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Low-cost impedance analyzer and IDC sensors: an imperfect tool for dielectric condition monitoring

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***Abstract-* Low voltage (LV) cables, like medium or high voltage ones, are prone to ageing. However, as they are usually exposed to lower electrical stresses, they are seldom monitored. In this work, an IDC (Inter-Digital Capacitive) sensor combined with two different commercial impedance analyzers (Hioki IM3570 and AD5940) is evaluated. The sensitivity and the penetration of the electric field are calculated using Comsol Multiphyisics simulations and measurements performed on low voltage PVC cables help comparing the two systems and assessing their performance. It was found that, for low capacitive samples, such as a LV cable's insulation, the variation found between consecutive measurements is too important to consider the AD5940 as a reliable tool for dielectric condition monitoring.**

I. Introduction

Low voltage (LV) cables used, for example, for connecting PV panels with a buildings' micro-grid, are prone to ageing. These cables are subjected to stresses which will accelerate their degradation and therefore limit their usage time. For outdoor cables, mostly environmental constraints (UV, temperature, mechanical strain due to wind etc.) should be considered on top of the more common, electrical stresses.

In Switzerland, there are few standardized methods used by independent inspection institutions in order to diagnose the condition of the insulation of low voltage cables during the periodic inspections of electrical installations. Below is a comparative table of the periodicity of inspections (adapted from the "Swiss directive for low voltage installations"):

TABLE I
Installation Types and the Time Between Two Consecutive Inspections

Periodicity [years]	Type of installation
1	Medical facilities, construction sites and markets
5	Large private and industrial buildings
10	Administrative buildings and industrial shops
20	Private buildings (houses)

During these periodic inspections, the principle of insulation measurement is based on Ohm's law: by applying a DC voltage between the internal an outer conductor, with a pre-imposed current of 1mA, an Ohm-meter will return the resistance of the cable's insulation. This value indicates the quality of the insulation and if leakage currents are present in the circuit. Although it has the advantage of being non-destructive, this method requires decommissioning and disconnecting all the devices connected on the line. For the results, as an order of magnitude, expected insulation resistance values vary between 2 MΩ (for normal conditions) and 0.05 MΩ (for moist or corrosive environment).

In the last decade, other methods have been developed or are currently in the process of being developed in order to diagnose the degradation of low voltage cables. When possible, the indication of the defect's localization is also expected. These more recent methods have been considered for specific applications such as the cable wiring of nuclear power plants, airplanes, boats, etc., where aging and stresses are higher. TFDR (Time Frequency Domain Refractometry) [1], a combination of TDR (Time Domain Reflectometry) and FDR (Frequency Domain Reflectometry), or PDC (Polarization Depolarization Current) [2], can be considered among these modern methods. The IDC (Inter-Digital Capacitive) sensor, initially proposed by prof. Bowler [3], should also be mentioned. Regarding this technique, interesting results have been published recently by prof. Bowler and Dr. Glass' team from PNNL. They have shown in 2019 [4] how an inter-digital capacitive (IDC) sensor has a strong potential to be used to measure dielectric properties of cable insulation polymeric material. Their results were obtained by initially using a commercial impedance analyzer (Novocontrol Alpha Analyzer) and, afterwards, using a smaller, low cost, capacitance measuring commercial PCB board (model FDC1004).

This work continues the investigation of similar low-cost solutions by comparing the results obtained using a commercial impedance analyzer (Hioki IM3570) and those obtained using the low-cost, compact, AD5940 impedance analyzer. Even though Analog Devices proposes an evaluation board for their system, an in house, PCB measuring board was designed by our team around the AD5940 chip, to facilitate the measurements and the calibration step. With both devices, silver, inkjet-printed IDC electrodes were used to investigate low voltage PVC cables.

II. Working Principle of Inter-Digital Capacitive (IDC) Sensors

The beforementioned inter-digital capacitive sensor [3] was designed for monitoring the insulation of LV, non-screened, cables. Consequently, the test samples are usually single-phase cables, without shielding and with a single layer of insulation. This facilitates the understanding of the measurement principle and the evaluation of the obtained results.

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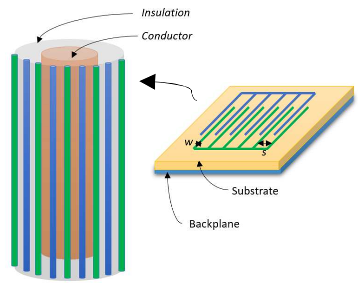


Fig. 1. IDC electrodes on a cable, with the “drive” digits in green and the “sense” digits in blue

The principle of operation is quite simple to understand: a voltage is applied to the intercalated “drive” electrodes and a displacement current appears in the insulation. This displacement current turns into a conduction current once it has passed through the insulation and then it is measured by the “sensing” electrodes. Depending on the obtained impedance and phase shift, plus the frequency used for the measurement, it is possible to calculate the capacitance.

As shown in Figure 1, the capacitive sensor is composed of two comb-shaped electrodes (called digits) which are placed in contact with the test object, here the cable insulation. The electrodes should be printed on a flexible dielectric substrate, that will allow the operator to easily fit the sensor over the cylindrical shape of a LV cable. The conductive electrodes are usually made using copper, aluminum or silver and are strongly dependent on the manufacturing method. Under the substrate used for the sensor, a grounded conductive layer, called "backplane", can be added in order to obtain a greater capacity while acting as a shield for the electrodes.

The IDC sensor is characterized by two parameters: its sensitivity and the penetration of the generated electric field into the insulation. In order to optimize these two factors, the geometry parameters, such as the length, width or the spacing of the digits should be optimized. While performing a measurement, the fringing electric fields that penetrates the material under test allows the measurement of the capacitance that varies as function of the dielectric constant of the material. Thus, depending on the electrode characteristics, higher sensitivity can be expected. Depending on the voltage that is applied on each electrode, and by considering the way the cable’s conductor will be connected, or not, to the circuit (either floating or grounded), it is possible to measure the cable’s capacitance in several configurations. The backplane could also be considered, or not. Out of the various possible combinations, three possibilities are given in Table 2.

TABLE II
IDC VS. CONDUCTOR SPECIFIC VOLTAGES

	Config. 1	Config. 2	Config. 3
Positive digits « driven electrode »	+1 V	+1 V	+1 V
Negative digits « sensing electrodes »	-1 V	+1 V	0 V
Conductor	Ground	Ground	Floating
Backplane	Yes / No	Yes / No	Yes / No

The choice between one of the possible voltage electrode & conductor configuration is mostly dictated by the way the measurement could be conducted in the field. Having one or two power supplies will point the user towards choosing between methods 1 and 2. Between method 2 and 3, it is mostly the practical aspect that will play a role in the choice. If the conductor cannot be grounded on site, and just kept floating, then configuration 3 might represent a simpler alternative, and so on. A study – based on Comsol Multiphysics ® simulation results and presented in Section 3 – will present a comparison between these three methods based on the capacitance, the sensibility along with the penetration of the electric field. Please note that further in this work, only configuration 3 will be considered as both the Hioki IM3570 and the AD5940 board only have one voltage source and thus do not allow us to provide two different potentials (±1V). For optimization and measurements, method 2 will be used and a comparison between the obtained capacitances will be carried out for an electrode topology in Section 3.

Terminal configuration and the connection to the impedance analyzer represent additional important aspects that should be considered. For example, for a two-terminal configuration (2T), which is the simplest, the potential terminals as well as the current terminals are shorted. With this configuration, the measurement results contain many errors due to longitudinal inductances, parasitic transverse capacitance and resistances of the cable, as well as those of the connections [5]. In comparison, three-terminal (3T) and two-terminal shielded (2T-S) configuration make it possible to be more precise and to measure smaller capacitances due to the shielding of coaxial cables that would be typically used. However, a four-terminal topology (4T) has an even higher reliability, as it reduces the effects of measuring cable’s transverse inductances and resistances, as well as the connection resistances. Since the four terminals are independent, each having its own connection point, they are not short-circuited. Last but not least, the five terminal (5T) and four shielded terminal (4T-S) configuration are the most complex yet the most reliable configurations. The measurement cables are shielded coaxial cables grounded at the base (5T) (and at the end of the cable (4T-S)), while the voltage and the current measurement have different channels. This way, the measurement range is enlarged and despite still presenting the same disadvantages as 3T or 2T-S topologies, the influence of the parasitic elements is diminished. For this study, Hioki L2000 probe, based on the five-terminal principle, is used, whereas for the AD5940 board, the 4T topology is used.

The terminal configuration is not the only difference worth mentioning between the two devices. During a preliminary study, performed on a PVC cable with a “simple” configuration, using a top aluminum electrode, glued on the external insulation, and the conductor, it was found that the accuracy of the AD5940 is much lower, compared to that of the Hioki impedance analyzer. Both results were also compared with those obtained with Comsol simulations and the obtained average values are given in Table 3. In each case, three consecutive measurements were performed, at 200 Hz.

TABLE III

MEASURED VALUES FOR THE PVC CABLE USING THE "SIMPLE" SETUP

		Conductor cross-section		Error [%]	
		50 mm²	25 mm²	50 mm²	25 mm²
AD5940 Board	C [pF]	76.9	55.7	+0.1	-1.7
		79.9	56.3	+4.1	-0.8
		75.9	54.0	-1.0	-4.7
HIOKI IM3570		73.8	54.9	-3.8	-3.2
Analytical calculation		76.7	56.7	-0.0	-0.0
Comsol calculation		76.8	56.7	0.0	0.0

As shown in the table above, the measurement error of the Hioki IM3570 and the AD5940 board, at 200Hz, is of the same order of magnitude, with slightly higher values obtained for the AD5940 board (≈ 5% max). Another difference worth mentioning is that the AD5940 board usually performs a significantly high number of measurements before returning the average value (10'000 by default) so the higher error cannot be justified by a low sampling. By analyzing the 10'000 values, it was also found that the impedance modulus and the phase measured were sometimes distorted due to a measurement bug or error. Here is an example of an exact data extract from the 1st test, as obtained for the 50 mm^2 cable:

TABLE IV

EXAMPLE OF MEASURED VALUES USING THE AD5940 IMPEDANCE ANALYSER, FOR THE PVC CABLE, AT 200 HZ

Repetition	$\lvert Z^* \rvert$ [Ω]	θ [°]	Comment
N-1	10'567'201	-89.508	Valid value
N	8'778'434	260.94	Invalid value
N+1	10'634'094	-89.582	Valid value
N+2	13'212'892	-89.579	Valid value

Last but not least, another important aspect worth mentioning when performing this type of capacitive measurements is related to the influence of the surrounding environment and that of the IDC sensor itself. Actually, it should be considered that more than one capacitance is measured at the same time, as shown in Figure 2. This is why a calibration step is mandatory before performing actual measurements.

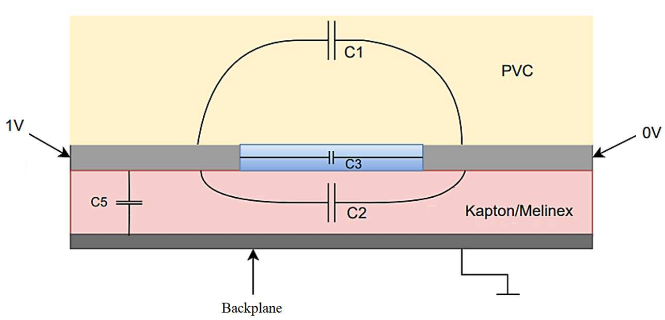


Fig. 2. Two coplanar electrodes, in parallel, and the parasitic capacitance (here in configuration n°3, with a backplane)

III. SENSOR CARACTERISTICS AND PRELIMINARY RESULTS

To perform the sizing and optimization analysis of the IDC's sensor electrodes, Comsol was used to calculate the capacitances, the sensitivity and electric field penetration into the insulation. As a reminder of the state of the art [6], the following electrode parameters can be varied: the width of a digit (w), the distance between two consecutive digits (s), the length of a digit (l) and the number of digits (n).

For the first simulations, it was decided to design a sensor having 22 total digits, thus $n = 11$ digits forming the drive or the sensing electrode. The spacing between digits was 0.6 mm, the length of a digit was 60 mm, the width of a digit was 0.4 mm. The drive electrodes have a fixed potential of 1 V_{rms}, the sensing electrodes are grounded and the conductor is floating. The voltage distribution and the electric field, as obtained using the simulation, are given in Figure 3 (cross-cut).

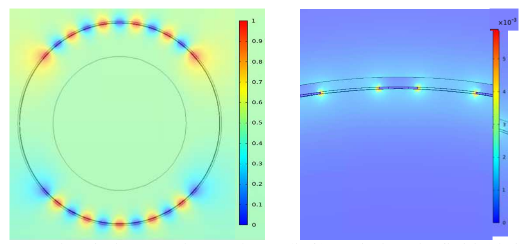


Fig. 3. Simulation results : voltage (left) and electric field (right)

As mentioned, the sensitivity S of the IDC is an important parameter: the higher the sensitivity, the smaller the capacitance variations that could be detected. Sensitivity is calculated as the slope of the capacitance versus permittivity variation [7]:

$$S = \frac{\partial C}{\partial \varepsilon} \cong \frac{\Delta C}{\Delta \varepsilon} \tag{1}$$

Concerning the sensitivity calculation, a Comsol parametric study was created to variate the relative permittivity of the insulation. For our designed geometry, the variation presented in Figure 4 was found, with a sensitivity of 5 pF per unit change of permittivity.

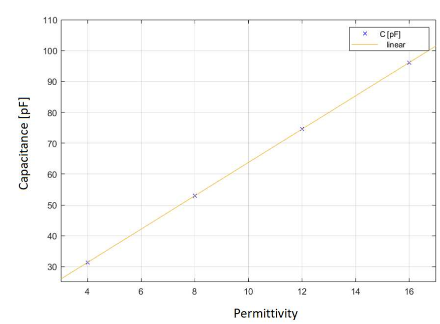
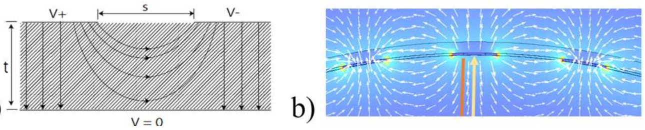


Fig. 4. Electrode sensitivity calculation

Another important parameter – the electric field penetration – was also evaluated. According to [3], the field penetration is ideal when the electric field reaches a balanced form between the electrodes, as shown in Figure 5a). The results obtained for our study are presented in Figure 5b) and it corresponds to the expected behavior.



a) b)

Fig. 5. Theoretical (left, [3]) and simulated electric field distribution (right)

To calculate the penetration of the electric field (orange arrow) in the insulation (yellow arrow), the following formula can be used [1]:

$$\delta = b - a_{10} \tag{2}$$

where δ is the penetration of the electric field (in mm), b represents the thickness of the insulation (in mm) and a_{10} represents the radius allowing a capacitance increase of 10% with respect to the case without conductor (a_0 = 0 mm). For our electrode configuration, it was found that the electric field penetration is of about 23%. Higher electric field penetration values could be obtained if the measurement configuration (Table 2) is changed. Table 5 resumes the obtained results.

TABLE V

Comparison Between Different Measurement Configurations (Simulation Results)

	Measurement technique		
	Config. 1	Config.2	Config. 3
Capacitance [pF]	72.8	29.7	36.8
Sensibility [pF]	11.4	3.0	5.8
Penetration depth [mm]	0.62	0.84	0.50
Penetration depth [%]	31.2	42.0	25.2

In order to increase the penetration of the electric field, two additional electrode configurations were designed. The results obtained by varying the electrode geometry, in measurement configuration n°3, are given in Table 6. Although, in theory, many parameters can be variated, in our case, the thickness of a digit is imposed by the manufacturing process (inkjet printer) and the same goes for the permittivity of the substrate that is used. It is also the manufacturing process that limits the minimum possible spacing between the digits, based on the compatibility (wetting) between the conductive ink and the substrate. Additionally, the spacing between the two electrodes is limited by the diameter of the cable, the width of the digits and the spacing between the digits. This shows that, in our case, there are only three variable parameters that can be used in an optimization loop: the width of a digit, the total length of the electrodes as well as the number of drive / sensing digits.

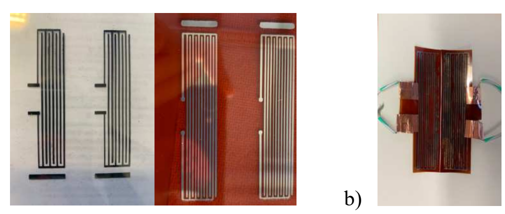
TABLE VI

Comparison Between Different Electrode Configurations and Measuring Setups

Electrodes	1 V1.1	1 V2.1	1 V3.1	2 V1.1	2 V2.1	3 V1	3 V2	3 V3
N° of digits [-]	22	22	22	18	18	14	14	14
Digit thickness [mm]	0.4	0.45	0.5	0.7	0.8	0.8	0.9	1
Capacitance [pF] @10kHz	34.2	35.3	36.8	32.6	34.0	26.1	27.0	27.9
Sensibility [pF]	5.3	5.6	5.8	5.2	5.5	4.2	4.4	4.5
Penetration depth [mm]	0.46	0.48	0.50	0.59	0.63	0.66	0.69	0.72
Penetration depth [%]	23.0	24.4	25.2	29.6	31.5	33.0	34.6	36.4

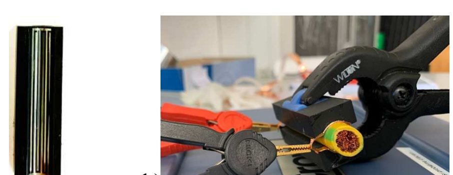
The obtained results show that the capacitance increases when the number of digits increases, which was an expected result, but also when the *w/s* ratio is amplified. As *s* has a minimum value imposed by the process in our case (60 µm), if the ratio should be increased, then the width *w* of the digits should be increased. The same can be said about the dependence of the sensitivity. As for the depth of electric field penetration, its evolution is opposite to the previously mentioned case, as it decreases when the number of digits increases. For the final design, the number of digits will be reduced to obtain better penetration and the width of the digits will be increased in order to obtain greater sensitivity and sufficient capacitance (impedance). As the length of the electrodes will not influence the depth of penetration of the electric field into the cable insulation, only the capacitance value, it was decided that a length of 60 mm would be ideal in practice, for easily handling the electrodes and the exterior support clamp. As mentioned, the sensor was manufactured using inkjet technology and silver inter-digital electrodes were deposited on Kapton® or Melinex® dielectric substrates. It was also decided to use an aluminum backplane to separate the sensor from the plastic clamps that were holding them in contact with the cable to be measured. Also, given that, at low frequencies, both measuring devices are prone to a higher SNR (signal-to-noise ratio), it was decided that further measurements with be performed at 10 kHz.

The inkjet-printed electrodes used in this study are shown in Figure 6a) while Figure 6b) shows the electrodes and their electrical connections. The 3D-printed support, which matches the diameter of the investigated cables, is shown in Figure 7a) while Figure 7b) shows the complete measurement assembly (backplane not visible). The home-made measuring board, using the AD5940 analyzer, is shown in Figure 8.



a) b)

Fig. 6a) Inkjet-printed electrodes on Melinex (left) an Kapton (right) substrate and (b) example of the electrical connection



a) b)

Fig. 7a) 3D printed support and (b) the complete measurement assembly

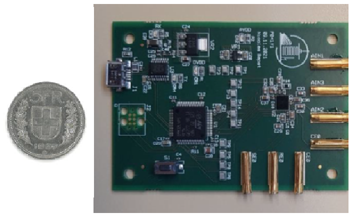


Fig. 8. Home-made PCB board for the AD5940 impedance analyzer

IV. Measurement Results and Discussion

Table 7 presents the results obtained for the 50 mm² PVC cable, at 10 kHz, for the three electrode designs and using configuration 3 for the measurements. Comsol was used for calculating the modeled capacitance value and an analytical formula, for an IDC sensor with backplane, from [8], given hereafter, was used for the analytical validation.

$$Measured\ Capacitance = C_{tot} = (C_1 + C_2 + C_3) \cdot N + C_{122} + C_{33}$$

$$= \left(\underbrace{\varepsilon_0 \cdot l \cdot \frac{\varepsilon_1 + \varepsilon_2}{2} \cdot \frac{K\left[\sqrt{1-\left(\frac{a}{b}\right)^2}\right]}{K\left[\frac{a}{b}\right]}}_{C_1+C_2} + \underbrace{\varepsilon_0 \cdot \varepsilon_3 \cdot l \cdot \frac{h}{a}}_{C_3} \right) \cdot (N-1) + \underbrace{\varepsilon_0 \cdot l \cdot \frac{\varepsilon_1 + \varepsilon_2}{2} \cdot \frac{K\left[\sqrt{1-\left(\frac{g}{bb}\right)^2}\right]}{K\left[\frac{g}{bb}\right]}}_{C_{11}+C_{22}} + \underbrace{\varepsilon_0 \cdot \varepsilon_3 \cdot l \cdot \frac{h}{g}}_{C_{33}} \quad (3)$$

where ε_0 is the vacuum permittivity, a is the space between two digits (previously named s in our study), b is the area of two digits + the space between two digits ($b=2 \cdot w+a$), h is the thickness of a digit, ε_1 is the relative permittivity of the dielectric to be tested, ε_2 is the relative permittivity of the substrate and ε_3 is the relative permittivity of the fluid contained between the substrate and the dielectric (air in the case of the IDC) and l is the length of the electrode. Finally, *K[x]* is the first-order elliptic integral used for calculating the overlapping electric field.

TABLE VII
Measured Values for the 500 mm² PVC Cable, at 10 kHz

Electrodes	Comsol	Matlab	HIOKI IM3570		AD5940BIOZ	
1 V3.1 [pF]	33.0	34.1	32.6	31.5	42.4	44.7
Error [%]	0.0	+3.3	-1.1	-4.5	+28.4	+35.5
2 V2.1 [pF]	30.5	31.8	30.1	30.7	53.6	56.0
Error [%]	0.0	+4.4	-1.2	+0.6	+75.9	+83.7
3 V3 [pF]	21.3	23.3	22.3	21.7	48.4	47.1
Error [%]	0.0	+9.1	+4.4	+1.7	+126.8	+120.7

As shown in Table 7, large differences were found between the measurement performed with the Hioki IM3570 analyzer and those performed with the AD5940. One explanation could come from the connection between the sensor and the analyzer during the measurement, as the Hioki was connected with the proprietary Hioki L2000 probe to the sensor, which is a 5T type probe, while for the AD5940 board, a 4T topology was used. Also, the calibration of the AD5940 board is not as versatile as that ok the Hioki analyzer, which can also have an impact for sensitive measurements.

The comparison between the three electrode topologies used in this study has shown that the measurement error is also strongly dependent on the electrode configuration. For electrode type 3, the AD5940 board exhibited the highest error while version 1 seemed to give the best results with the board. Meanwhile, for the Hioki Analyzer, it was design n°2 that has the smallest difference between the measured and the theoretical values. Nevertheless, the relative difference between the capacitance values measured by the Hioki equipment are rather small and within what can be considered as acceptable variation for these capacitance levels (±1 pF).

V. Conclusion

In this work, IDC (Inter-Digital Capacitive) sensors combined with two different commercial impedance analyzers (Hioki IM3570 and an AD5940 board) have been evaluated. The obtained results have shown that the AD5940 board shows results that are sometimes even 120% higher than those that were expected. Meanwhile, the Hioki IM3570, although still displaying results that are slightly different than the theoretically calculated ones, they are still below 5% of error, which makes this impedance analyzer a more reliable investigation tool compared to the AD5940 board. It was also shown that the electrode configuration along with the measurement setup play an important role and strongly influence the obtained results.

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References

[1] S. W. Glass, A. M. Jones, L. S. Fifield, and T. S. Hartman , "Frequency domain reflectometry NDE for aging cables in nuclear power plants", AIP Conference Proceedings 1806, 080015 (2017).

[2] Wei Li et al., "Studies of the polarization/depolarization current characteristics of XLPE cable," 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2016, pp. 677-680, doi: 10.1109/APPEEC.2016.7779589.

[3] Robert T. Sheldon, and Nicola Bowler: "An Interdigital Capacitive Sensor for Nondestructive Evaluation of Wire Insulation", IEEE SENSORS JOURNAL, VOL. 14, NO. 4, APRIL 2014

[4] S. W. Glass, L. S. Fifield, A. Sriraman, W. C. Palmer, and N. Bowler ,"Inter-digital capacitive sensor for evaluating cable jacket and insulation aging", AIP Conference Proceedings 2102, 020024 (2019)

[5] https://www.keysight.com/us/en/assets/7018-06840/application-notes/5950-3000.pdf

[6] L.Pu, X.Zhao, W. Duan, H. Sun : « Interdigital Capacitance Sensor for Monitor Ageing of Power Cable – Simulation », State Grid Shaanxi Electric Power, Reseach Institue, Xian, China

[7] Fuzeng Zhang, Yongsheng Xu, Shaojie Chen et Tingting Wang : « Three-dimensional modeling and Optimization of a Fully-covered Interdigital Capacitive Sensor for Power Cable Insulation Detection », China Southern Power Grid, Electrical Power Research Institute, Guangzhou, China, 2019.

[8] Alexandre V. Mamishev : « Interdigital Dielectrometry Sensors Design and Parameter Estimation Algorithms for Non-Destructive Materials Evaluation », pages : 234-235, Massachusetts Institute of Technology, USA. Mai 1999.