Adapted coil sensors for measuring the external magnetic field of electrical machines

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ABSTRACT

This paper proposes a criterion in the choice of coil sensors which can be used in the diagnosis of electrical machines. These sensors allow us to measure external magnetic field of the machine. Their interest is due to their robustness, reliability and longevity. The principle of the coil sensors is to measure the magnetic flux located around the electrical machine in order to be analyzed to detect faults. The performance of the measured signal for a constant coil area depends on the number of turns and the wire diameter. Their influence is analyzed in the paper. The developed diagnosis method is based on the analysis of the radial magnetic field present around the machine comparing to the changes of two signals obtained from a pair of sensors. So, the sensibility of the sensor in the coil number is also analyzed in the paper.

CCS Concepts

Hardware → Hardware design engineering; Hardware → Sensors.

Keywords

coil sensors, magnetic field, frequency responses, parameters influence.

1. INTRODUCTION

Currently, sensors are ubiquitous in our environment and magnetic sensors can be used directly for magnetic field measurements, but also for measurements of distances, speeds, current, detection of metal parts, or for non-destructive tests [1]. The principles used for magnetic sensors are quite numerous. Their applications are also very different, not only according to their cost but also according to their measurement range, their resolution, the effect used, etc. In addition, they are also a key element in many maintenance and control operations. The search for the best compromise between the cost of production, performance and miniaturization has been growing steadily for several decades, making it possible today to respond to both large-volume markets. According to the principle practiced for measuring the field, the magnetic sensors can be classified into two main categories:

- field sensors measuring one or more axes such Hall Effect sensor [2], Anisotropic Magneto Resistance (AMR), Giant Magneto Resistance (GMR) [3], Tunnel Magneto Resistance (TMR), Giant and Magneto-Impedance (GMI).
- Coil flux sensors measuring the integral of the field passing through a surface such Air coils, Fluxgate, SQUID (low and high Tc), Mixed sensors and Atomic magnetometers [4].

It is always difficult to compare magnetic sensors to the extent that each one has particular advantages and disadvantages. For example, Hall Effect sensors have the advantage of being absolute and linear over a very large field of view. They are therefore essential in applications, which measure high magnitude field; however, they have low cost, low power and high sensitivity [4]. Another decisive aspect in the choice of the sensor is the spatial extension of the magnetic field which must be measured. If it is large, as for terrestrial imaging, it is necessary to use flux sensors that are more sensitive than the field sensors. It is for this reason that Giant-Magneto Resistance “GMR” sensors derived from spin electronics are implanted in the read heads, instead of the inductive coils, and they can be miniaturized to sizes of a few tens of microns and integrated into “CMOS” systems containing signal processing electronics [5]. Finally, the frequency of the field which must be detected is also important because at very high frequency, the inductive sensors (coil sensors) become more efficient since they have a sensitivity proportional to the derivative of the flux which increases with the frequency [6].

The coil sensors “CS” measures the integral of the field which passes through a surface and their main advantage is the simple construction which allows an easy manufacture according to the needs and makes it possible to consider the general characteristics of the sensors as well as to define their performances. This type of sensor allows a simple and direct measurement of the magnetic field because it does not require associated electronics, except to amplify the signal of the induced electromotive force. The performance of the measurement depends on the surface and the number of the turns [7]. In addition, since about sixteen years the sensors are used in research works to measure a magnetic field created by an electric current or by a magnetic object (magnet or coil) in order to realize a diagnosis of the studied machine [8].

Among the various sensors, we are interested in this work in wound magnetic field sensors, which are very promising for the use in the diagnosis of electrical machines or for the measurement of currents without contact [9, 10]. This paper presents the developed wound sensors and their suitable modalities to choose for measuring the leakage flux of rotating machines.

The principle of the wound sensors is to measure the flux embraced by a coil located around the machine. The main advantage of these sensors lies in their simple construction, which allows easy manufacturing according to the needs and allows to take into account the general characteristics of the sensors as well as to define their performances [7, 11].

They are currently used in research work to detect and to measure a magnetic field created by a magnetic object (magnet) or by an electric current (in a coil) through its radiating magnetic field. The performances of this type of sensors have given very satisfactory results.

This paper is organized as follows. In Section 2, the principles of coil sensors are recalled. The design and choice of the coil sensors are presented in Section 3. In Section 4, experimental studies are conducted on different sensors, and finally conclusions are exposed in Section 5.

2. PRINCIPLES OF COIL SENSORS CS

Faraday's law states that the electromotive force induced "e" in a closed coil placed in a magnetic field is proportional to the variation over time of the flux of the magnetic field entering the circuit according to the following formula [12]:

$$e = -\frac{d\emptyset}{dt} \quad (1)$$

Figure 1 represents the schemes with "e" the voltage induced in a circuit which embraces the flux φ (t) during the duration dt [13]. In practice, the magnetic induction is often caused by several turns, each of which produces the same electromotive force "e.m.f". For this reason, a term "N" representing the number of turns is added, and it can be written:

$$V = -N\frac{d\emptyset}{dt} \quad (2)$$

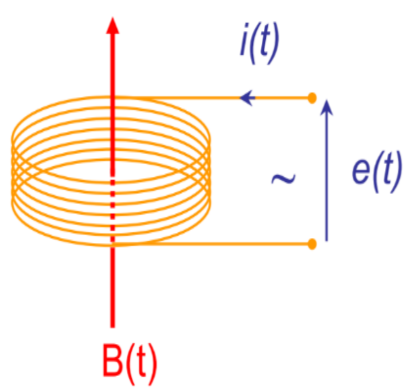

Figure 1. Schemes with (e) the voltage induced in a circuit which embraces the flux φ (t) during the duration dt.

The magnetic flux is determined considering the density of the magnetic field and the surface S of the coil:

$$\emptyset = \int N.B.\boldsymbol{ds} \quad (3)$$

When, *B* is constant on the surface *S*:

$$\emptyset = N.B.\,S \quad (4)$$

$$V = V_{max}\, sin(2\pi.\,ft) \quad (5)$$

From (2) and (5) we obtain:

$$\emptyset = \frac{V_{max}}{2\pi f.N}.\cos(2\pi ft) \quad (6)$$

From (3) and (6) we obtain the formula to calculate the flux of the induced magnetic field in each sensor:

$$\hat{B} = \frac{V_{max}}{2\pi f.S.N} \quad (7)$$

The effective value of the applied magnetic field can be calculated by:

$$B_{eff} = \frac{V_{max}}{2\pi f.S.N\sqrt{2}} \quad (8)$$

This formula contains essentially the factors that make up the sensitivity of the coil sensors and which must be taken in consideration for their manufacturing.

3. THE DESIGN AND CHOICE OF SENSORS CS

The diagnostic method of applications, considered in this paper, focuses on inter-turn short-circuit faults in the windings of AC machines. It is based on the analysis of the magnetic field radiating around the machine by comparing the changes of two signals obtained from a pair of sensors placed at 180° from each other with respect to the axis of the machine [14]. The principle is to obtain information from sensitive spectral lines in the external magnetic field. Thus, the obtained information is merged and can be analyzed by different methods such as belief functions [9] or Pearson's correlation coefficient [15]. The analysis is based on variations in the magnetic field outside the machine when the load varies. The signals from the opposite sensors must be identical, except in the event of a fault.

Failure of the sensor introduces measurement errors and misreads the physical state of the system (loss of machine control, failure to detect a fault [16], etc). A picture of coil sensors is presented in figure 2.

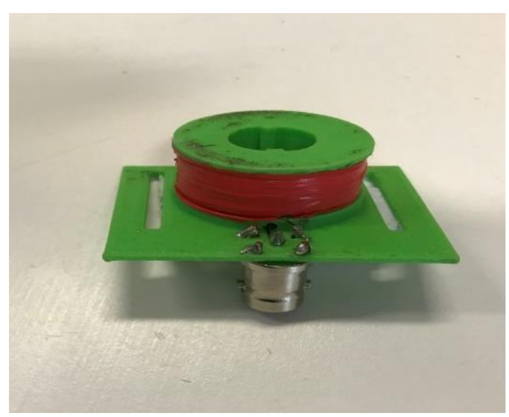

Figure 2. Coil sensor developed in the laboratory for the experimental investigations.

Therefore, it was required to design and manufacture this type of sensors with high accuracy and suitable size for the applications of detecting fault in the machine.

These small sensors were developed by the authors on the same principle as the commercial wound sensor. In the design of the sensor, it is necessary to take into account that

- the sensor must have a wide bandwidth to allow measurements of the signals at low and high frequency <2 kHz.
- the signal amplitude is enough for signal processing and analysis "several millivolts".

4. EXPERIMENTAL TESTS

For the study of the design and choice of adapted sensors in the measurement of the magnetic field around electrical machines, 20 sensors have been manufactured for study and analysis of the following procedures:

- the influence of the number of turns "N" on the frequency response.
- the influence of the wire diameter "d" on the frequency response.

The sensors are all wound around an identical frame to maintain the same surface. Table I sums up the different sensors used for the study.

Table 1. THE DIFFERENT SENSORS USED FOR THE STUDY

Sensors name	Number of turns	Diameter (d) mm
S 1	185	0.1
S2	185	0.3
S3	100	0.5
S4	100	0.1
S5	100	0.3
S6	200	0.3
S7	200	0.3
S8	197	0.3
S9	1000	0.1
S10	200	0.1
S11	360	0.3
S12	3000	0.1
S13	750	0.1
S14	75	0.71
S15	20	0.1
S16	20	0.71
S17	197	0.1
S18	360	0.3
S21	360	0.1
S22	200	0.3

4.1 The influence of the number of turns on the frequency response

In the case of a coil without additional circuit, resonance can occur under certain conditions because a coil can be modeled by a circuit R -L – C where "R" is the resistance of the wire, "L" the inductance of the coil and "C" the stray capacitance created between the turns of the coil.

In order to determine the frequency responses and the components of the circuit R - L - C, for the analysis an impedance-meter was used for all sensors.

The frequency response obtained for the sensors is given in figures 3. and 4.

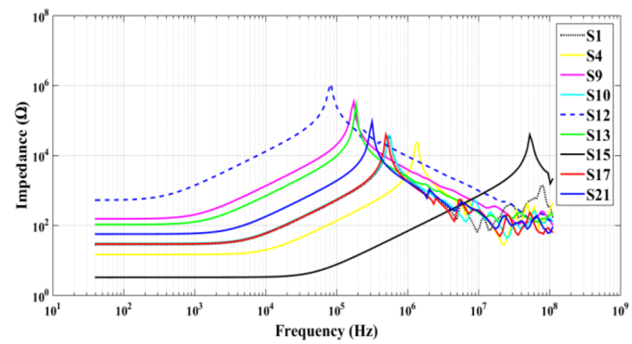

Figure 3. Frequency response of sensors made with wire diameter d = 0.1mm .

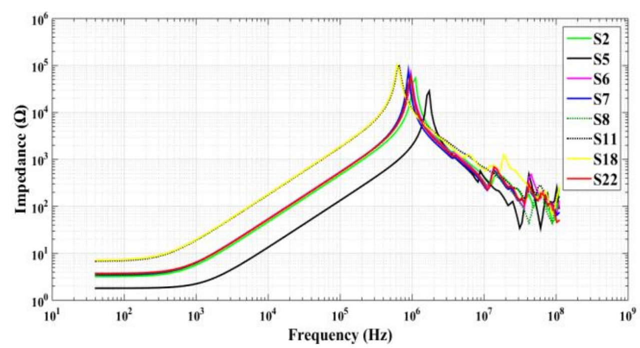

Figure 4. Frequency response of sensors made with wire diameter d = 0.3mm.

Here we can note the appearance of the resonant frequency and an increase in the impedance of the coil between 1 and 100 kHz. This increase depends on the construction of the sensor.

From figure 3, it is possible to analyze the performances with regard to the section of the winding wire and the number of turns for the different sensors. For sensors made with a wire of d = 0.1mm, the frequency response shows a F0 resonance between 82.85 kHz and 52.410 MHz. For example, for the sensor S15 with N = 20 turns, we notice a resonance around F0 = 52.41 MHz. In comparison with the sensor S21 with the same surface produced and 360 turns, the resonance frequency is around F0 = 314.7 kHz.

As a result, an increase in the number of turns of the sensor leads to decrease the resonant frequency and to limit the band of use of the sensor.

On the other hand, it should be noted that an increase in the number of turns makes it possible to increase the emf and therefore the visibility of the signal.

As the useful frequency range of the sensor must be far from the resonant frequency, we conclude that these sensors are suitable for measuring the flux in the frequency range that we operate (less than 2 kHz). Based on practical observations, we suggest that the study band is at least 7 times far from the resonant frequency where the impedance value in the measurement range is very linear.

4.2 The influence of the wire diameter on the frequency response

To study the influence of the diameter of the wire on the frequency response of the sensors, in table I are considered three sensors S3, S4 and S5 which have the same surface S = 0.031416 m^2 and the same number of turns (N = 100 turns). The difference lies in the wire diameter corresponding to ds3 = 0.5 mm, ds4 = 0.1 mm and ds5 = 0.3 mm. The frequency response of these sensors is shown in Figure 5. The S3 sensor has a first resonance at 2.163 MHz for an impedance Z3 = 49.37 kΩ, the S4 sensor at 1.386 MHz for an impedance Z4 = 23.53 kΩ and the sensor S5 has a resonance at 1.731 MHz for an impedance Z5 = 28.51 kΩ.

This displays that an increase in the diameter of the sensor winding wire allows the resonant frequency "F0" to shift towards the high frequencies with a decrease in the value of the impedance "Z" for the low frequencies. On the other hand, increasing the diameter of the wire reduces the frequency range where the impedance is constant. This is a criterion in the choice of sensor.

The low frequency analysis of characteristics presented in figure 5 shows a decrease (with the increase in the diameter of the wire) of the frequency interval where the signal can be considered almost stable. This interval corresponds to that which must be used for the study frequencies in the diagnosis of the machine and which passes from 10 kHz for S4 (wire with small diameter) to 300 Hz for S3 (wire with large diameter).

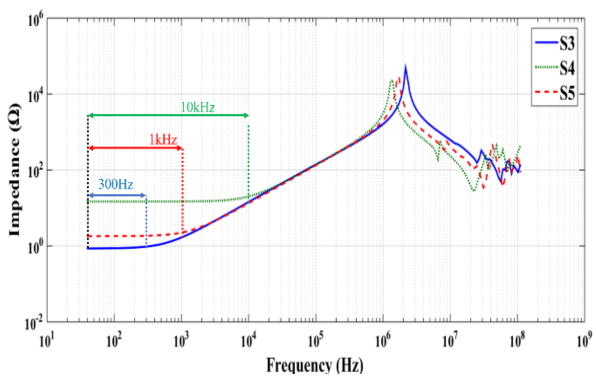

Figure 5. The influence of the diameter d of the wire on the linearity of the sensor and its resonant frequency.

4.3 Choice of sensor

To study the design and choice of sensors for measuring the magnetic field around a machine, it was necessary to create a uniform magnetic field generator device adapted to measure each sensor under the same conditions.

This generator is a specially created coil with a wire diameter of d = 0.85mm and N = 600 turns. The dimensions of the generator are shown in Figure 6.

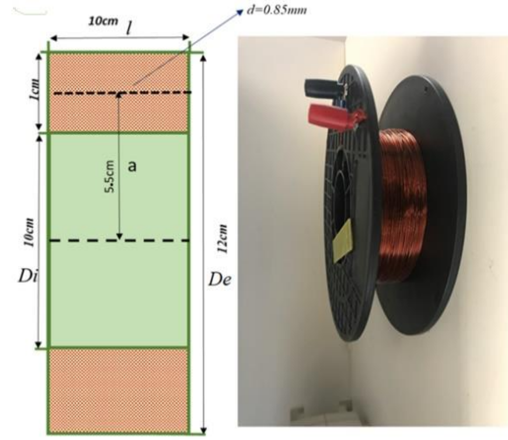

Figure 6. Uniform magnetic field generator developed for testing sensors.

This generator presented in Figure 7 is used to test the sensors and makes it possible to tune the intensity of the magnetic field B in its center.

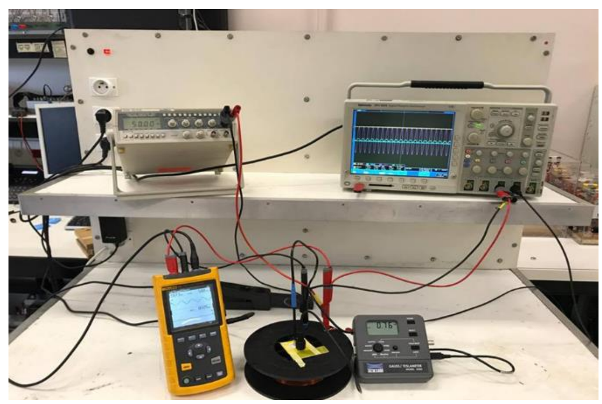

Figure 7. Field generator developed for testing the sensors.

Different values of the intensity "I" of the current are used to characterize the sensors which give in the output a "e.m.f." When the current "I" supplies the coil of the field generator, a temporal variation of the magnetic flux is generated.
Figure 8 shows the time variation of the e.m.f for different current values in the generator coils (I = 25 mA, 50 mA, 75 mA, 100 mA and 125 mA) for a signal frequency of 50 Hz.

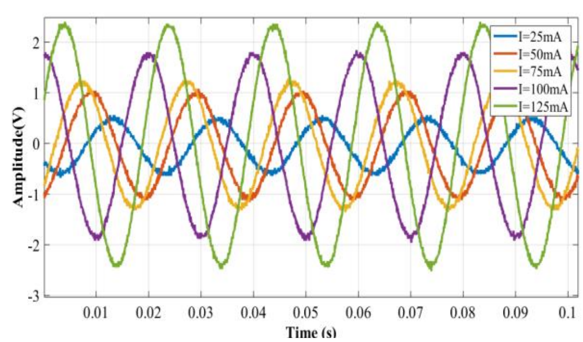

Figure 8. E.m.f induced for different values of the current in the magnetic field generator.

For measuring signal, a "Tesla-Meter" probe and the coil, sensors are placed in the center "O" of the field generator as shown in Figure 7 for one of the sensors.

Table 2 shows the results of the magnetic field measured by the Tesla-meter and the results obtained by calculation of "B_0" using the induction formula in a short solenoid:

$$B_0 = \frac{\mu_0 N I}{2R} \quad (9)$$

With $\mu_0 = 4*\pi*10^{-7}$, N = 600 spires, R = 5.5 cm: mean radius of the coil. There are close values obtained between B measured and B calculated.

Table 2. Values of the magnetic field measured and calculated in the center "O" of the field generator.

I (mA)	0	25	50	75	100	125
Voltage generator (V)	0	0.35	0.67	0.99	1.31	1.63
B calculated (mT)	0	0.17	0.33	0.49	0.65	0.83
B measured (mT)	0	0.17	0.32	0.46	0.62	0.76

A graphical representation of the variation of the e.m.f and the induction B0 given by the sensor as a function of the current intensity in the generator is presented in figure 9. From this graph we can observe an almost linear dependency between the concerned parameters. In addition, the linear nature of the observed dependency confirms the validity in this device of Faraday's law on induction and forecasts of the developed statistical model called "coefficient of determination" noted "R^2" which characterizes the alignment of the measurement points with a value of "$R^2 = 1$" for perfect alignment. The coefficient of determination "R^2 is the square of the linear correlation coefficient r" [17] is an indicator which makes it possible to judge the quality of a simple linear regression as shown in Figure 9. It give the correlation between the intensity "I" of the magnetic field "B" induced in the center of the generator and the applied current "I" to the generator. This coefficient give a strong linear relationship between "I" and "B" for the case of the calculated values "(9)" and the case of measured ones by the Tesla-meter.

For analyzing the value of the magnetic induction measured by the Tesla-meter, the value calculated with equation 8 and the value obtained from the measurement with sensor S13 in the center of the field generator are given in Table 3.

TABLE 3. Variation of the intensity of the magnetic field (B) as a function of the current; comparison with results obtained by S13.

I (mA)	0	25	50	75	100	125
B calculated (mT)	0	0.169	0.329	0.494	0.655	0.825
B measured (mT)	0	0 .17	0.32	0.46	0.62	0.76
B S13 (mT) using (8)	0	0.171	0.31	0.459	0.61	0.75

We can observe good performance for sensor S13. This sensor is characterized by N = 750 turns, wire diameter d = 0.1mm and an area S = 3.1416e-04 cm2. Table 3 presents the different values of the magnetic field obtained for a variation of the current intensity of the test coil.

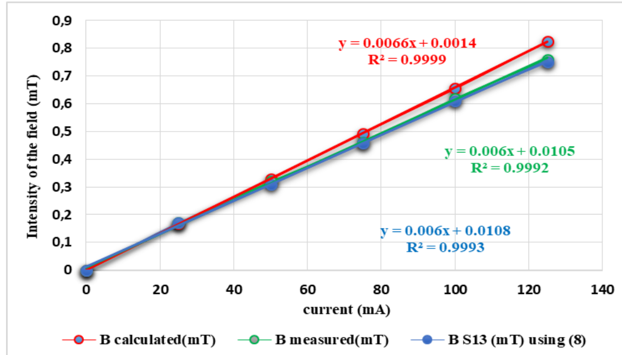

Figure 9. Linear intensity variation of the calculated magnetic field (B), measured by Tesla-meter and measured by S13 sensor.

The intensity variation of the magnetic field "B" obtained by analytical calculation, by direct measure with Tesla-meter in the center of the developed field generator, and by measure with developed sensor S13 is presented in Figure 9.

It is noted a linear variation of the magnetic field intensity with measured value by the sensor S13 close to the value obtained with the Tesla-meter. So, this type of sensor is adapted for measuring low values of magnetic field with sufficient accuracy.

4.4 The signals provided by the sensors

The signals emitted by two sensors placed at 180° from each other are transmitted to the LABVIEW analyzer, which calculates the FFT of the signal and displays its spectrum. If the machine is healthy, the field distribution on each side of the machine is uniform. In this case, the signal amplitudes are approximately the same on each side as shown in Figure 10.

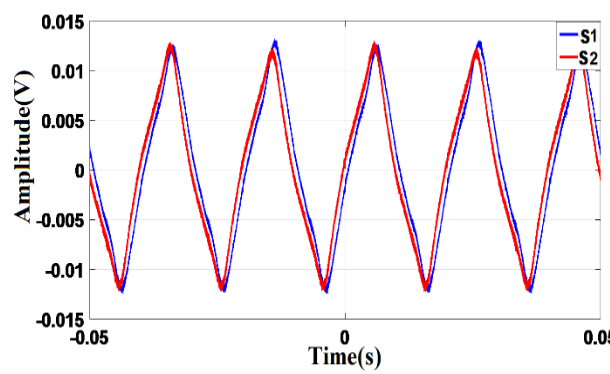

Figure 10. E.m.f induced in the sensors for a healthy machine.

The magnetic asymmetry generated by the fault leads to a difference between the signals delivered by the sensors placed 180° around the machine and to a difference between the amplitudes of the sensitive harmonics measured by each sensor S1 and S2.

When the machine has an inter-turn short-circuit fault, the amplitudes of the diametrically opposite sensitive signals (in this case 750 Hz and 850 Hz) can be significantly different as shown Figure 11. This dissymmetry can be highlighted if the sensors are correctly manufactured and choose.

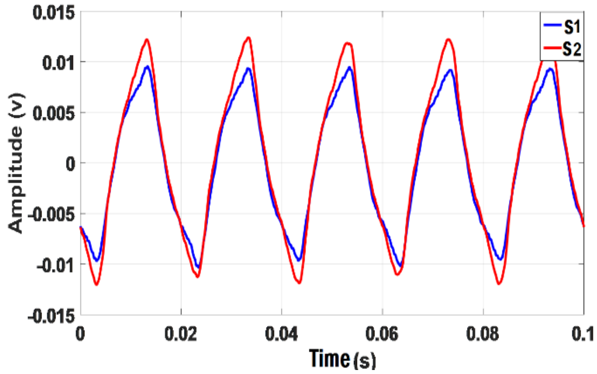

Figure 11. E.m.f induced in the sensors for a faulty machine.

5. CONCLUSION

This paper analyzes the influence of different building parameters in the performances of the coil sensors used for diagnosis of the healthy state of electrical machines. For practical application the study gives information about the parameters which must be considered for the design of coil sensors. It is therefore preferable for a good interpretation of the measurements to have identical manufactured sensors adapted to the machine size in order to increases the percentage of the fault detection.

The study was carried out considering 20 wound manufactured sensors. Obtained results show that:

- an increase in the number of the sensor turns leads to a decrease in the resonant frequency (F0) accompanied with an increase in the measured signal amplitude.
- an increase of the wire diameter allows a shift of the resonant frequency towards the high frequencies with a decrease in the amplitude of the measured signal.

Therefore, it is advantageous to produce sensors with a large number of turns and the lowest possible wire diameter in order to obtain a sensor with a relatively constant characteristic on the bandwidth of the studied frequencies and a resonance frequency further from the range of analysis. However, a compromise must be found between the number of turns, the wire diameter and the size of the sensor.

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