Current Transducer Based on Thermoformed Piezo-magnetic-electrets

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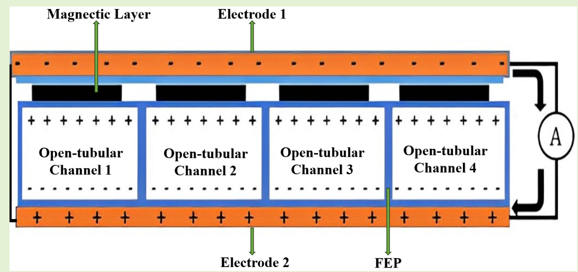
Abstract—**Thermoformed tubular channels piezoelectrets exhibiting piezoelectric-magnetic behaviors were recently presented as Thermoformed Magnetic-Piezoelectrets (TMPs). This alternative sensor was suitable for detecting external magnetic fields from distant magnets. In this contribution, TMPs transducer was investigated as current transducer, where the magnetic field produced by an electrical current passing through a energized wire mechanically stimulates the TMP and consequently disrupts the electrical charge equilibrium providing a proportional electrical signal. The charge variation was correlated with the magnetic field intensity, providing a piezo-magnetic coefficient, similar to those noted in traditional piezoelectrets. It has been noticed that under certain conditions, TMP could have coefficients up to 498×10^5 pC/T. From these results, it was concluded that such a polymer-based device is suitable for monitoring electrical current in live wires, providing an interesting solution for non-invasive current transducers (CT) with a reduced footprint. These novel transducers can thus provide an effective replacement for coil-based CTs reducing installation cost and space, without the need for wire re-connection (as required by the coil CTs), enabling hot-plug capabilities, as well as providing a direct and cost-effective replacement for high-frequency current transformers.**



Index Terms—**Electrets, Polymers, Piezoelectricity, Magnetic-electrical effect.**

I. Introduction

THE ferroelectrets, also referred to as electromechanical films, have garnered significant attention due to their remarkable ability to exhibit a strong piezoelectric effect. Consisting mainly of electrically charged polymer foams, these materials exhibit internal positive and negative electrical charges, leading to the occurrence of an electric polarization phenomenon. Such materials, when exposed to the influence of perpendicular mechanical stresses, reacts with an electrical signal that is proportional to the applied stress [1]–[3]. The notable combination of considerable charge trapping capability and the inherent low density of these electrically charged polymeric foams consistently engenders piezoelectric coefficients (d_{33}) that surpass those observed in conventional piezoelectric polymers like polyvinylidene fluoride (PVDF). As a result, they are increasingly finding applicability across a broad spectrum of mechanical stimulus scenarios [4], [5].

However, propelled by the wave of technological advancements that encompasses equipment refinement, novel materials, and innovative processing techniques, a distinct path emerged to amplify piezoelectricity within ferroelectrets. This novel route involved molding and fusing polymer layers. This layered association ushered in an alternative means of enhancing the thermal stability within ferroelectrets [4], [6]–[10]. In these composite formations, polymers capable of charge trapping capabilities, such as polytetrafluoroethylene (PTFE) and its copolymer fluoroethylene propylene (FEP), were seamlessly integrated with structures of minimal density, culminating in higher thermal-electromechanical responsiveness [11].

Through the molding and fusion approach, ferroelectrets with different geometric configurations and distributions of their internal cavities were fabricated [12]–[14]. Various methodologies for fabricating optimized polymeric structures have been recently described in the literature [8], [9]. Furthermore, regularly shaped air cavities affected the uniformity of electrical charging, thereby intricately enhancing the piezoelectric characteristics of the material, as scholarly highlighted in [15], [16]. A successful paradigm for fabricating

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fluoropolymer matrices featuring precisely arranged tubular cavities was introduced by Altafim [15]. In this innovative approach, the arrangement of open tubular channels was achieved by laminating FEP films alongside a precisely aligned PTFE rectangular template, creating a parallel configuration. This methodology not only offers the ability to fine-tune the geometric attributes of internal cavities for meticulous characterization but also demonstrates its prowess in engineering multi-layered structures with systematically organized channels, thereby further amplifying the piezoelectric potential [17], [18].

In a recent stride of advancement, this lamination technique was extended to incorporate overlapping polymer strata, resulting in the creation of a ferroelectret exhibiting not only piezoelectric properties but also endowed with magnetic response. This innovative step resulted in the discovery of a concept where a piezoelectret material demonstrates a significant magnetic-electric response. This achievement was made possible by adding a magnetic polymer layer on top of the tubular channel structure. The resultant phenomenon observed on these “magnetic-piezoelectrets” does not resembles traditional magnetoelectricity, wherein the interplay between materials possessing ferroelectric or magnetic attributes gives rise to a characteristic effect through hysteresis, what is known as the magnetoelectric effect [19], [20].

It is known that magnetoelectric effect can manifest either as direct or inverse in nature, since magnetic polarization can be modified through electric fields [19]. In magnetic piezoelectrets, only a direct effect is observed, that is, when a magnetic field initiates a mechanical stress that interacts synergistically with the piezoelectric layer, thereby engendering a mechanical deformation effect, which culminates in the emergence of an electric field response (E) [20], [21]. In the literature, there are various MEMS sensor prototypes designed for monitoring AC current in residential and commercial settings. One such sensor features a piezoelectric MEMS cantilever with a mounted permanent magnet, generating voltage proportional to the current being measured. Fabrication involves a four-mask process and the integration of microscale composite permanent magnets, providing a compact solution for monitoring end-use electricity or piezoelectric energy harvesting from AC current-carrying wires [22], [23]. Additionally, a study explores a zero-power multifunctional device combining piezoelectric technology and a magnet mass for current monitoring and energy harvesting in power lines. The performance of this device is influenced by the type of wire, the stiffness of the cantilever and the magnet characteristics, showing potential for smart grid applications. In contrast, the thermoformed magnetic-piezoelectrets (TMPs) differ from these sensors in terms of assembly, characterization, and physical principles [24], [25].

Therefore, the configuration devised by Altafim *et al.* [26], incorporates ferroelectrets in lieu of conventional piezoelectric materials, thereby yielding a material of enhanced direct magnetic sensitivity. In the current investigation, these TMPs were undertaken, subjecting them as noninvasive electric current sensors under magnetic fields of varying intensities.

II. Piezoelectrets with Magnetic Behavior

For a proper understanding of the piezo-magnetic behavior observed on thermoformed magnetic-piezoelectrets, one must consider the simplified structure presented in Fig.1.

From this, one can observe that the presence of an external magnetic field attracts or repels the magnetic layer, represented here as the black layer above the channel and attached to the channel surface. This magnetic force influence results in a deformation in the channel thickness (d), which leads to an electric-charged variation on the ferroelectret electrodes. This magnetic-mechanical deformation is therefore responsible for producing an electrical response, proportional to the external magnetic field.

For a better description of the relation between electrical charge variation on ferroelectrets and the external magnetic field, a piezoelectric-magnetic coefficient (d_{p-m}) is proposed. This coefficient derives from those observed in traditional piezoelectric materials, where the polarization may be observed in different orthogonal axes and is represented by a three-dimensional tensor (d_{ij}) [11], [27].

In ferroelectrets, the electric polarization $\vec{P}$ results from the electrical charging, which occurs in the direction of the external electrical field, in this case, the out-plane direction, referred to as the third axis. Since the mechanical deformation or electrical stimulation is applied in this direction the d_{33} tensor is generally used to define the piezoelectric coefficient in ferroelectrets [28].

The d_{33} coefficient is expressed in (1), representing the relation between a mechanical stress variation (Δ_p) that is applied perpendicular to the ferroelectret thickness (out-of-plane direction), and the variation in the electrical charge densities (Δ_σ) that is induced on the ferroelectret electrodes [11], [27], [28].

$$d_{33} = \frac{\Delta_\sigma}{\Delta_p}. \tag{1}$$

In the thermoformed magnetic-piezoelectrets, the same concept is employed, however, the mechanical stress now results from the presence of an external magnetic field, and it was redefined in (2) as the external magnetic field variation (Δ_m), which provide the magnetic-piezoelectric effect (d_{p-m}).

$$d_{p-m} = \frac{\Delta_\sigma}{\Delta_m}. \tag{2}$$

III. Materials and Methods

The Thermoformed Magnetic Piezoelectrets (TMP) examined in this study adhered to the preparation methodology elucidated in [26]. Following this methodology, a polymer-based laminate with longitudinal hollows is produced by fusing two thin sheets of PET using a thermal lamination process. To produce the hollows, a PTFE template is inserted between these two PET sheets during the thermal lamination process. This laminate structure is then covered by a set of strips made from a magnetic polymer. A third layer of FEP foil covers the entire structure. Finally, an aluminum film covers the top and bottom surfaces to provide the electrodes.

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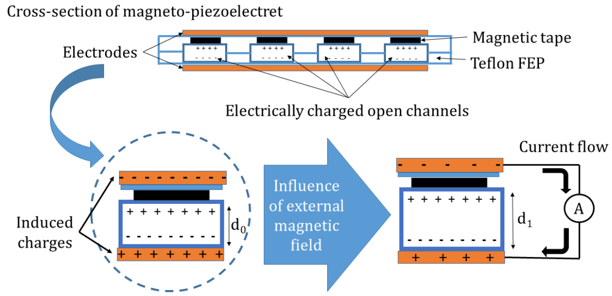

Fig. 1. Schematic representation of the magnetic-piezoelectret structure, illustrating the effect of the external magnetic field on its mechanical structure and consequent modification of the macroscopic dipoles

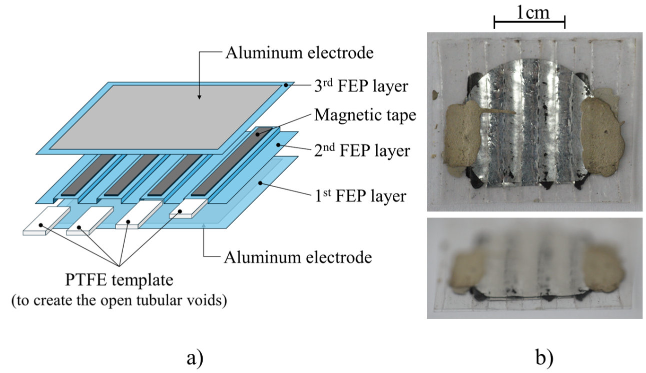

Fig. 2. (a) Layup sequence of the Thermoformed Magneto-Piezoelectret (TMP) with open tubular channels. (b) Produced TMP device with aluminum electrodes ($20mm$ of diameter).

A. Materials

As described above, the laminate consists of three thin sheets of FEP, each with a thickness of 50 μm. Two of these FEP sheets make up the main hollow structure of the device, while the third one completes the laminate structure to support the top conductive electrode.

A temporary template used to create the hollows inside the laminate is laser cut from a PTFE sheet with a thickness of 100 μm.

The magnetic layer is made up of several rectangular stripes (1.5 mm × 15 mm), which have been precision-cut from a magnetic adhesive mat with a thickness of 300 μm, sourced from Fermag-BR.

B. Magnetic-Piezoelectret Fabrication Process

The entire magnetic-piezoelectret structure is produced using a heated lamination process. In accordance with the procedure applied by Altafim *et al.* [26], two sheets of FEP were meticulously fused at a temperature of $300°C$ using a thermal-lamination device, resulting in the formation of a stratified structure. Preceding the lamination process, the PTFE template, featuring precisely incised rectangular patterns, was intercalated between the layers of FEP. This strategic placement facilitated the fusion of the FEP layers in alignment with the prescribed template. Notably, the template implemented in this investigation was strategically designed to engender four distinct channels, each exhibiting a width of 2 mm, arranged equidistantly and parallel.

Subsequently, in the ensuing processing phase, the channels were superimposed on an arrangement of rectangular magnetic tape strips. The inherent magnetic layer introduced an incompatible surface irregularity with the electrode formation, therefore a supplementary FEP film was adeptly laminated over the stratum of magnetic strips, using a temperature of $300°C$ to ensure its effective integration.

After the final lamination process, the PTFE template was meticulously extracted, revealing the unobstructed and empty channels integrated into the FEP matrix. Aluminum electrodes of approximately 50 nm thickness were then deposited on the outer layers through a vacuum-assisted evaporation process, and an electrical charge was applied for 10 seconds using a direct current (DC) voltage of 3.5 kV. A schematic representation of the production process is provided in Fig.2.

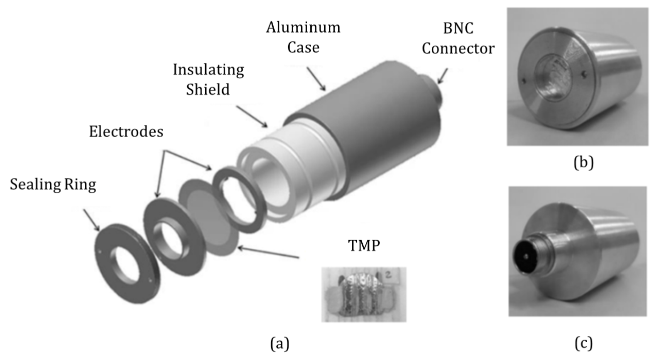

Fig. 3. (a) Schematic representation of the TMP current sensor assembling. (b) Image of the front of the metal casing. (c) Image of the back of the metal enclosure.

C. Assembly of the Current Transducer

An electrically charged TMP, was used as sensing element in the Electro-magnetic current transducer. Therefore, the TMP was assembled into an aluminum casing, equipped with a BNC connector and insulating materials, as shown in Fig.3.

The insulating material was made from Polyvinyl chloride (PVC), and two aluminum planar electrodes were fabricated to provide electrical contact to the TMP. A sealing ring was used to avoid mechanical vibrations of the sensor. Notice that the front part of the transducer (Figure 3b) is open to provide direct access to the TMP if necessary. A Keithley 6517 Digital Electrometer, was used in this study to measure the electrical charge generated during the experiments.

D. Characterization of current transducer - Electrical current sensitivity test

To verify the influence of magnetic fields on the TMP transducer, a setup according to Fig.4 was mounted. This experiment consisted of stimulating the wire with different electrical currents in amperes (A), to produce a magnetic field with several magnitudes. The TMP transducer shown in Fig.4(a), was initially placed above a variable alternate current

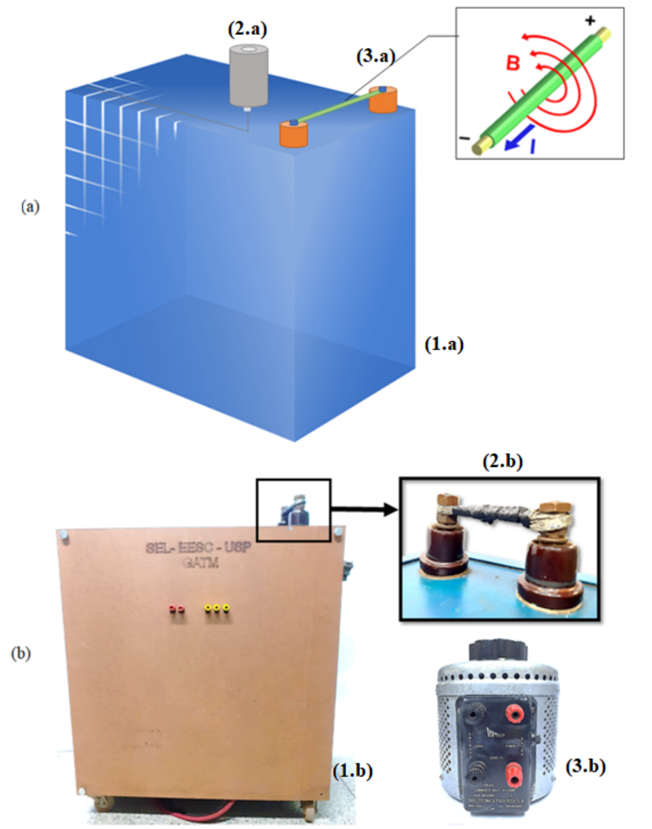

Fig. 4. (a) Alternate current (AC) power supply (1.a), Schematic drawing of TMP (2.a) and live wire with current flow and magnetic field orientation (3.a). (b) Current Transformer (CT) (1.b), Secondary wire of the CT (2.b) and Variac (3.b).

Fig. 5. Electrical charge produced by the TMP when placed at different distances from the electrical wire under several electrical currents.

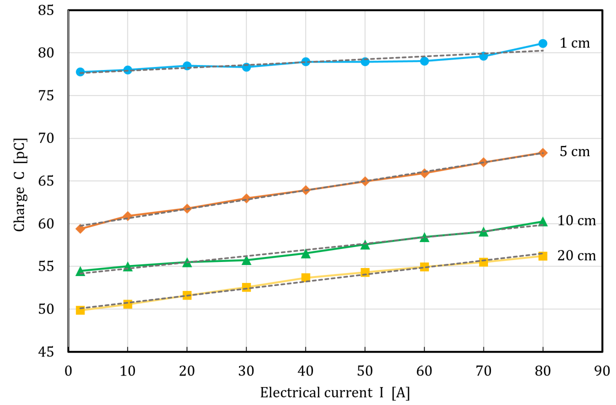

TABLE I
MEASURED PIEZOELECTRIC-MAGNETIC COEFFICIENTS

Electrical Current [A]	d_{p-m} $[pC/T] \times 10^4$			
	1 cm	5 cm	10 cm	20 cm
2	195.95	990.00	1350.00	4980.00
10	38.80	145.00	324.12	631.25
20	24.50	98.10	168.18	321.88
30	14.10	57.71	113.88	181.03
40	11.12	43.24	76.49	148.61
50	8.27	35.66	56.37	128.81
60	7.12	25.94	50.26	96.14
70	6.12	24.83	46.90	75.89
80	5.33	21.68	42.17	71.01

(AC) power supply and later positioned at several distances from the live wire, Fig.4(b).

However, before conducting any tests with the TMP, the currents were calibrated to $2, 10, 20, 30, 40, 50, 60, 70,$ and 80 A. For each current, the TMP was positioned at distances of $1, 5, 10,$ and 20 cm away from the wire.

IV. RESULTS AND DISCUSSION

The magnetic layer, placed above the piezoelectret channels, under the influence of an oscillating external magnetic field reacts as a vibrating loading onto the piezoelectret. This dynamic load is then responsible for deforming the electrically charged channels, disturbing the TMP electrical field, resulting in an electrical charge flow.

The graph depicted in Fig.5 presents the electrical charge values measured at different positions and current intensities, while the results presented in Table I, represent these values converted into magnetic-piezoelectric coefficients (d_{p-m}). From these, one may observe that when TMP is fixed at a certain position, the electrical charge output increases linearly with the current intensity (I). And that the transducer sensibility is much affected by its position, since a charge decay is observed when the TMP is moved away from the wire.

The material behavior becomes thus non-linear, and the transducer response loses the direct linear relation to the measured electrical field intensity. This behavior is graphically represented in Fig.6, where the distribution of the piezoelectric-magnetic coefficient is plotted for different values of electrical current passing through the electrical wire. From this, one can observe that:

- When measuring low levels of the electrical current (below 10 A), the distance between the transducer and the observed electrical wire has a significant effect on the piezoelectric-magnetic coefficient.
- The higher value for this coefficient, 498×10^5 pC/T, is reached for the lowest electrical current applied to the observed electrical wire (2 A) when the transducer is located at 20 cm from that wire.
- For higher values of electrical current (> 10 A) the effect of the distance between the transducer and the electrical wire becomes less significant.

Representing this graph in a logarithmic scale, as depicted in Fig. 7, two major observations can be drawn:

- The distribution of the piezoelectric-magnetic coefficients for each distance assumes a linear shape parallel to the diagonal lines in the Log-Log graph.
- The vertical distances between the piezoelectric-magnetic values for the four distances herein considered ($1, 5, 10$ and 20 cm) are practically constant and independent from the value of the electrical current under observation.

From the first observation, one can conclude, as expected, that there is an inversely proportional relation between the piezoelectric-magnetic coefficient and the value of the electrical current that is passing through the wire. According to Equation (2), this coefficient varies inversely with the magnetic

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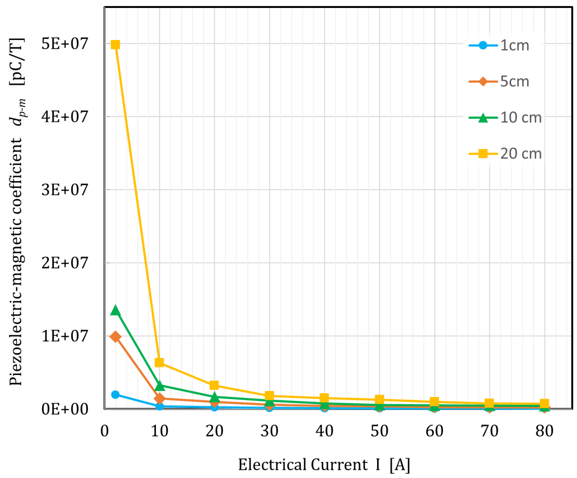

Fig. 6. Piezoelectric-magnetic coefficients (d_{p-m}) measure for different electrical current values and for the four distances between the transducer and the electrical wire considered in this study ($\mathbf{1, 5, 10}$ and $\mathbf{20}\ cm$).

field, whereas there is a direct relation between the electrical current value and the resulting magnetic field.

The second observation suggests a direct relation between the distance (from the transducer to the live wire) and the piezoelectric-magnetic coefficient. Fig.8 shows the piezoelectric-magnetic coefficient distribution against the transducer-wire distance (again using a logarithmic scale) to understand better and assess this last observation.

As depicted, the values assume a linear distribution parallel to the diagonal lines, indicating a proportional direct relation between the piezoelectric-magnetic coefficient and the distance between the transducer and the wire. Once again, this can be justified using Equation (2) because the magnetic field created by an electrical wire is inversely proportional to the distance between the observed magnetic field and the wire that is producing it. It is also observed that this linearity is more evident for higher values of the electrical current.

V. Conclusions

A novel characterization procedure for the biphasic material named thermoformed magnetic-piezoelectret (TMP) was presented in this study. The piezoelectrets constructed with an extra magnetic layer were able to exhibit a magnetoelectric effect when subjected to an external magnetic field, suffering an elastic deformation in the soft and electrically charged component. The electromagnetic field was created by an electrical current passing along an electrical conductor (live wire). By changing the TMP position and the current intensity it was possible to better understand the TMP behavior, and more accurate piezo-magnetic coefficients (d_{p-m}) were calculated. Results presented here revealed that under certain conditions (i.e., at a distance of 20 cm and an applied current of 2 A), d_{p-m} up to 498 $\times$ 10^5 pC/T were obtained. Although there is very little research on TMP, it is difficult to compare these results. Nevertheless, the method presented here indicates another direction to measure TMP sensitivity and validates their use as non-invasive electrical current transducers.

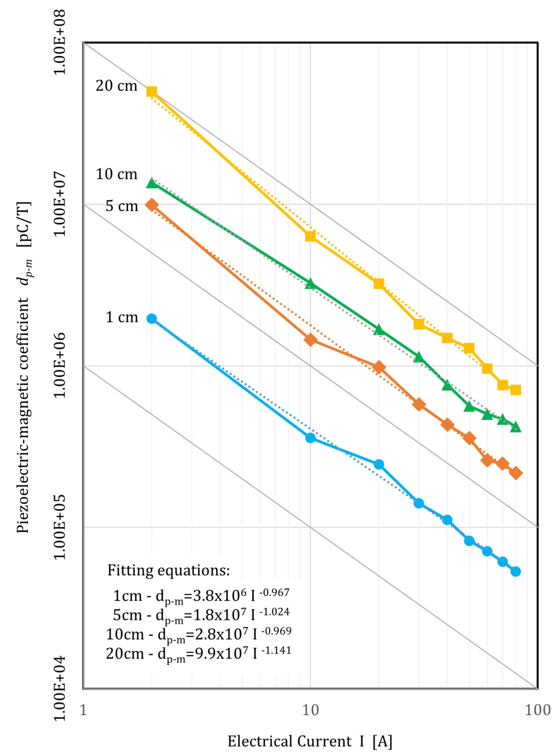

Fig. 7. Piezoelectric-magnetic coefficients (d_{p-m}) versus electrical current – Logarithmic representation.

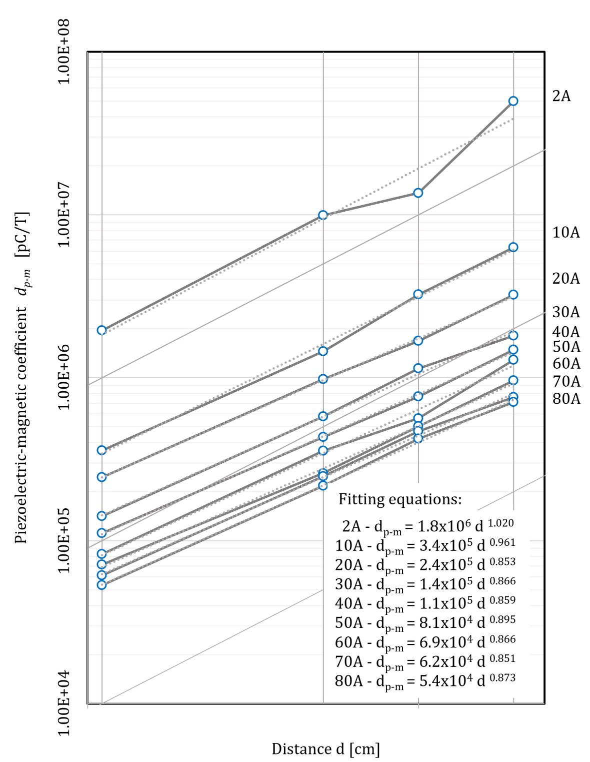

Fig. 8. Piezoelectric-magnetic coefficients (d_{p-m}) versus transducer-wire distance.

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This study has unveiled a novel approach in the field of electrical current transducers, demonstrating the feasibility of using TMP devices. These devices offer a unique set of characteristics that pique curiosity and warrant further research and validation studies. One such interesting feature is the linearity of the relation between the electrical current (observed parameter) and the measured response in TMP. Moreover, the potential of these polymer structures lies in their ability to provide non-invasive and reduced-size current transducers, a departure from the conventional invasive and large coils typically used for this purpose. Furthermore, TMP provide an interesting alternative to high-frequency current transformers, typically used for measuring transient current signals on power transformation and transmission facilities (power transformers and power transmission lines), such as high-frequency partial discharges.
However, to fully harness this potential, further investigation is required to optimize and assess this novel transducer concept. One promising research direction is the development of optimized configurations for the hollow structure to improve transducer linearity and sensitivity, covering different electrical current ranges.

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