


Article

Interpretation of Eccentricity of an Enameled Wire by Capacitance Measurements

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Abstract: There are systems dedicated to measuring the eccentricity of enameled wires based on optical and electromagnetic phenomena. However, these methods are limited by the nature of the insulation and the conductor. The proposed solution consists of checking the wire eccentricity by an electrical measurement. Since it is a conductor on which an insulator is placed, the idea consists of forming a capacitor and measuring its capacitance in order to deduce the insulation thickness.

Keywords: dielectric; enameled wire; capacitance; eccentricity

1. Introduction

The conventional magnet wires used to make the windings of electrical machines are achieved using a polymeric insulation coating on the copper conductor called the enameled wire. The classic enameling process consists of applying very thin layers of polymeric varnish to the copper wire. The multipass process is used to obtain an increased diameter according to the specifications of international standards [1–3].

The manufacturing process is well controlled. The viscosity of the varnish is optimized. When the wire passes through a felt applicator, it takes calibrated drops of varnish in the wire by the pressure of the varnish. It is calibrated in thickness by dies or by a metered deposit between felts. The copper conductor is then well centered with respect to the die. Dielectric tests [4,5] are carried out on standardized twisted specimens [6] to check the wire characteristics, such as copper centricity.

The application of each layer by dies is followed directly by passing the wire through an enameling oven at 600 °C. The polymerization of the insulating layers is obtained by the actions of the heat and the solvents included in the initial varnish. These solvents represent approximately 60% of the varnish. They are classified as harmful and carcinogenic products. Every year in Europe, 40,000 tons of enamel varnishes are used, and 25,000 tons of solvents are eliminated into the air. Adding to this, due to the exothermic reaction of these solvents, 50,000 tons of CO₂ are generated [7,8].

The awareness of our societies to respect our environment makes it necessary to develop new manufacturing processes by extrusion that are less harmful and more economical [1,9]. The first results relative to electrical measurements suggest the use of the extruded coating wires [9,10]. One of the technological obstacles of these processes is mastering the centering of copper in its insulation. Indeed, the windings of electrical machines are made in such a way as to be able to create an electromagnetic field that allows the proper functioning of the machine. In the event of poor centering, the insulation will have thinner thicknesses in certain places. These will be vulnerable areas as the imposed electrical field is higher, which will lead to the premature appearance of partial discharges accelerating the aging of the insulation and leading to a premature fault [11–15]. Therefore, the enameled wire concentricity is a parameter that intervenes in the lifespan of the windings of the electric machines.



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The article proposes the study of a device for measuring the eccentricity of enameled wire on a continuous line. It exploits capacitance measurements to determine the thickness of the wire insulation. When the copper conductor is centered in the enamel, the insulation thickness should be the same all around and all along the enameled wire. Differential mode measurements compare the thicknesses by electrical measurements, which make it possible to deduce the centering of the enameled wire. This original method is noninvasive and can be operated without stopping the enameled wire production line and without any modification on the conductor and for all insulated varnishes. Only pulleys require special machining for each wire diameter. Finally, this device has advantages over the optical [16,17], magnetic [17] or electromagnetic [16] systems already used that cannot meet the needs of opaque or nanofilled varnishes and nonmagnetic wires, such as copper and aluminum.

2. Proposed Solution Principle

The proposed solution consists of verifying the eccentricity of the wire by an electrical measurement. Since this is a conductor with an insulator placed on it (Figure 1), the idea is to form a capacitor and measure its capacitance.

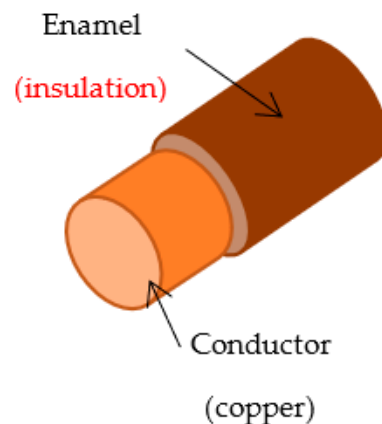


Figure 1. Illustration of an enameled wire.

As a reminder, a capacitor is presented as two metal frames separated by an insulator (Figure 2). It is, therefore, sufficient to add a second conductor (metal frame) on the insulation of the wire to form a capacitor.

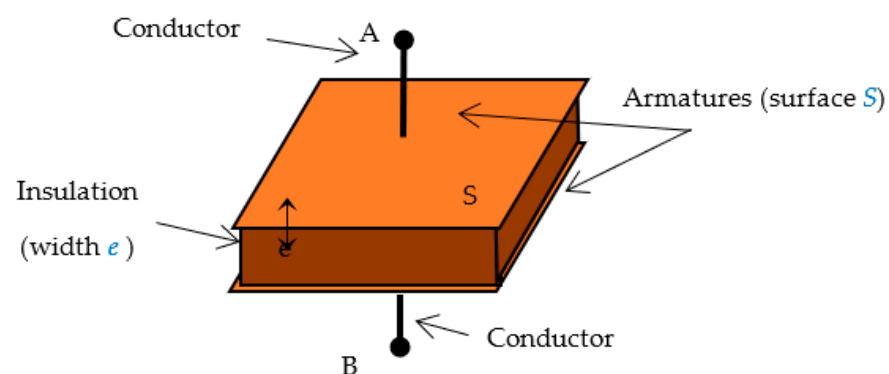


Figure 2. Representation of a planar capacitor.

In order to respect the circular shape of the wire, a metal disc with a diameter of 0.1 m was used as the second reinforcement. On the outer edge, a circular slot with a radius of 0.5×10^{-3} m was made so that it could contain the enameled wire (Figures 3 and 4). This creates a cylindrical capacitor on the contact distance between the wire and the disc.

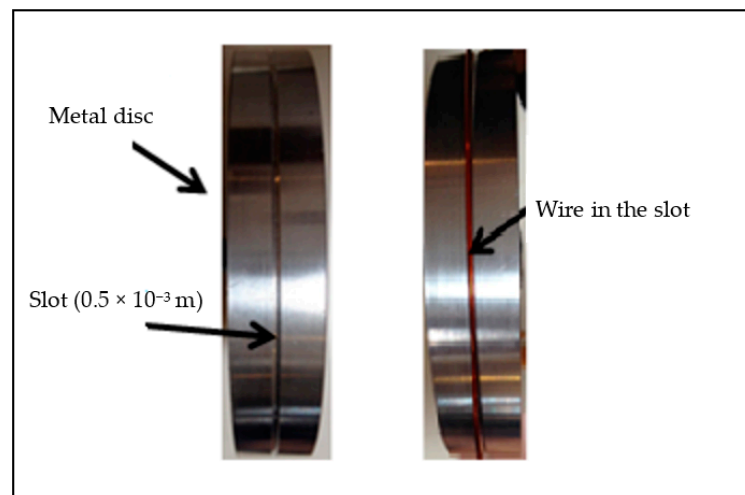


Figure 3. Disc with a slot on the outer edge.

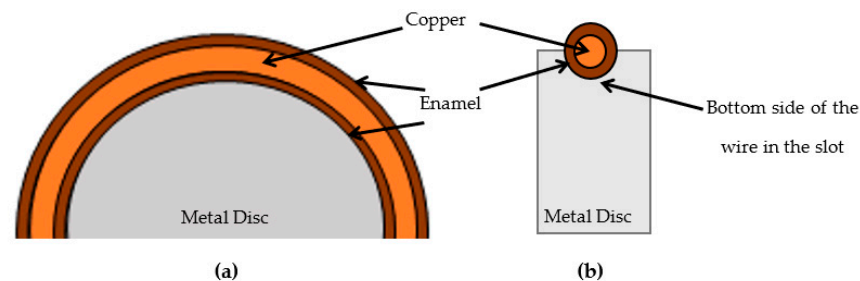


Figure 4. Frontal (a) and longitudinal (b) sections of the formed capacitor.

In the case of the cylindrical coaxial capacitor of length l , the capacitance is given by the following [18]:

$$C = 2\pi\epsilon_0\epsilon_r \frac{l}{\log\left(\frac{R_2}{R_1}\right)} \quad (1)$$

with:

$$R_2 = R_1 + e \quad (2)$$

C : capacitance of the capacitor (F)

ϵ_0 : permittivity of the vacuum ($8.854 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$)

ϵ_r : relative permittivity of the insulation (unitless)

R_1 : inner radius of the cylinder (m); this corresponds to the wire radius in this configuration

R_2 : outer radius of the cylinder (m)

e : Insulation thickness of the wire (m)

l : length of the cylinder (m); this is the arc formed by the contact between the disc and the wire

As only the longitudinal half of the cylinder is considered, half of the capacitance is determined. The relationship between the capacitance of the capacitor and the thickness of the dielectric in this case is given by the following equation:

$$C = \pi\epsilon_0\epsilon_r \frac{l}{\log\left(1 + \frac{e}{R_1}\right)} \quad (3)$$

As the wire has a diameter of $0.95 \times 10^{-3} \text{ m}$, the enamel thickness is about $35 \times 10^{-6} \text{ m}$ and the slot in the disc has a diameter of 10^{-3} m , so the contact will only be made on half of the circumference of the wire (Figure 4b).

To find out if the conductor is centered on both sides of the wire, two disks are used (Figure 5) to form two capacitors using the two halves of the wire circumference (top and bottom sides). This makes it possible to compare the thicknesses of the insulation on both sides of the wire, from the values of the capacities of the two capacitors.

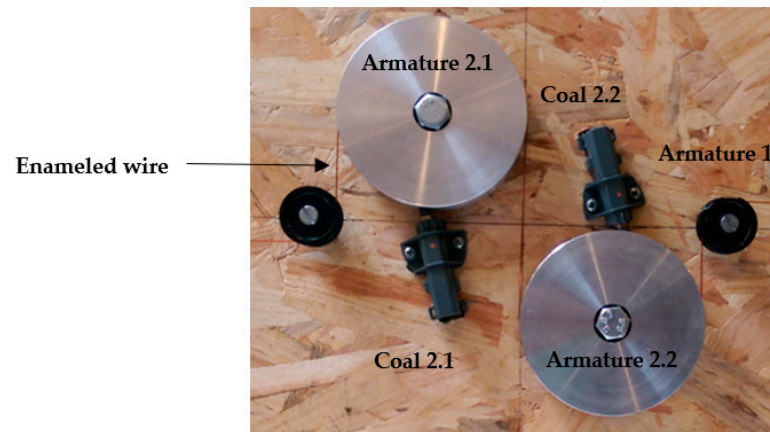


Figure 5. Synoptic system.

The two coils will serve as contact for the two armatures, for each capacitor, and the contacts of the armature 1 will be recovered by clamps fixed on the stripped wire (without insulation).

3. Experimental Setup

3.1. Description

The measuring device model consists of two parts. The first consists of creating a capacitor between a pulley and the conductor of the enameled wire (Figure 5). Two capacitors at opposite sides of the wire are achieved. The measurement of their capacitance will be carried out by an electronic card used as the second part (Figure 6). It converts differential capacitances in a proportional voltage signal.

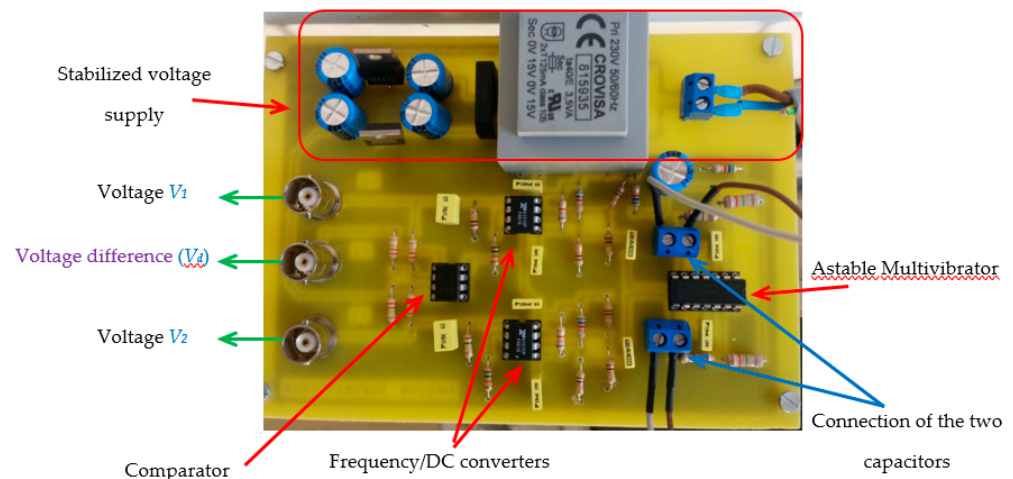


Figure 6. Electronic card made for measurements.

Knowing that the capacitance is inversely proportional to the thickness of the dielectric (Equation (1)), it is possible to know the insulator thickness modification by the capacitance monitoring measurement. To make this measurement, an electronic circuit that can include the capacitor and provide a varying quantity according to its capacitance was best suited. The diagram in Figure 7 shows the process of this measurement for two sides of the wire.

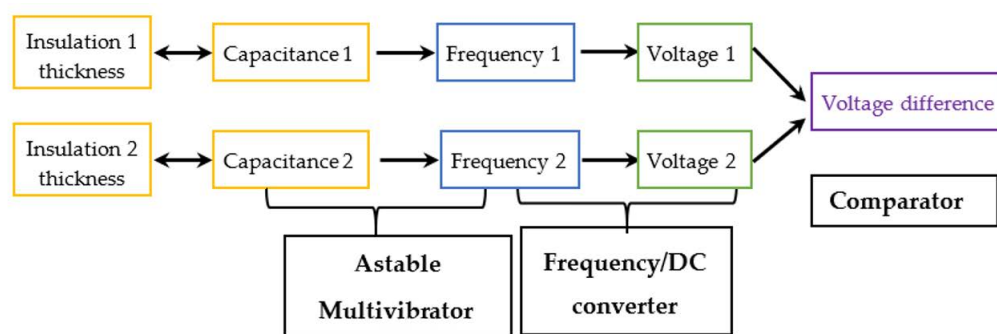


Figure 7. Illustration of the process measurement principle.

Firstly, an integrated circuit for precision timing NE555 is used as an astable multivibrator mode for the two capacitors of our device. The principle of this circuit is to provide a rectangular signal with a frequency that varies according to the passive components (resistors and capacitors) added to it.

To compare the two thicknesses, it suffices to compare the two frequencies. However, the comparison of frequencies seems delicate. Then, these frequencies are converted into direct voltages by using an XR4151 frequency/Dc converter. The voltage amplitudes vary as a function of these frequencies. If the thickness of the insulation is the same everywhere around the conductor and the measurement conditions are the same, then there is no reason for these voltages to be different.

To compare the two DC voltages from the converters, the LM833 operational amplifier is used as a comparator. It operates with a high-gain bandwidth, high slew rate and low noise. It is mounted as a difference amplifier (subtractor) with a gain of unity. Thereby, the measurement uses a differential mode that is much less sensitive to disturbances [19]. Furthermore, it does not depend on the type of varnish (more or less dielectric).

3.2. Validation

Two disks are used to form two capacitors using the two halves of the wire circumference. This makes it possible to compare the insulation thicknesses on both wire sides, based on the capacitance values. To compare the two thicknesses, it is sufficient to compare the two frequencies obtained by an adapted electronic circuit. If the thickness of the insulation is the same everywhere around the conductor and the measurement conditions are similar, the voltages are constant.

An electronic card has been produced. In order to validate its operation, a measurement with variable capacitors was firstly carried out.

Table 1 shows the voltages measured at the output of the electronic card for the three possible cases of capacitance values. The voltages V_1 and V_2 depend on the thickness of dielectric 1 (with the capacitance C_1) and dielectric 2 (with capacitance C_2), respectively. The difference between them, at the output of the comparator, is V_d (Figure 6). The difference in voltage when the capacitances values are different is observed.

Table 1. Voltage values at the outer of the electronic card.

	V_1 (V)	V_2 (V)	V_d (V)
$C_1 > C_2$	4.935	6.998	2.223
$C_1 < C_2$	5.277	2.920	−2.197
$C_1 = C_2$	2.390	2.327	0.089

4. Determination of Influencing Phenomena

The purpose of this part is to identify all the aspects (other than the thickness of the dielectric) that can contribute to the variation of the capacitances of the capacitors. An

Agilent 4294A impedance analyzer is used to observe the capacitance in different situations. The measurement precision is 0.08% at 10×10^3 Hz.

4.1. The Mechanical Constraint Applied on the Wire

Different masses were used to apply mechanical constraint on the wire when it is on the disc (Figure 8). Depending on the load, we can see the result in Figure 9.

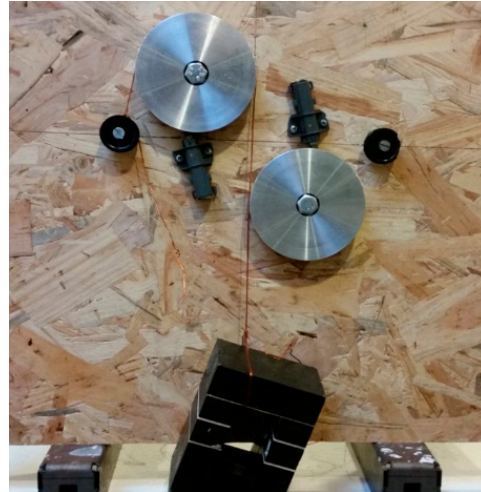


Figure 8. Test bench for the application on a mechanical constraint.

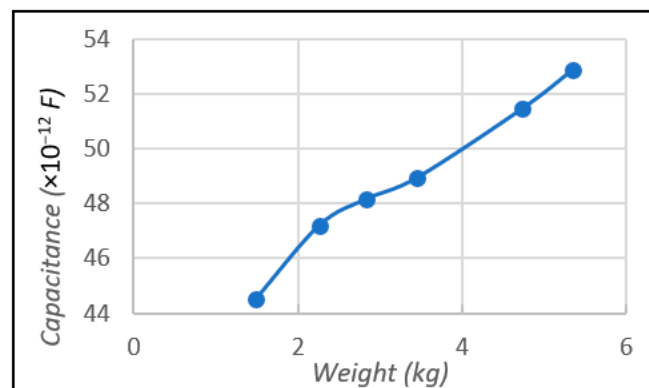


Figure 9. Evolution of the capacitance as a function of the weight applied on the wire.

The results of this part lead to reflection on two points, namely, the pressure between the two armatures and the dielectric and the thickness of the dielectric.

Indeed, when the mass increases, the capacitance rises. However, the latter can result in increased pressure or decreased thickness. It is difficult to make this distinction and to prevent the thickness from decreasing as the wire is kept as tight as possible. In addition, a very high mechanical constraint of the wire can modify the physicochemical properties of the dielectric, which, consequently, will involve considerable errors and would make the obtained results false.

4.2. The Length of the Wire in Contact with the Disc

For the six fixtures in Figure 10, the same enameled wire (0.95×10^{-3} m) was used with different occupancy lengths shown in red dots on the discs. In each case, a mass of 1.3 kg on each side allows the wire to be stretched as shown in Figure 11. The results are given in Table 2. The greater the contact length, the larger the capacitance.

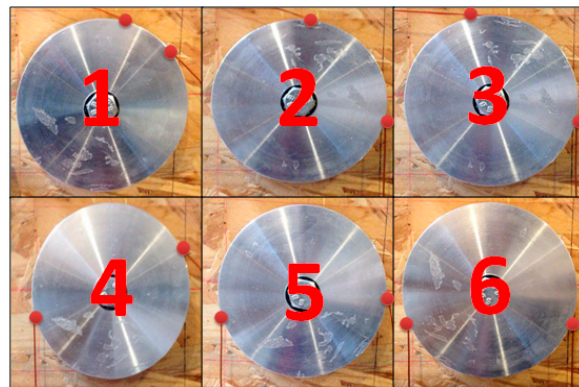


Figure 10. Assemblies for different lengths of wire on the disc.

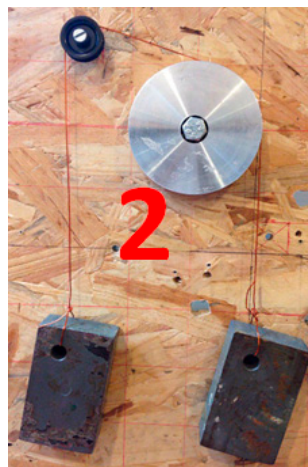


Figure 11. Assembly with occupancy of the quarter disc.

Table 2. Capacitance for different wire lengths.

Assembly No.	Capacitance ($\times 10^{-12}$ F)
1	17.7
2	29.60
3	35.40
4	57.83
5	63.50
6	70.55

5. Results and Discussion

The Laboratoire Systèmes Electrotechniques et Environnement (LSEE), The Electrotechnical Systems and Environment Laboratory (LSEE), is a university research laboratory that has a laboratory-scale enameling line. The effectiveness of this device is verified on an enamelled wire sample manufactured by this line, without worrying about the centering of the copper conductor. The insulation is based on the classical PAI-PEI insulation of 0.95×10^{-3} m.

The configuration 2 has been used in order to have maximum contact between the wire and the disc, making sure to have a low amount of stretched wire. If we assume that the difference in capacitance is due only to the difference in thicknesses, we can calculate the corresponding thicknesses in order to analyze their values.

The voltages at the output of the electronic board were measured. $V_1 = 3.171$ V, $V_2 = 3.292$ V and $V_d = 0.303$ V are measured for the capacitors 1, 2 and the output of the

comparator, respectively (Table 3). They are converted into frequency according to the datasheet of the converter, namely the following:

$$f_{int} = 10^3 * \frac{V}{0.6} \quad (4)$$

Table 3. Results.

	Voltage (V)	Capacitance ($\times 10^{-12}$ F)	Width ($\times 10^{-6}$ m)
V_1	3.171	49.20	25.68
V_2	3.292	47.38	26.66

We know the frequency makes it possible to calculate the capacitance from the astable circuit component value.

Equation (3) allows us to return to the values of the thicknesses of the dielectrics of our two capacitors. As $\frac{e}{R_1} \simeq 0$, then the following is used :

$$C \approx \frac{\pi \epsilon_0 \epsilon_r l}{\frac{e}{R_1}} = \frac{\pi \epsilon_0 \epsilon_r l}{e} * R_1 \quad (5)$$

For the used system, the capacitance is as follows:

$$C = \frac{\pi 2 \epsilon_0 \epsilon_r}{2 * e} * R_1 * (R_D - R_1 - e) \quad (6)$$

C: capacitance of the capacitor (F)

ϵ_0 : permittivity of the vacuum (8.854×10^{-12} F·m⁻¹)

ϵ_r : relative permittivity of the insulation (unitless)

R_1 : radius of the wire (m)

e : insulation thickness (m)

R_D : disc radius (m)

then:

$$e = \frac{\pi 2 \epsilon_0 \epsilon_r * R_1 (R_D - R_1)}{2C + \epsilon_0 \epsilon_r R_1 \pi^2} \quad (7)$$

The results are given in Table 3. The length of the wire that is in contact with the disc is not known with precision. However, by using the above formula, it is assumed that it is exactly half of the circumference of the disc.

This example makes it possible to definitively validate the feasibility of the concept of dielectric measurement. Indeed, the deviation of the value of the capacitance results in a voltage difference.

A complete study of wire eccentricity requires training at least four capacitors to compare the thicknesses on four sides of the wire. Thus, the measuring device will be formed of four discs having a slot with a perimeter equal to a quarter of that of the wire.

6. Conclusions

The preliminary study carried out in this paper makes it possible to check the principle of the eccentricity measurement of an enameled wire by an electrical method. As it is possible to translate the thickness of the dielectric into DC voltage, it is possible to make the comparison between several thicknesses.

The device designed will be added to the wire production line available at the laboratory in order to determine the wire eccentricity. This will allow a precise adjustment at the beginning of the process and also a continuous monitoring during the manufacture of the wire. A complete study of the eccentricity of the wire requires the formation of at least four capacitors to compare the thickness on the four sides of the wire.

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