On the Calculation of Electrical Surges in Underground Cables due to a Direct Lightning Strike

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***Abstract*—When a building is struck by lightning, the lightning current travels through its reinforcement and along the lightning channel, generating a transient electromagnetic field. A part of the current reaches the ground termination system and the other part is distributed among the cable ducts and soil-containing conductors leading away from the building. Electrical surges can be induced by the transient fields, the coupling between the structures, and a partial lightning current entering the cables via its grounding. Since the Lightning Protection System (LPS) is generally designed based on the worst-case scenario, a parametric study is conducted using the FDTD method to identify the configurations in which the surges in the cables interconnecting two buildings are maximized. The results are compared to the case in which the cables are grounded at the entrance to the buildings. The direct connection to the reinforcement increases the currents and shifts the resonances towards higher frequencies.**

***Index Terms*—lightning, lightning protection, surges, industrial facility, finite-difference time-domain**

I. Introduction

Electrical surges are considered as one of the most harmful indirect effects of lightning. They can cause permanent physical damage and the malfunctioning of sensitive devices. These surges are generally induced in the cables nearby by the transient electromagnetic field and the ground potential rise generated by a lightning strike. During a direct strike, the current travels along the lightning channel and through the struck object; yet, only a part of the current goes straight to the earth termination system. The other part is distributed among the cable ducts and soil-contacting conductors leading away from the striking point. Therefore, electrical surges can also be induced by the coupling of the cables to the struck object itself and the ducts, or by a partial lightning current entering the wires via their grounding. An interesting example of the lightning current distribution in the grounding system and the cable networks of a radio base station is presented in [1].

To appropriately design the Lightning Protection System (LPS) and the protection measures against the Lightning Electromagnetic Pulse (LEMP) in industrial facilities, electrical surges need to be estimated. Numerous studies have been carried out to deepen the understanding of the phenomenon [2]–[7], and one can find simplified methods to assess overvoltages in international standards, see e.g. [8]. However, experience has shown that the methods are not always adapted to the characteristics of French industrial facilities [9]. Since modeling all the elements of a full-scale industrial facility at once is almost impossible, this paper aims to identify the parameters that could be neglected by considering a worst-case scenario. We focus on parameters that are commonly assumed to be invariable, and may still have an important influence on the results. The study is conducted on a simplified industrial facility: two reinforced concrete buildings interconnected by a reinforced concrete cable duct, where two cables are laid. First, the cables are connected to an internal grounding system and then to the reinforcement at the entrance to the buildings. The results are compared to two worst-case scenarios.

Even though the Transmission Line (TL) theory is still widely used to calculate surges due to the simplicity of circuit-based simulations, the complexity of the installations and the need for more accurate results have made the Full Wave methods gain popularity. Hence, the simulations of the industrial facility are carried out using TEMSI-FD (Transient ElectroMagnetic Simulator - Finite Difference) [10], a solver based on the finite-difference time-domain (FDTD) method. A non-uniform grid is implemented with cell sizes varying from 25 cm to 2.5 m, and all the conducting wires, including the cables, the rebars, and the channel, are modeled as thin wires [11].

II. Reference Case

To study the surges resulting from a direct lightning strike in an industrial facility, a simplified case is defined: two 20-meters-tall reinforced concrete buildings facing each other, with a horizontal cross-sectional area of 20 m $\times$ 50 m. The external walls, the roof, and the foundation of the buildings are made up of a single-layered reinforcing grid, given that a multi-layered reinforcing grid can be replaced by an equivalent single-layered grid [12]. The grids have a squared mesh size of 50 cm $\times$ 50 cm and are embedded in 25 cm of concrete, which is modeled as a lossy dielectric material with a conductivity of 0.0052 S/m and a relative permittivity of 8.6. The rebars forming the grid have a radius of 1 cm, and their conductivity is set to 8.33×10^6 S/m. The foundations are buried five meters below the surface. No internal walls, columns, or beams are considered. A 100-meters reinforced concrete duct interconnects the buildings in the middle, as shown in Fig. 1. The duct has a cross-sectional area of 3 m × 2.5 m and is positioned 50 cm above the foundations of the buildings. The reinforcing grid of the duct has a mesh size of 25 cm × 25 cm and is also embedded in 25 cm of concrete. Its rebars have the same conductivity but a radius of 8 mm.

The external grounding system consists of two grounding rings, one around each building, connected to a grounding grid with squared meshes of 20 m × 20 m. The conductors are buried 87.5 cm below the surface, have a radius of 7.5 mm, and are made of copper. Accordingly, their conductivity is set to 59.6×10^6 S/m. The soil is considered homogeneous with a relative permittivity of 10 and a conductivity of 0.01 S/m. The buildings are connected to the grounding rings at each corner, as shown in Fig. 2. The internal grounding system of each building consists of collective ground conductors forming five rings. The grounding rings are interconnected in the corners, as shown in Fig. 3. The first ring is also connected in the corners to the reinforcement of the building and thus directly to the external grounding system.

There are two wires in parallel in the duct: an insulated wire loaded with 50 Ω at the beginning and the end, and an auxiliary copper wire. The wires follow the same path inside the buildings but are positioned differently inside the duct (see Fig. 4). They are connected to the fifth grounding ring inside the buildings. The distances from the wires to the walls are 5 m on the x-axis and 75 cm on the y-axis. The cable shelves and the support rails inside the duct are not modeled. Each cable is divided into nine segments named S1 to S9, respectively. Segments S1 to S4 are the ones inside the first building, segment S5 is inside the duct, and segments S6 to S9 are inside the second building. A detailed view of the path followed inside the first building is also shown in Fig. 3. The currents are computed in the middle of each segment.

The lightning channel is represented as a monopole antenna by a 200-meters vertical lossy wire, excited at its base by a lumped current source and connected at the top end to a perfectly matched layer (PML) [13]. Aiming to conduct the study in the frequency domain, the current waveform is defined as a Gaussian function of 1 A, covering a frequency range from 0 Hz to 1 MHz. Its magnitude is attenuated by 10 at 1 MHz and an attenuation of 10^6 is set at the time instant t = 0 s to avoid any noise in the response. All the results in the frequency domain are normalized to this source, i.e., they are divided by the spectrum of the Gaussian pulse. Thus, they are independent of the current waveform.

A. *Extrapolation with the Matrix Pencil Method*

Even though the Gaussian pulse has a duration of just a few microseconds, the energy had not been completely dissipated after 50 μs due to the presence of resonances. The resonances are most likely associated with the total length of the path to the ground termination system. Since a single simulation up to 50 μs, running in parallel in 10 CPUs was taking 22 hours, instead of increasing the simulation time, we decided to extrapolate all the results applying the Matrix Pencil method [14]. The method consists of modeling the late-time response of a system as a sum of complex exponentials and estimating the parameters of the model using a linear technique. From the

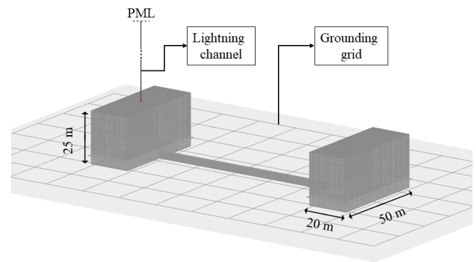


Fig. 1. Calculation model of the reference case.

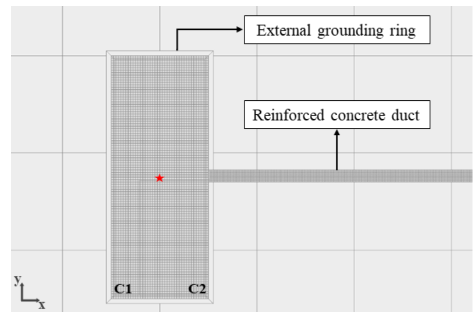


Fig. 2. Upper view of the first building in the reference case.

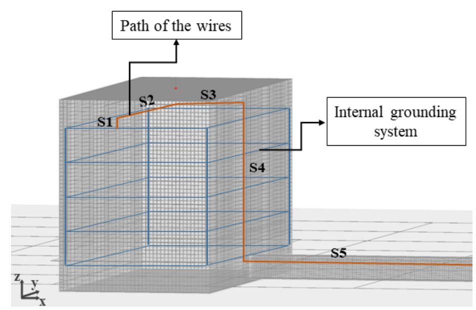


Fig. 3. Detailed view of the first building in the reference case.

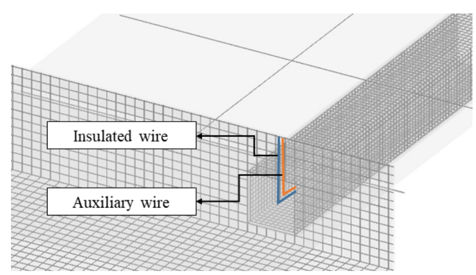


Fig. 4. Position of the wires inside the reinforced concrete duct.

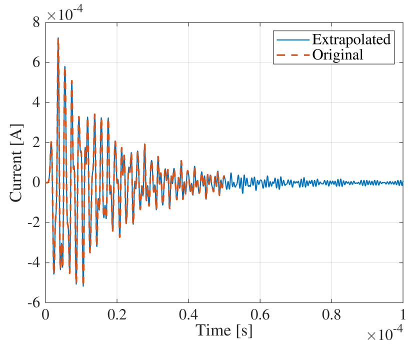


Fig. 5. Extrapolation of the current in segment S1 of the auxiliary wire.

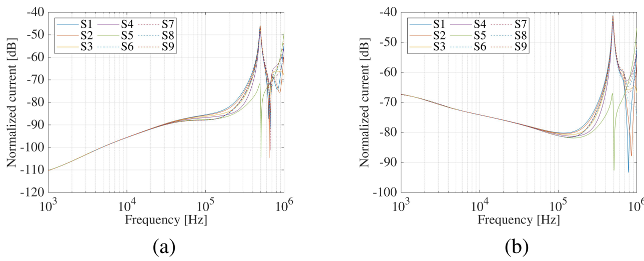


Fig. 6. Normalized currents in the reference case. (a) Insulated wire. (b) Auxiliary wire.

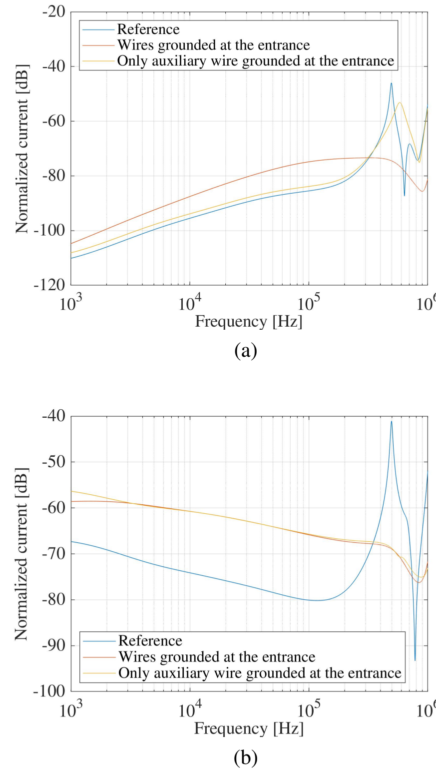


Fig. 7. Normalized currents in segment S1 when the wires are grounded at the entrance to the buildings. (a) Insulated wire. (b) Auxiliary wire.

poles and the residues obtained after solving the optimization problem, the response can be well approximated in both time and frequency domains. Fig. 5 shows the extrapolation of the current in segment S1 of the auxiliary copper wire in the time domain. The normalized currents in all the segments in the frequency domain are shown in Fig. 6.

To estimate electrical surges, the cables are often considered to be grounded at the beginning and the end of the duct. It can be observed in Fig. 7 that if both wires in the reference case are connected to the reinforcement at the entrance to the buildings, instead of being connected to the internal grounding system, the currents rise significantly and the resonances are no longer present below 1 MHz. If only the auxiliary wire is grounded at the entrance to the buildings, the current in the insulated wire increases around 2 dB at low frequency and decreases at the frequency of the first resonance.

III. Parametric Study

Due to the complexity of industrial facilities, the effects of a direct lightning strike are influenced by numerous parameters. In this study, we decided to focus on parameters that are rarely mentioned in lightning protection standards. The objective is to define a worst-case scenario from which, eventually, a more generalized parametric study could be conducted. The parameters are varied independently, and the results are analyzed at low frequency and the frequency of the first resonance. Even though the effects of the resonances are reduced, if not completely erased, when using the waveforms of the first positive and the first negative return strokes, they may create a major difference when using the waveform of the subsequent stroke. Table I summarizes the cases from which the highest normalized currents are obtained for each parameter. The corresponding frequency responses in segment S1 are shown in Table II and Fig. 8.

TABLE I
Cases in Which the Highest Normalized Currents Are Observed for Each Parameter

No.	Case
1	One connection from the internal to the external grounding system in corner C2.
2	One connection between the internal grounding rings in the second building.
3	Cables connected to the first grounding ring in the first building.
4	Cables connected to the first grounding ring in the second building.
5	One connection between the first building and the external grounding grid, in corner C1.
6	The external grounding system consists of interconnected rings.
7	Strike in corner C1.
8	Strike in corner C2 and duct positioned 1 m away from the edge.

A. Internal Grounding System

Significant variations in the currents are not observed when modifying the configuration of the internal grounding system. Nor are there significant variations when reducing the number of connections from the internal to the external grounding system in the second building. In the struck building, the currents are slightly higher if there is a reduction in the number of connections to the external grounding and the reinforcement. A small rise is also obtained when the internal grounding rings are connected once, rather than at each corner. Since the currents collected will converge to one point, the coupling between the rings and the wires may be stronger. In both cases, the length of the path to the ground is modified, and consequently, the frequency of resonance is shifted.

B. Connection of the Wires to the Internal Grounding System

At low frequency, as long as the wires are relatively far from the walls and they are connected to the same internal grounding ring, the changes are negligible. As the connection is moved away from the roof, the currents start decreasing and then increase when it approaches the foundation. The highest currents are observed when the wires are connected to the first grounding ring inside the first building. Slightly higher currents are also found when the length of the cables and thus their impedance is reduced. On the contrary, at the frequency of the first resonance, the effect of the distance to the walls is more pronounced, and the highest currents are observed when the wires are connected to the first grounding ring inside the second building.

C. External Grounding System

The effect of modifying the configuration of the external grounding system, or varying the number of connections to the buildings, is only noticeable at low frequency. The portion of the current flowing to the grounding system increases when its impedance decreases, resulting in a lower current flowing through the duct and consequently a decrease in the currents induced in the cables. Hence, the highest currents are observed when the grounding system consists only of two interconnected grounding rings, one around each building. Naturally, the currents also increase if the buildings are not connected to the external grounding system. Fortunately, there is always at least one connection. The analysis is then similar to the one made for the interconnection of the internal grounding rings: the coupling may be stronger if the number of connections is reduced and placed close to the wires' path.

D. Striking Point

Instead of striking the building in the center of the roof, the lightning channel is attached to the corners. When the wires are connected close to the striking point, the highest currents are observed at low frequency and the lowest at the frequency of the first resonance. The increase is comparable to the effect obtained when the building is struck in corner C2, probably because there is a higher current running through the duct and, therefore, the coupling is stronger. The highest currents at the frequency of the first resonance are observed in the reference case, suggesting that the symmetry reinforces the phenomenon.

TABLE II
HIGHEST NORMALIZED CURRENTS OBSERVED IN SEGMENT S1

No.	Insulated wire		Auxiliary wire	
	10 kHz	***First resonance***	***10 kHz***	***First resonance***
Ref	-95.50 dB	-45.99 dB	-74.13 dB	-41.08
1	Ref + 0.66 dB	Ref + 1.36 dB	Ref + 0.60 dB	Ref + 1.09 dB
2	Ref + 1.17 dB	Ref + 0.96 dB	Ref + 1.10 dB	Ref + 0.34 dB
3	Ref + 4.45 dB	Ref − 19.51 dB	Ref + 5.07 dB	Ref − 19.08 dB
4	Ref − 2.24 dB	Ref + 0.50 dB	Ref − 1.10 dB	Ref + 0.55 dB
5	Ref + 5.31 dB	Ref − 0.16 dB	Ref + 4.58 dB	Ref − 0.17 dB
6	Ref + 9.40 dB	Ref + 0.09 dB	Ref + 8.53 dB	Ref + 0.08 dB
7	Ref + 6.69 dB	Ref − 12.87 dB	Ref + 6.08 dB	Ref − 12.66 dB
8	Ref + 8.36 dB	Ref − 11.74 dB	Ref + 7.89 dB	Ref − 5.78 dB

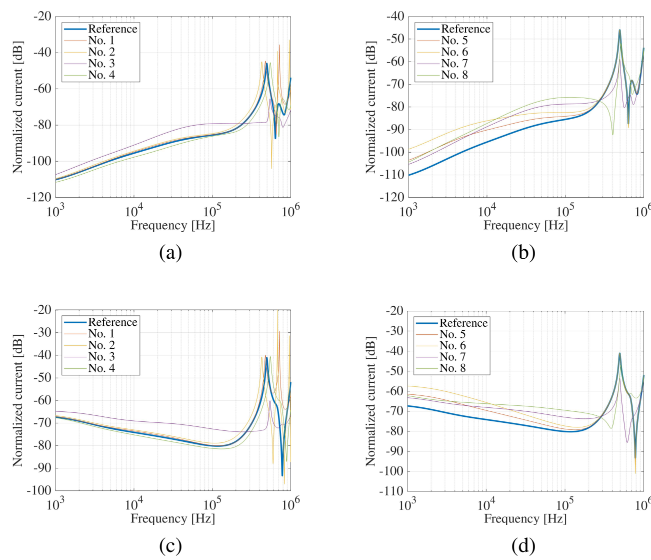


Fig. 8. Cases in which the highest normalized currents are observed in segment S1. (a) Insulated wire, cases 1 to 4. (b) Insulated wire, cases 5 to 8. (c) Auxiliary wire, cases 1 to 4. (d) Auxiliary wire, cases 5 to 8.

E. Position of the Duct

We consider the duct to be positioned at a distance to the edges varying between 1 m and 24 m. The lightning channel is attached first to the center of the roof and then to the corner C2. As expected, the closer the duct is to the edges and to the striking point, the bigger the portion of the current that flows through it. Additionally, changing the position of the duct also changes the path the wires follow inside the building; thus, at low frequency, the highest currents are obtained when the building is struck in the corner because of the proximity of the down conductor in the edge to segment S4. At the frequency of the first resonance, the values are still lower than in the reference case.

IV. Worst-Case Scenario

From the parameters studied, the one that increases the surges the most is the configuration of the external grounding grid, followed by the position of the duct. Yet, the place where the different elements are connected can play an important role. Accordingly, a first scenario is defined, including the following differences to the reference case:

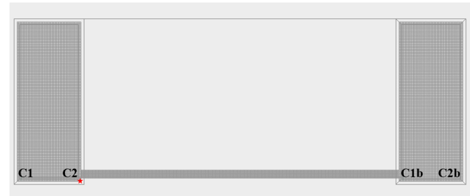
- The building is struck in corner C2.
- The duct is placed one meter away from the down conductor in corner C2.
- The external grounding system consists of two interconnected grounding rings, one around each building.
- The first building and its internal grounding system are connected to the external grounding system only once, passing by the corner C1.
- The rings of the internal grounding system of the first building are also connected once. The connection is close to the striking point.
- The wires are connected to the first grounding ring in each building, one meter away from the down conductors in corners C1 and C1b. The connection in the second building is close to C1b to reduce the cable length. In the first building, it is close to C1 to strengthen the coupling between the wires and the other conductors.

Given that the highest currents at the frequency of the first resonance were observed when the configuration was symmetrical, a second scenario is defined with the following differences:

- The external grounding system consists of two interconnected grounding rings, one around each building.
- The first building and its internal grounding system are connected to the external grounding system only once, passing by the corner C2.
- The rings of the internal grounding system of the first building are also connected once. The connection is close to C2.
- The wires are connected to the first grounding ring in each building, one meter away from the down conductors in corners C2 and C1b.

An upper view of the configurations is presented in Fig. 9. The results in the frequency domain are shown in Fig. 10. From these curves, the currents in the time domain, for any slow waveform can be obtained, by multiplying the spectrum of the desired waveform and computing the inverse Fourier transform. They are transfer functions. As an example, Fig. 11 shows the currents computed for the waveform of a first positive stroke and a subsequent negative stroke as defined in [8], protection level I. Since the waveform of the subsequent stroke has a short rising time, to compute the currents from the transfer functions, the simulations and the extrapolation were repeated using a shorter Gaussian pulse covering a 10 MHz bandwidth.

In the first scenario, the currents increase by 13.13 dB in the insulated wire and 17.03 dB in the auxiliary copper wire at 10 kHz. At the frequency of the first resonance, they increase by 7.26 dB and 8.25 dB, respectively. The currents are lower at 10 kHz in the second scenario; however, they are around 10 dB higher at the frequency of the first resonance. Compared to this increase, the rise in the currents observed in Fig. 7, when connecting both wires to the reinforcement in the reference case, no longer appears to be a significant overestimation. Fig. 10 also shows that if the wires in the worst-case scenarios are grounded at the entrance to the buildings, the currents at low frequency reach similar values. Hence, as long as the external grounding system is modeled appropriately one could estimate the currents in the worst-case scenarios by connecting the wires to the reinforcement. Nevertheless, Fig. 12 shows that it would reduce the resonant behavior when computing the time response for a fast waveform. Also, the currents may still be overestimated for slow waveforms if the wires are not loaded.



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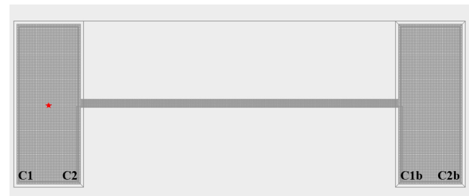
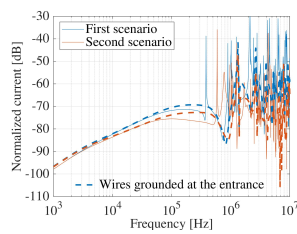


(b)

Fig. 9. Upper view of the calculation models. (a) First scenario. (b) Second scenario.



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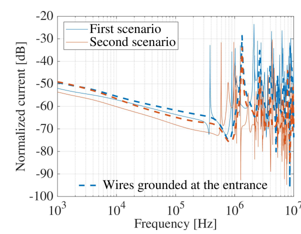
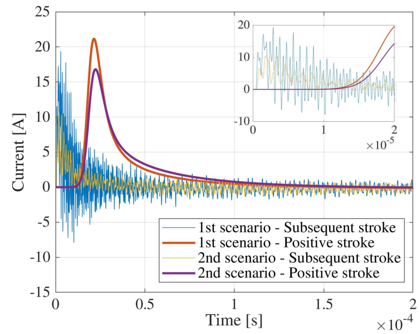


(b)

Fig. 10. Normalized currents in segment S1 in the worst-case scenarios. (a) Insulated wire. (b) Auxiliary wire.

V. Conclusion

Lightning-induced surges in industrial facilities are strongly dependent on the configuration of the external grounding system, the position of the ducts with respect to the striking point, and the path the wires follow inside the buildings. To design the LPS, it would be preferable to consider at least two worst-case scenarios, one for slow excitations and another in which the resonances are intensified. Under the simplifications



(a)

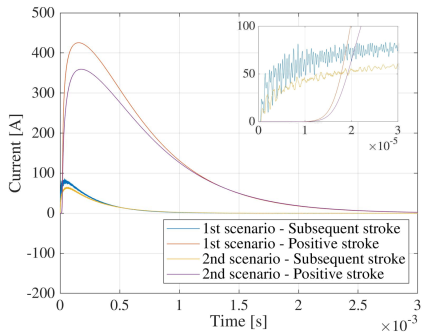


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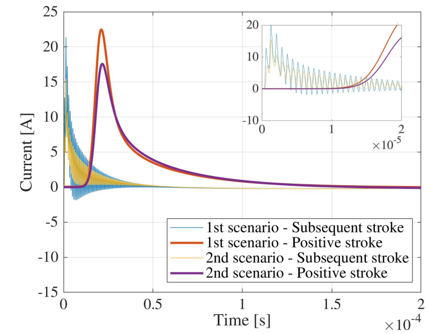
Fig. 11. Currents in segment S1 in the worst-case scenarios. (a) Insulated wire. (b) Auxiliary wire.



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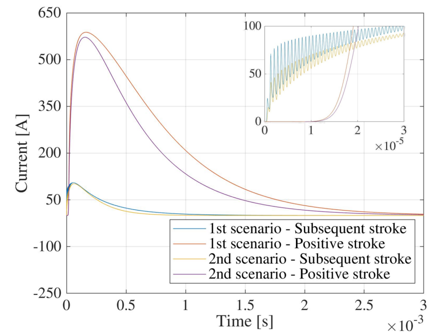

(b)

Fig. 12. Currents in segment S1 in the worst-case scenarios when the wires are grounded at the entrance to the buildings. (a) Insulated wire. (b) Auxiliary wire.

and the conditions defined in the study, the currents calculated when the cables are connected to the reinforcement at both ends of the ducts can give a good idea of the currents expected in the worst-case scenarios. Moreover, they could be used to estimate the surges. Further work is required to establish if the approach can be generalized. By grounding the cables at the entrance of the buildings, all the parameters associated with the internal grounding system could be disregarded in the model.

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