}{x_{st}}} \text{ [Hz]} \quad (1)$$

where:

k – elasticity constant of the suspension [N/m];
m – machine mass [kg];
g –gravitational acceleration (g = 9,81 m/s^2);
x_{st} – static deformation [m].

The majority of vibration monitoring systems determines the vibration characteristics as a graph of displacement of the monitored surface versus time. Following from eq. (1), the static deformation x_{st} is given by:

$$x_{st} = \frac{1}{4\pi^2} \cdot \frac{g}{f_m^2} \quad (2)$$

In the case of a loaded induction motor, the expression for calculating the static deformation becomes [32], [35]:

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$$x_{st} = \frac{900}{n^2} \cdot \left(1 + \frac{1}{T_s}\right) \tag{3}$$

where:

n – motor speed;

T_s –transmissibility.

The sound represents a consequence of vibrations transmitted in an elastic environment of different states (solid, liquid or gaseous) with frequencies between 20 Hz – 20 kHz within the acoustic range (perceptible to the human ear) [31], [32].

The acoustic pressure represents the pressure exerted by a sound wave on the human ear in an elastic environment:

$$p = \sqrt{\frac{1}{T}\int_0^T p_i^2(t)\cdot \mathrm{d}t} \tag{4}$$

where:

p_i – instantaneous acoustic pressure;

T – period of time.

The acoustic pressure level (L) of a sound by effective pressure [p], is given by:

$$L = 20 \cdot \log \frac{p}{p_0}, \text{ or } L = 10 \cdot \log \left(\frac{p}{p_0}\right)^2 \tag{5}$$

where p_0 is the reference pressure or the threshold level, that is equivalent to the strength level frequency of standard sound at 1 kHz and hearing threshold 20 µPa.

The sound power level (L_p) of a sound source characterized by power P is calculated by [21], [36]:

$$L_p = 10 \cdot \log \frac{P}{P_0} \tag{6}$$

where the reference acoustic power is P_0=10^{-12} W.

The acoustic power level is the ratio of two physical quantities, one determined directly and the other being assigned a conventionally adopted value [30].

Table I shows the maximum weighted acoustic power levels (L_{WA}) [dB] for asynchronous squirrel cage three-phase induction motors at no-load conditions, required by IEC 60034-9.

TABLE I. MAXIMUM LEVELS OF WEIGHTED ACOUSTIC POWER (L_{WA}) REQUIRED BY IEC 60034-9

Nominal power (P_n) [kW]	**8 poles**		**6 poles**		**4 poles**		**2 poles**	
	50 Hz	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**	**50 Hz**	**60 Hz**
1C.0 < $P_n \le 2.2$	70	71	70	71	70	71	78	85
2.2 < $P_n \le 5.5$	73	76	73	76	73	76	83	88
5.5< $P_n \le 11$	77	80	**77**	**80**	78	81	88	91
11< $P_n \le 22$	81	84	81	84	85	88	91	94
22< $P_n \le 37$	84	87	84	87	88	91	93	100
37< $P_n \le 55$	86	90	87	91	91	95	95	101
55< $P_n \le 110$	89	93	91	95	95	98	97	104
110< $P_n \le 220$	94	97	96	99	99	102	100	107
220< $P_n \le 440$	96	98	98	101	102	105	103	109
440 < $P_n \le$ 1000	97	99	99	102	105	108	105	110
1000 < P_n	It is established by contractual agreement							

The selective marking of values (in bold) in the table above corresponds to maximum noise levels admitted for the two analyzed motors.

III. THE SV–100 INTEGRATED PLATFORM FOR ANALYSIS OF NOISES AND VIBRATIONS OF INDUCTION MOTORS

Regarding its structural description, this product consists of a software tool and a hardware tool. The software tool was developed in LabView, version 2013 [41]. The connected software and hardware tools (Vibro M-100 Analyzer) allow visualization and analysis of the above described phenomena.

A. The software tool

The front panel of the SV – 100 platform software tool is presented in Fig. 1.

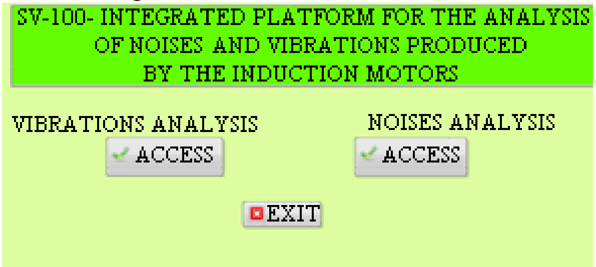

Figure 1. SV – 100 – The Front Panel

1. The vibration analysis function displays the response of three accelerometers, which can be connected to the *Vibro M-100 analyzer*. The displacements versus time on the three axes (X, Y and Z) can also be visualized for each accelerometer (simultaneously or individually, Fig. 2). This function is presented in demonstrative purpose, in order to show the possibilities offered by the platform (Fig. 3).

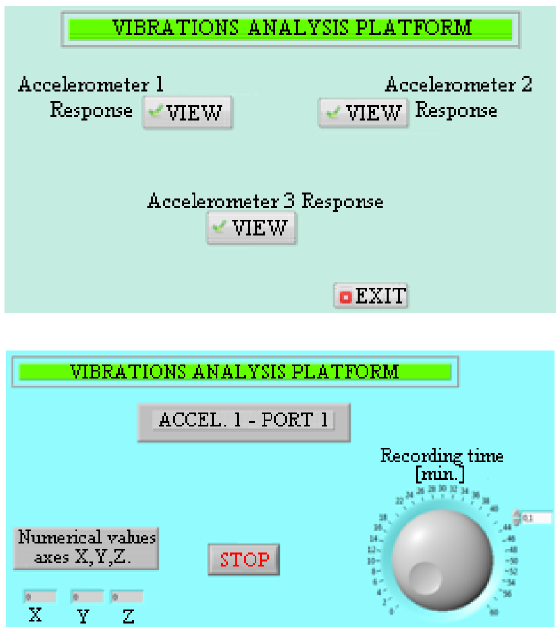

Figure 2. SV-100 - The vibration analysis interface.

The program can record events over one hour; the desired monitoring interval must be set at beginning of every session.

2. The noise analysis function allows the easy visualization of the spectral analysis for a recorded noise/sound. The major advantage of this software instrument (Figs. 4 and 5) is that it does not require auxiliary hardware.

Any sound level meter manufactured at present, contains, in addition to the software interface, also signal processing hardware including an electro-acoustic transducer [11].

In the present case, the electro-acoustic transducer is a condenser microphone. The signal processing is achieved through the soundcard of the computer system on which the application runs. The soundcard existing in the computer configuration and also the microphone are detected automatically when the application is launched

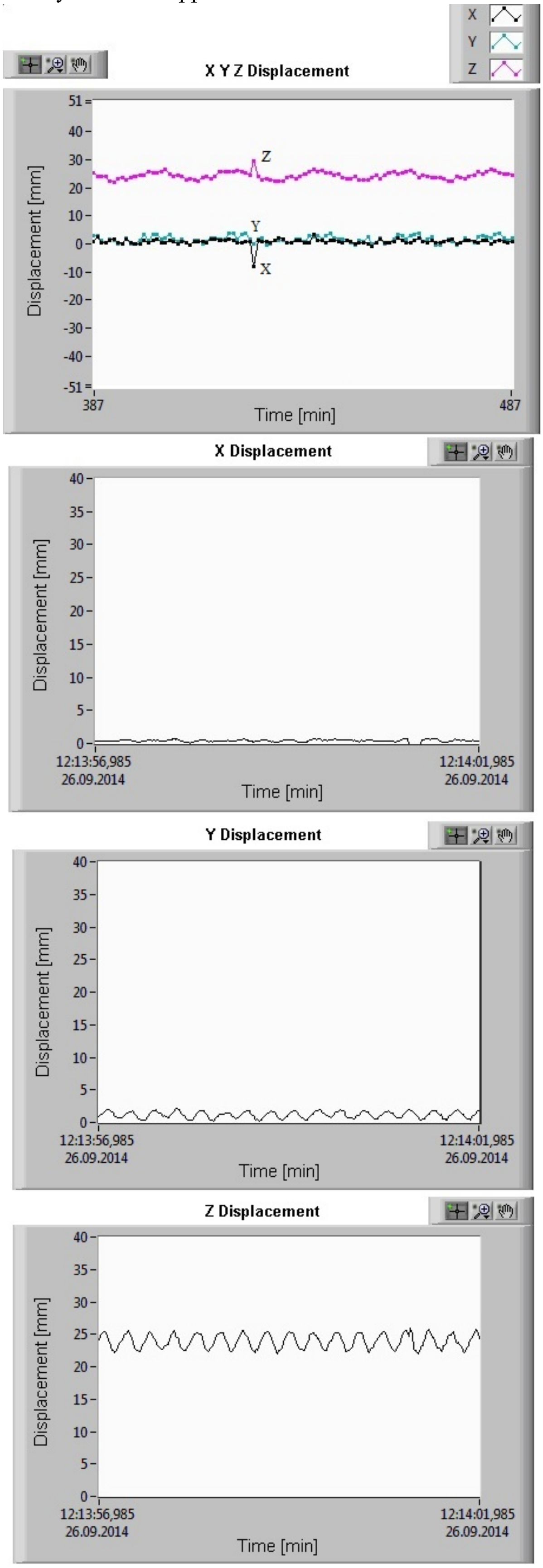

Figure 3. The vibration analysis platform.

Further, for a good calibration, the position of each accelerometer is controlled by its 3D visualization mode.

Any vibration is recorded and displayed in real time. The data of each graph can be exported by Excel.

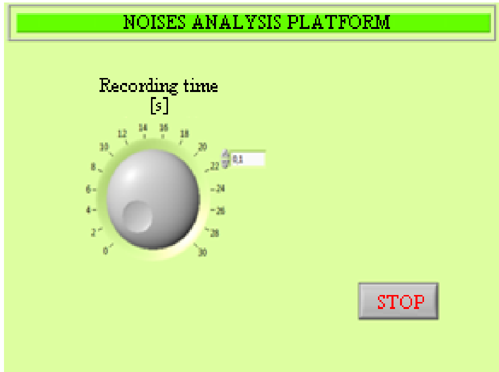

Figure 4. The interface of the noise analysis platform

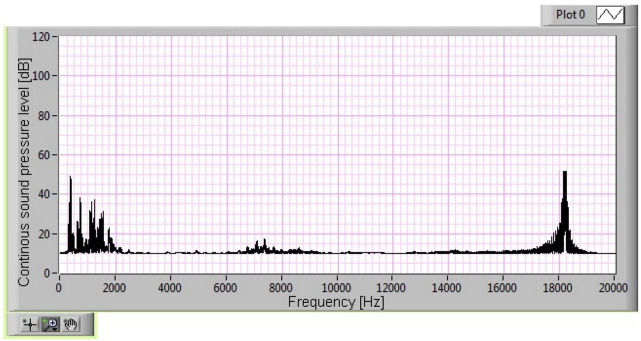

Figure 5. The interface of the noise analysis platform, spectral analysis

B. The hardware tool

This equipment performs the processing and transmission of signals given by three accelerometers individually connected to the three ports (Fig. 6).

Figure 6. Vibro M-100 analyzer – the front panel

The main element of the internal electronic unit is the ATMEGA 328 P microcontroller that acquires data from accelerometers (SDA + SCL) over the corresponding input pins A0- A5 and sends them by means of I2C protocol to the USB port of a user (block diagram Fig. 7).

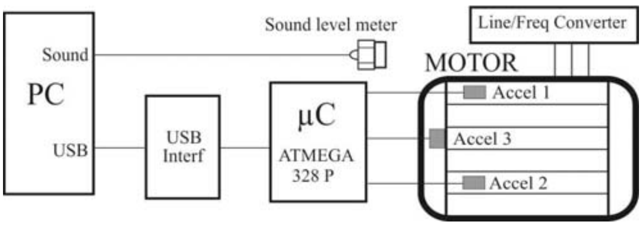

Figure 7. The block diagram of the platform

This electronic equipment contains also a battery, which can be charged via the connection jacks on the rear panel of the unit.

The autonomy of the equipment is of 72 hours continuous functioning.

The accelerometers used with this device are of ADXL 345 type (Analog Devices).

IV. Experimental Results

Further the measurements of the A-weighted acoustic pressure level for the studied three-phase induction motors will be presented and discussed.

A. Noise measurements for two three-phase induction motors of 7.5 kW/1000 rpm and 11kW/1000 rpm, respectively

In accordance with the 1680/1 ISO standard, the noise produced by electric motors is measured by using a sound-level meter inside the anechoic room [17].

In a first stage the noise levels were determined by means of a Bruel&Kjaer sound level meter (Fig. 8), whose characteristics are presented in Table II.

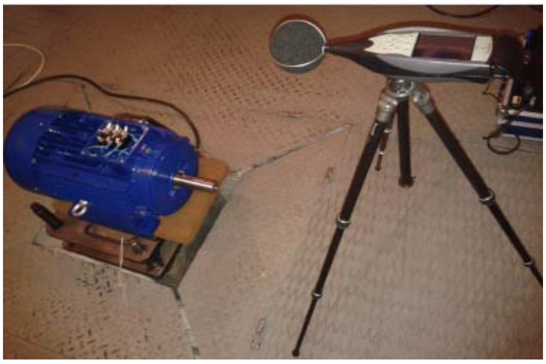

Figure 8. Experimental installation for noise level measurement by means of the Bruel&Kjaer sound-level meter.

TABLE II. Technical Characteristics of the Bruel&Kjaer Sound Level Meter

Linear frequency domain	3 Hz – 20 kHz
Real time frequency analysis	1/1 or 1/3 bands octave
Possibility of weighting curves	A, C or Z
Communication	standard PC USB interface
Precision class	1
Measuring standard	IEC 61672 - 1

In a second stage the noise level was measured via the SV-100 platform and by means of the sound-level meter.

The measured noises, generated by each of the two motors, are presented in Table III (7.5 kW/1000 rpm) and Table IV (11 kW/1000 rpm). The results obtained for the network supply (50 Hz) and inverter supply (50 Hz) are typed in **bold**. The obtained results show a very good sensitivity of the platform.

TABLE III. Total Noise Levels generated by the asynchronous Motor, Type MAL 160 M – **7.5 kW/1000 rpm**

No.	Mode of supply	The total level of measured noise [dB]	
		Bruel & Kjaer sound-level meter	SV-100 Platform
1	Inverter 40 Hz	68.8	68.2
2	**Inverter 50 Hz**	**68.0**	**68.1**
3	Inverter 60 Hz	69.3	69.4
4	**Network 50 Hz**	**66.1**	**66.2**

TABLE IV. Total Noise Levels generated by the asynchronous Motor, Type MAL 160 L – **11 kW/1000 rpm**

No.	Mode of supply	The total level of measured noise [dB]	
		Bruel & Kjaer sound-level meter	SV-100 Platform
1	Inverter 40 Hz	69.6	69.1
2	**Inverter 50 Hz**	**68.8**	**68.9**
3	Inverter 60 Hz	69.4	69.6
4	**Network 50 Hz**	**67.9**	**68.0**

B. Measurement of vibrations for three-phase induction motors of 7.5 kW/1000 rpm and 11 kW/1000 rpm

This section presents the results of vibration and noise measurements for the two studied three-phase induction motors. These motors operate in normal mode, with no-load on the shaft, supplied firstly from the three-phase network and secondly through a three-phase inverter (Altivar 58).

Vibration analysis is presented graphically as displacement [mm] versus time, over the three axes, X, Y and Z.

From a practical viewpoint, each induction motor has a certain allowed displacement (vibration) depending on its output. Any failure or abnormal operation has impact directly on the vibration level of the motor.

Fig. 9 shows the vibration level of the no-load MAL 160 M motor (7.5 kW/1000 rpm), supplied from the three-phase network (50 Hz), as the IEC 60034-9 norm requires.

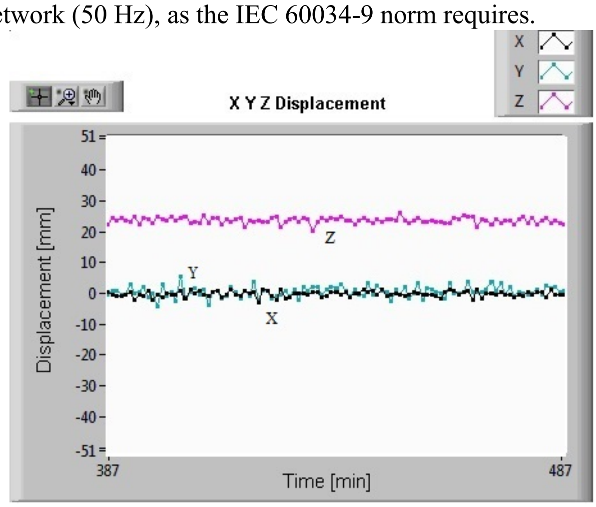

Figure 9. The vibration level of the MAL 160 M motor at no-load, supplied from the three-phase network (50 Hz).

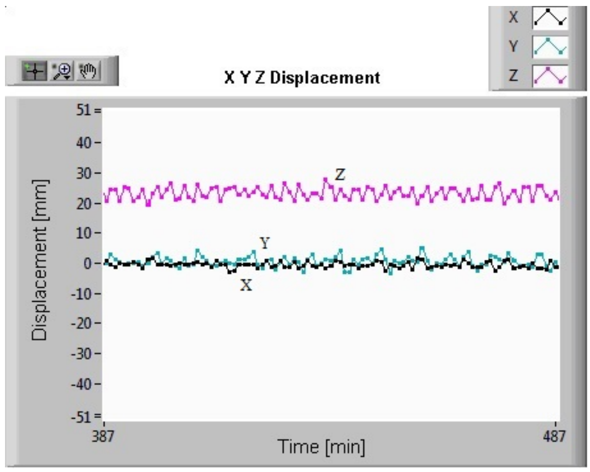

Figure 10. The vibration level of the MAL 160 M motor at no-load, supplied from the three-phase inverter (60 Hz).

All presented data were provided by accelerometer no. 1. Fig. 10 shows the vibration level of the MAL 160 L motor

(11 kW/1000 rpm), premium efficiency, at no-load, supplied from the three-phase inverter (60 Hz).

Fig. 11 shows the position of the accelerometer on the motor.

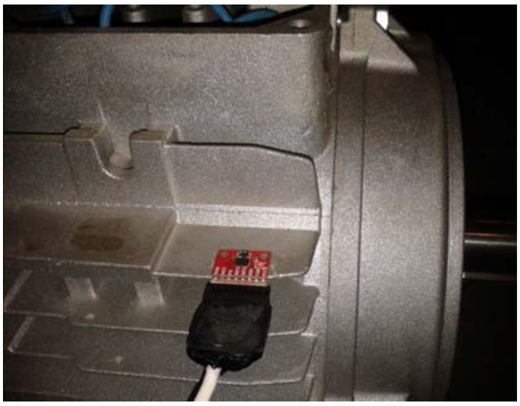

Figure 11. Position of the accelerometer

V. Conclusions

The novelty of the SV-100 platform consists in the effective integration of the two topics of the analysis: vibrations and noises.

At present the instruments available in this field cannot be found embedded in a compact platform, but only separate, from both structural and functional point of view.

The SV-100 platform is very convenient also for economic reasons. The total cost of designing and manufacturing the platform represents maximum 10% of the commercial value of a partly similar product, available on the market at present [42].

All noise measurements performed on the two three-phase induction motors presented above fall within the noise classes specified in IEC 60034 Part 9 standard. The maximum permitted noise level, according to the mentioned standard (Table I), is of 77 dB for 50 Hz supply and of 80 dB for 60 Hz supply, respectively.

Noise measurements performed comparatively by means of the proposed SV-100 platform and the type 2250 Bruel & Kjaer sound-level meter have very similar values (Table III and IV), confirming the good measurement accuracy of this new platform.

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