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Experimental Characterization of Reinforced Concrete Cable Ducts

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***Abstract*—When a building is struck by lightning in an industrial facility, a partial lightning current can flow through the reinforcement of cable ducts, causing interference to the cables routing inside. The distribution of the lightning current among the paths leading away from the building depends on their impedance. In this paper, we present the impedance measured in two different cable ducts: one duct with a wire-tied reinforcement and the other with a welded reinforcement. The measurements are compared to the results of numerical simulations carried out using the FDTD method.**

Keywords*— *lightning, reinforced concrete, cable duct, impedance, current distribution

I. INTRODUCTION

Lightning direct strikes can have severe consequences in industrial facilities. To prevent potential differences and reduce the magnetic field, all conducting components in the facility are typically interconnected. Thus, when one of the buildings is struck by lightning, only a part of the current flows to the earth-termination system. The other part is distributed among the low-impedance paths leading away from the building. Moreover, interference to the cables routing inside reinforced concrete ducts can be caused by coupling to the reinforcement of the duct and by a partial lightning current entering the cables via the bonding network.

The portion of the lightning current flowing along the reinforcement of the duct depends on the installation conditions, such as the dimensions of the structures and the grounding arrangement. In general, calculating the current distribution among the paths can become a very complex problem, especially in large facilities. The international standard IEC 62305-1 [1] assumes that half of the current goes straight to the building's earth-termination system and proposes a simple model to distribute the remaining half. The German standard KTA 2206 [2] specifies weighting factors to calculate the partial lightning current flowing through the reinforced concrete ducts and the soil-contacting conductors of the building, assuming that one-third of the current flows into earth. Also, it proposes a formula to calculate the axial voltage induced in cables routing inside the ducts, from the partial lightning current flowing through their reinforcement. The formula considers an inductive transfer mode and uses the coupling impedance obtained experimentally in [3]. An example of the application of the KTA approach is given in [4].

Since the weighting factor of reinforced concrete ducts is based on their inductance, the uncertainties of the implemented models with respect to actual constructions could have a significant influence on the results. Aiming to quantify the uncertainties, in this paper, we compare the impedance measured in various sections of two different reinforced concrete ducts and the results of numerical simulations.

II. II. EXPERIMENTAL SETUP

As a first step towards validating the numerical model of reinforced concrete ducts, we measured cable ducts at the new lightning testing facility of EDF Power Networks Lab.

A. Cable Ducts

The testing facility has two parallel reinforced concrete ducts, as shown in Fig. 1. The steel plates covering the ducts were removed during the measurements. The ducts are both 60-meters-long with a cross-sectional area of 1 m × 0.8 m. They are divided into three electrically isolated sections of 20 m, named S1 to S3. Their reinforcement is made up of a double-layered reinforcing grid embedded in 20 cm of concrete. The rebars have a radius of 5 mm, and they form squared meshes of 20 cm x 20 cm. In the first duct (C1), the rebars are wire-tied. In the second (C2), they are welded. The layers of the reinforcing grids are separated by 15 cm, and they are interconnected, as shown in Fig. 2. Note that all these values are approximated; they are more likely to correspond to an average of the real dimensions.

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The expansion joints between the sections of the ducts are filled with foam. Each section has 16 fixed grounding terminals: eight at the beginning and eight at the end. The reinforcement of adjacent sections can be interconnected using bridging braids, as shown in Fig. 3. To minimize unwanted effects at the boundaries and aiming to inject a current uniformly into the reinforcement, the ducts are terminated by copper plates, as shown in Fig.4.

B. *Impedance Measurements*

The impedance of a structure can provide useful information regarding its electromagnetic behavior. Using a vector network analyzer (VNA), we measured the impedance of each section of the ducts, then the impedance of two interconnected sections, and finally the impedance of three interconnected sections. Since the magnitude of the impedance was expected to be low, two different methods were used: One-Port reflection, also known as Shunt measurement, and Shunt-Thru. The connection setups are shown in Fig. 5.

Regardless of the method and the section of the duct being characterized, the length of the wires used to inject the current and create a return path was constant. Their impedance was measured independently to remove their contribution from the results. Also, all the measurements were repeated using One-Port reflection after performing a new open/short/load calibration in which the wires were taken into account. To differentiate the results, we named the method One-Port*.

Certainly, removing the covering plates could have a significant effect on the results, especially if they were electrically connected to the reinforcement. The values measured are not to be scaled-up and compared directly to the models of enclosed cable ducts one can find in the literature [3],[5]. The plates were removed to focus exclusively on the characteristics of the reinforcement and its representation in numerical simulations. Frequently, the rebars forming the reinforcement of cable ducts cannot be welded consistently at every intersection. One then wonders if it is necessary to consider a reinforcing grid with bigger meshes in the numerical model.

Fig. 1. Reinforced concrete ducts in the testing facility.

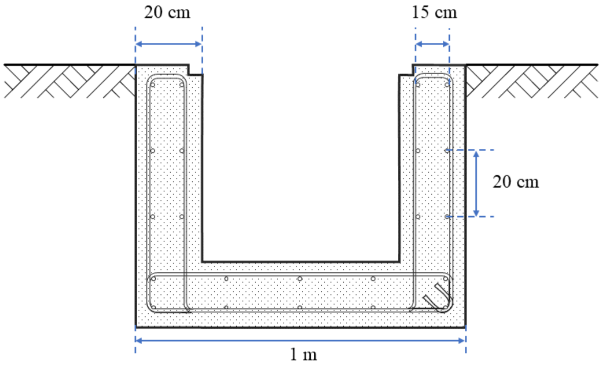


Fig. 2. Front view of the reinforcement of the ducts.

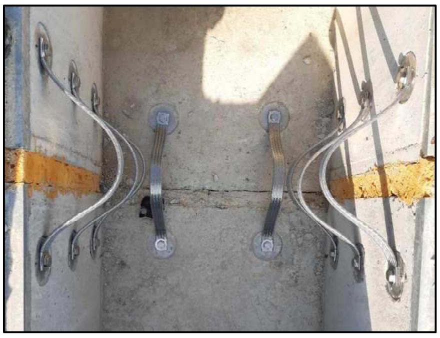


Fig. 3. Interconnection of two sections of the concrete duct.

Fig. 4. Copper termination plates.

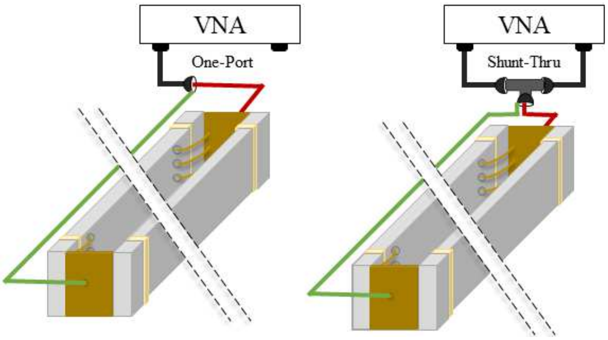


Fig. 5. Measurement setups.

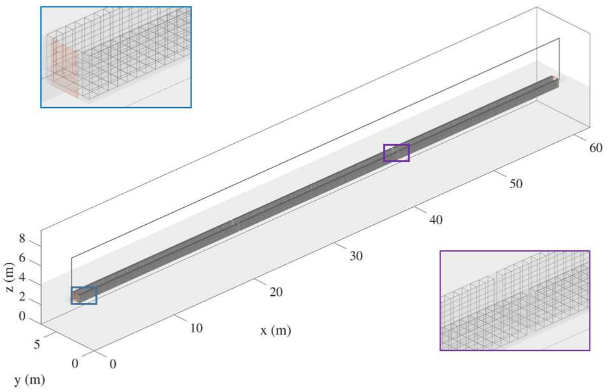


Fig. 6. Computation model of the reinforced concrete duct.

III. NUMERICAL MODEL

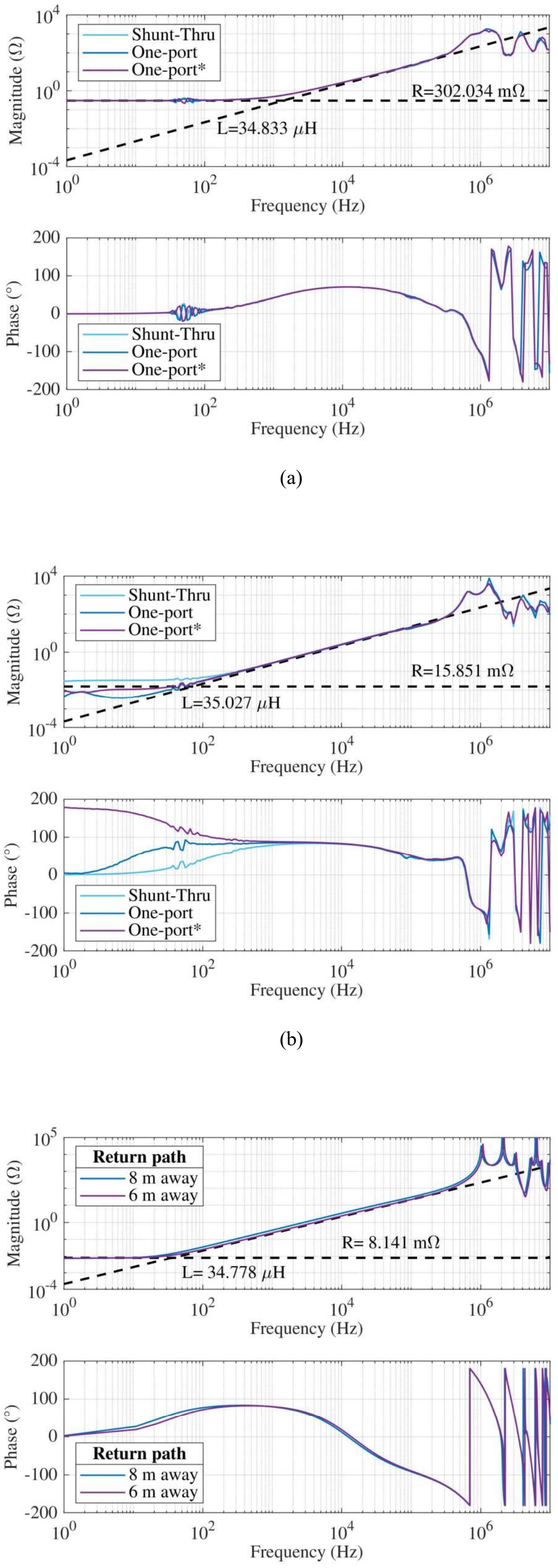
Considering a reinforced concrete duct with the dimensions given in section II.A, different simulations are carried out using TEMSI-FD [6], a full-wave solver based on the finite-difference time-domain (FDTD) method. All the conductors are modeled as thin wires [7] with a conductivity of 59.6×10^6 S/m. Except for the rebars forming the reinforcement, their conductivity is set to 8.33×10^6 S/m. The permeability of the steel is neglected. The concrete is modeled as a lossy dielectric material with a conductivity of 0.0052 S/m and a relative permittivity of 8.6. These values were obtained by fitting a Debye model to the data of a concrete sample with a moisture content of 5.5% [8]. The soil is considered homogeneous with a relative permittivity of 10 and a resistivity of 100 Ωm.

The impedance of the duct is calculated by dividing the voltage of a perfect voltage source over the current injected and then removing the effect of the return path. However, we observed that even if we try to remove the effect, the imaginary part of the impedance varies slightly with the position of the wires. Probably, it also happens when making measurements.

The voltage waveform is defined as a Gaussian function covering a frequency range from 0 Hz to 10 MHz. The maximum amplitude of the pulse is set to 100 V. All the external surfaces of the analysis space are defined as PMLs [9] to assume an open space. The computation model is shown in Fig. 6.

IV. RESULTS

The measurements and simulations in Fig.7 show that the reactance is predominantly inductive, and as expected, it does not vary significantly. All curves are well fitted with an inductance of approximately 35 μH. On the other hand, there is a considerable difference in the resistance. The results of the simulations are closer to the impedance measured in C2. The latter could be explained by the contact resistance of the wire-tied rebars in C1. Nevertheless, it is clear from the results in Fig.7(b) that there is an error at low frequency. The magnitude of the resistance measured in C2 may already be within the range of uncertainty of the measurement method.



(a)

(b)

(c)

Fig. 7. Impedance of the reinforced concrete duct. (a) Measured in C1. (b) Measured in C2. (c) Calculated using TEMSI-FD.

TABLE I. RESISTANCES AND INDUCTANCES CALCULATED FROM THE IMPEDANCE MESURED ON DIFFERENT SECTIONS OF THE DUCTS

Section	**C1**		**C2**	
	R (mΩ)	***L (µH)***	***R (mΩ)***	***L (µH)***
S1	59.652	8.962	8.175	8.189
S2	217.564	19.663	19.501	13.790
S3	87.399	13.599	53.291	11.938
S1 S2	258.329	25.832	12.474	16.934
S2 S3	249.848	27.808	14.999	28.742
S1 S2 S3	302.034	34.833	15.851	35.027

From the impedance measured on each section of the ducts, the resistance and inductance were calculated. The average of the values obtained with the different methods is presented in Table I. Even though the values differ between two sections of the same duct, the sum of the resistances and the inductances are not far from the values calculated with the sections interconnected. Moreover, the parameters of a transmission line model of the cable duct, as proposed in [5], could easily be calculated.

Differences between the two sections of the same duct are expected since, in reality, the ducts are not divided into three equally long sections. However, it is still interesting to observe the significant variations of the resistances calculated for the sections of C1. When wire-tying the rebars, it is complex to control the quality of the contact, and therefore, to define a load to adjust the values in numerical simulations of industrial facilities.

Nevertheless, adjusting the values may not be necessary because the reactance of the duct quickly becomes higher than its resistance. Thus, with a transmission line model of the ducts and the specifications of the grounding system and the bonding network, the partial current that may flow through the reinforcement could be approximated. The question that remains is if, from that partial current, one can accurately calculate the surges in the cables routing inside.

V. CONCLUSION

The fact that the rebars of reinforced concrete ducts may not always form perfectly symmetrical grids or be welded, has a negligible influence on the reactance of the ducts. Thus, if the distribution of the lighting current between the ducts depends mostly on their inductance, the uncertainties of the numerical models with respect to the constructions could be neglected.

The inductance of a reinforced concrete duct can be well approximated considering the average dimensions of the meshes of the reinforcing grid in full-wave simulations. However, including the resistance of the duct in the simulations could be tricky if the rebars are wire-tied. We observed that in the 60-meters-long ducts at the testing facility, the resistance was 20 times higher when the rebars were wire-tied. Besides, poor contact between the rebars could create non-linearities.

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