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OPTIMIZATION SOLUTION FOR STUDYING THE INFLUENCE OF DEFECTS IN ELECTRICAL CABLES IN FEMM

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Abstract: Defects in electrical cables can have major effects on the safety of electrical installations, which is why their theoretical and experimental study is of great importance. From a theoretical perspective, the influence of the defect on the electromagnetic field inside and around the cable can be modelled using the finite element method. This article proposes a solution for using the "Current Flow" mode in FEMM (Finite Element Method Magnetic) to study the influence of defect size in the dielectric of electrical cables and a method for automating this solution using LUA code.
Keywords: electrical cable, Finite Element Method Magnetic, LUA code

1. INTRODUCTION

Electrical cables are important for data transmission and connectivity. In electrical installations, they face vulnerabilities such as mechanical stress and environmental factors that cause damage and degradation. Thus, the most frequent defects in electrical cables are mechanical ones, which can occur due to conductor breakage, insulation cutting, insulation puncture, or the aging of the insulating material, leading to the appearance of holes. Electrical faults occur through short circuits when two conductors touch, accidental grounding when a conductor comes into contact with a grounding element, cable overheating, and many other factors. All these defects can lead to major socioeconomic losses and serious accidents (electrocution). In the energy industry, information about failures is rarely available; in other words, there is no catalogue of fault levels at which damage occurs. Therefore, theoretical and experimental studies on cable failures are very useful.

Experimental methods for testing for defects in cables are quite expensive, especially at high voltage [1], and thus a number of methods have been proposed to improve the detection of local defects. Among these methods, we mention the Born iteration method for low-voltage cables [2], the partial discharge method [3], [4], and the travelling wave method [2].The partial discharge method has a number of limitations, including the difficulty of monitoring and detecting partial discharge signals because they are weak [2], and the location of the partial discharge source is limited by the high-frequency attenuation of the partial discharge pulse as it propagates, due to the partial discharge signal frequency being in the hundreds of MHz range [2]. Thus, the partial discharge method is not effective in detecting multiple local defects [2]. The travelling wave method is based on transmitting a pulsed signal at one end of the cable. When the signal encounters a defect in the cable, it is reflected. By the return time of the reflected signal, the position of the cable fault can be detected. Like the partial discharge method and the travelling wave method, it cannot simultaneously detect multiple faults in a cable. [2].

A number of analytical studies on defects in transmission line cables can be found in the specialized literature [5], but analytical calculations regarding the influence of defects in electrical cables are very complex and sometimes unsolvable. In this context, numerical methods, such as the finite element method, can be used to analyze the disturbance of the electrostatic and magnetic fields due to defects in the electrical cable.Thus, there are studies in which the influence of defect dimensions in electrical cables has been numerically studied using the free FEMM (Finite Element Method Magnetic) package in electrostatic mode [6], [7], [8]. Other studies use 3D models to

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numerically study defects in the connection of high-voltage power cables [9], [10], [11]. These studies show that scratches on the insulation surface at cable joints have the greatest influence on insulation reliability and that at a sufficiently high voltage, significant electric field distortions can occur at points within the joints, which can lead to insulation damage.

A similarly recent work analytically, experimentally, and using the finite element method studies the influence of metal defects in the cable dielectric [12]. Studies show that these defects cause local distortions of the magnetic flux, which leads to current harmonics in the metal shield of the single-wire distribution cable analyzed.

As can be seen from a review of recent studies focusing on the analysis of defects in electrical cables, the finite element method can be very useful. This paper presents a solution in FEMM (Finite Element Method Magnetic) using the "Current flow" mode for dielectric materials and a method for optimizing this solution through LUA code to study the influence of defect dimensions in electrical cables.

This is how a spherical air-filled defect in the insulation of a single-core cable will be modeled in "Current Flow" mode. The LUA code will automatically modify the defect dimensions or the cable's operating voltage, and the results regarding the defect's influence on the electric field within the cable will be obtained.

When the electric field reaches values close to the air breakdown field (~3 MV/m), the air within a void in the dielectric of an electrical cable can ionize, and thus the phenomenon of partial discharge can occur locally.A partial discharge does not completely puncture the dielectric between the conductor and the sheath, but it is one of the most dangerous and important causes of insulation failure, especially in medium and high voltage cables. FEMM does not simulate discharges (it does not support non-linear modeling, self-ionization, etc.), but for a specific configuration of an electrical cable, you can see the voltage at which, if the conductor has voids, local discharges can occur in the sheath, and by pre-setting a constant conductivity of the air in the void, you can see its effect on the electric field.

2. FEMM MODELING OF THE DEFECT IN THE ELECTRICAL CABLE

A 2D planar base model will be created in FEMM for a single-core cable with a single dielectric layer, in air, with a Dirichlet Open Boundary condition, to be as close to reality as possible. The conductor diameter is considered to be 1.15 mm (AWG17), and the insulation layer thickness is 0.725 mm. An implicit Neumann-type insulation condition is applied to the FEMM dielectric's outside edge. We impose a fixed potential condition (e.g., 300 V) on the inner conductor. In FEMM, in "Current flow" mode, you can implicitly work only in conductive media. To extend this mode to other types of materials, those materials will need to be built because the library for this mode does not contain them. To build a lossy dielectric in FEMM, for example, using the "Current Flow" module, we need properties such as: electrical conductivity, relative electrical permittivity, and the loss angle tangent. According to specialized literature, the relative electrical permittivity for lossy PVC at 50 Hz [13] varies from 3.5 to 4 (3.5 is chosen), and the electrical conductivity for lossy PVC varies between 10^{-10} and 10^{-9} S/m (10^{-9} S/m is chosen). The tangent of the loss angle, tan δ, takes values ranging from 0.015 to 0.03 (0.02 is chosen) [13]. For atmospheric air, the electrical conductivity is around 10^{-15} S/m [13]. For ionized air in the context of partial discharges, the specialized literature gives a value of $\sigma > 10^{-7}$ S/m [14].

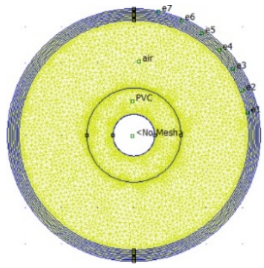


Figure 1. Model in the FEMM preprocessor for a single-core cable with a single dielectric layer without defects

Fig. 1 shows the model in the FEMM preprocessor for a single - core cable with a single dielectric layer without defects, and Fig. 2 shows the simulation results in the FEMM postprocessor for electric potential, electric field, and current density. Fig. 3 shows the electric field intensity as a function of distance in the mantle dielectric, and Fig. 4 shows the conduction current density as a function of distance in the mantle dielectric. The origin is taken on the surface of the conductor.

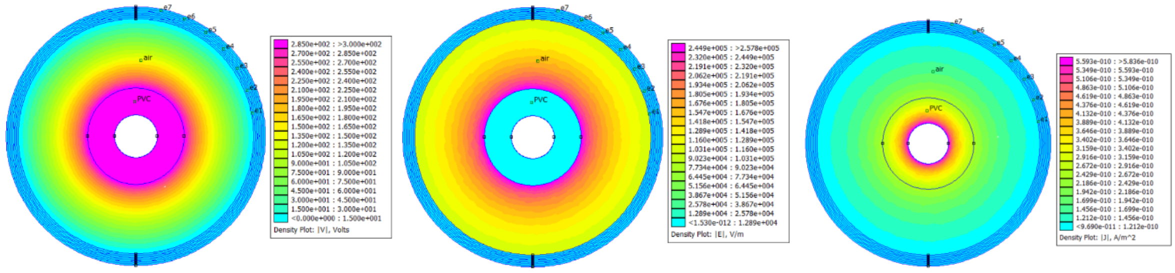


Figure 2. Electric potential, electric field, and current density for a single-core cable with a single defect-free dielectric layer

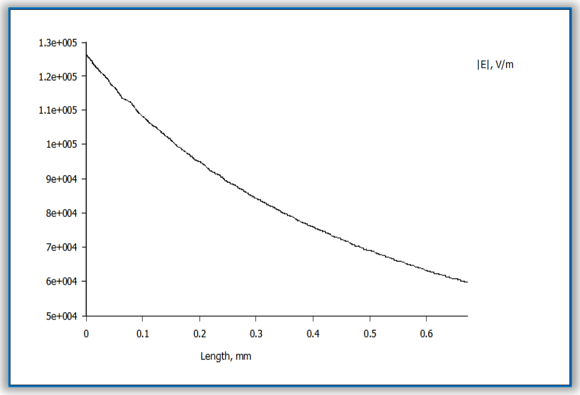


Figure 3. Electric field intensity as a function of distance in the sheath dielectric

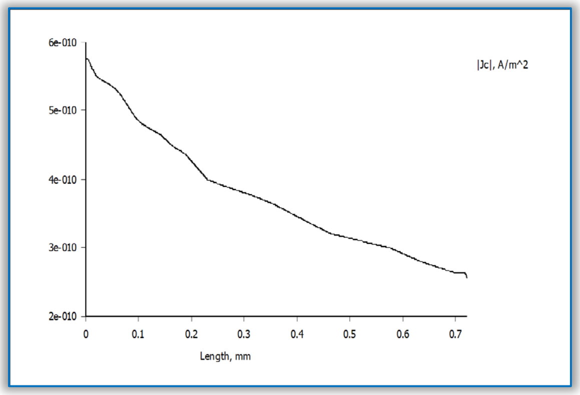


Figure 4. Conduction current density as a function of distance within the sheath dielectric

The defect is cylindrical in shape with a base radius of 1mm and a depth of 1mm. The defect will be filled with non-ionized air with an electrical conductivity of 10^{-15} S/m [13]. In the definition of the "Current Flow" type problem, the "Depth" parameter is set to 1 mm, which will represent the depth of the defect.

Fig. 5 shows the effects of the defect on the electric potential and the electric field in the single-core cable. From Figure 5, it can be observed that the electric potential in the dielectric is only slightly disturbed, while the electric field in the defect increases.

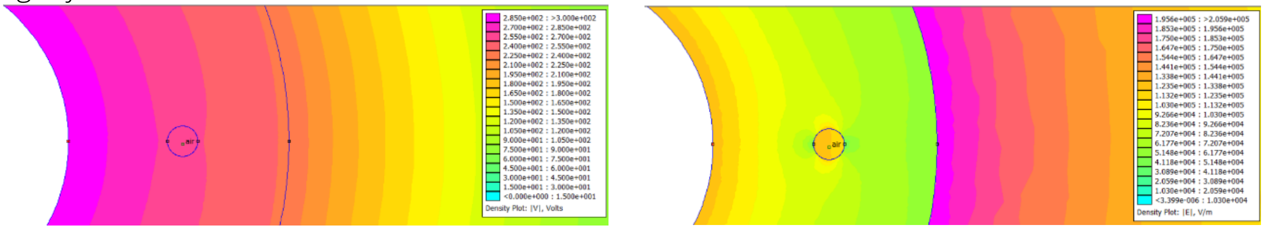


Figure 5. Distribution of electric potential and electric field in a single-core cable with a dielectric defect

In Fig. 6, we find the influence of the defect on the current density in the dielectric. From Fig. 6, a significant disturbance in the current density lines can be observed.

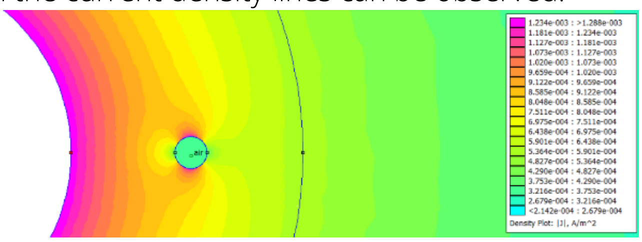


Figure 6. Influence of the defect on the current density thru the dielectric

Fig. 7 graphically represents the electric field intensity as a function of distance thru the conductor. Comparing Fig. 7 with Fig. 3, it can be observed that the presence of a defect in the PVC dielectric leads to a local increase in the electric field by a factor of 1.5 if the central conductor is at 300 V. From Fig. 7, it can also be observed that the electric field concentrates in the void where the material is less resistant and can lead to partial discharges that do not immediately puncture the dielectric but cause local material degradation, forming conductive channels that suggest a risk to cable safety.

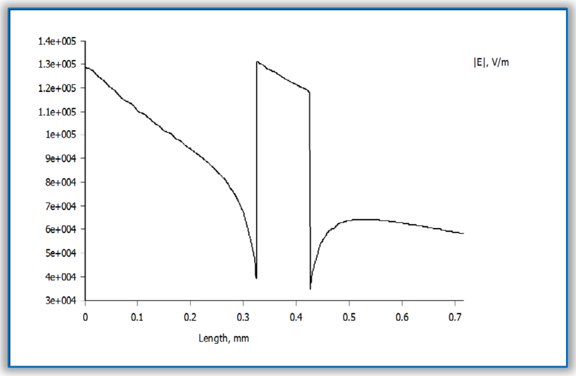


Figure 7. Electric field intensity as a function of distance within the mantle dielectric

```
R1=0.7
for i=1,10 do
open('./cablu_Cu_comp_l1.FEC')
ci_saveas('./cablu_Cu_comp_l1temp.FEC')
R2=0.7+0.05*i
---drawing points and arcs
ci_seteditmode("nodes")
ci_addnode(R1,0)
ci_addnode(R2,0)
ci_seteditmode("arcsegments")
ci_addarc(R1,0,R2,0,180,1)
ci_addarc(R2,0,R1,0,180,1)
---air block label placement
ci_seteditmode("blocks")
pozitie=(R1+R2)/2
ci_addblocklabel(pozitie,0)
---air block label setting
ci_selectlabel(pozitie,0)
ci_setblockprop("air1", 0, 0.1, 0)
ci_clearselected()
---creating mesh, calling solver and loading the solution into the postprocessor
ci_createmesh()
ci_showmesh()
ci_analyze()
ci_loadsolution()
co_showdensityplot(1,0,6)
fisier =  tostring(i)
  co_savebitmap("./gol" .. fisier..".png")
---set the postprocessor editing mode to contour
co_seteditmode("contour")
---draws a contour line between the specified coordinate points
co_addcontour(0.58,0)
co_addcontour(1.29,0)
---graph E=f(x) and save it in a png file
co_makeplot(4,200,"./E" .. fisier..".png")
---graph J=f(x) and save it in a png file
co_makeplot(1,200,"./J" .. fisier..".png")
---graph Jc=f(x) and save it in a png file
co_makeplot(7,200,"./Jc" .. fisier..".png")
ci_close()
co_close()
end
```

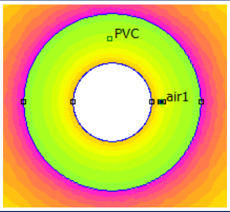
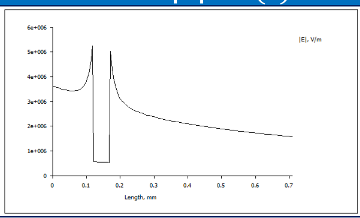
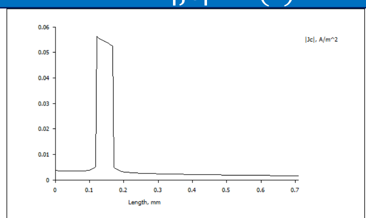
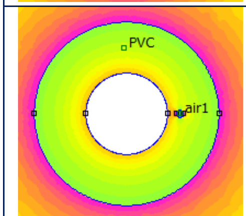
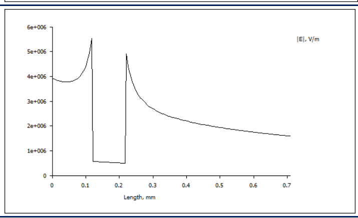
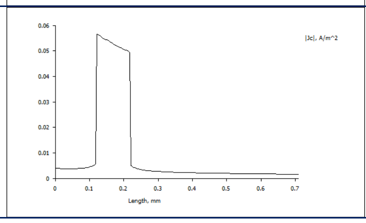
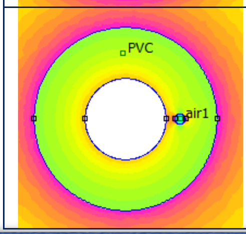
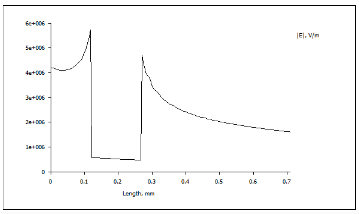
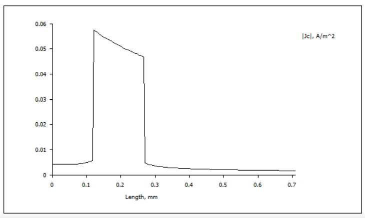
Figure 8. LUA code for optimizing the proposed solution

3. OPTIMIZATION METHOD FOR STUDYING THE INFLUENCE OF DEFECT DIMENSIONS IN ELECTRICAL CABLES USING LUA CODE

In the case of the analyzed electrical cable, a voltage value is set for which the electric field in the void reaches the value at which partial discharges can occur, V=8kV. We also modify the properties of the air in the void, making it weakly ionized with an electrical conductivity of $\sigma \approx 10^{-7}$ S/m [14]. We start from an initial model, like the one presented in Fig. 1, and using LUA code - Fig. 8, the proposed solution will be optimized.

The LUA code opens the corresponding preprocessor file from the current directory, saves it to a temporary file, and then, in a loop, allows for drawing and resizing the void, creating the discretization mesh, calling the solver, loading the solutions into the postprocessor, and saving the solutions to graphic files in the current directory. LUA code can be launched from FEMM. The graphical results obtained are presented in Table 1, showing the electric field in color code and the variation of the conduction current density as a function of distance in the hollow jacket dielectric (the contour line passes directly thru the hollow).

Table 1. Optimized Solution Results

|E| (V/m) in the color code	$\|E\| = f(x)$	$\|Jc\| = f(x)$
		
		
		

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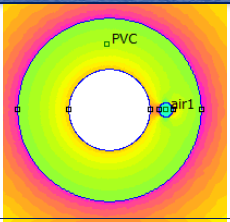	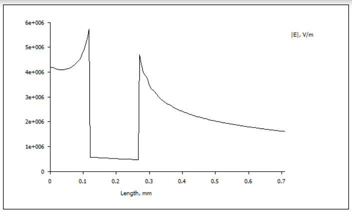	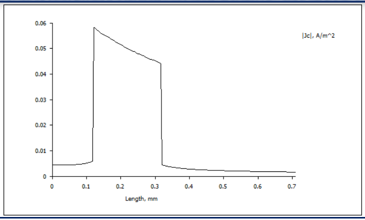
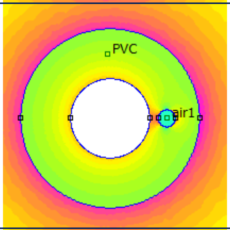	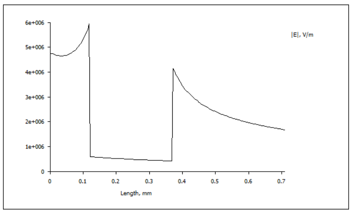	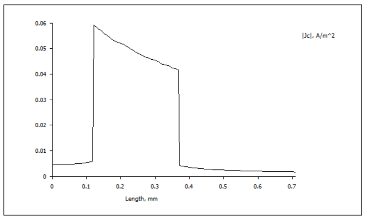
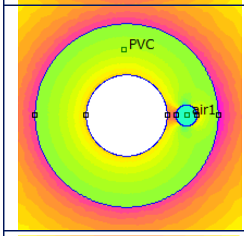	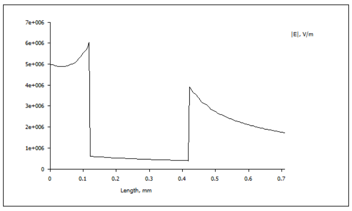	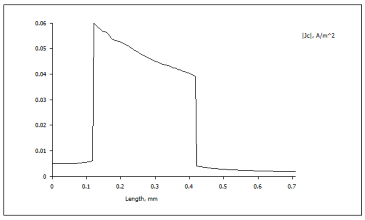
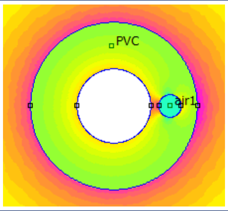	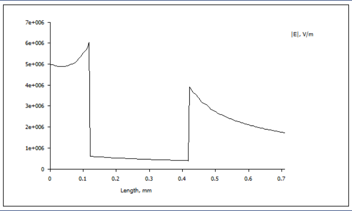	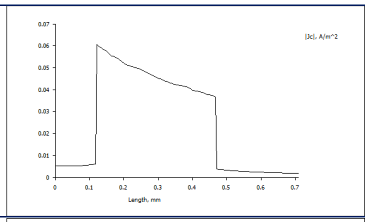
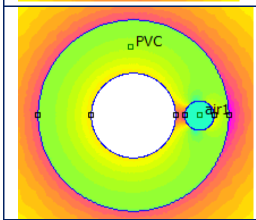	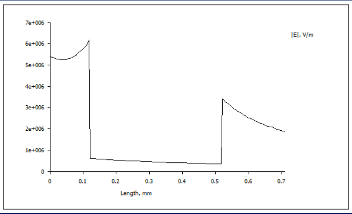	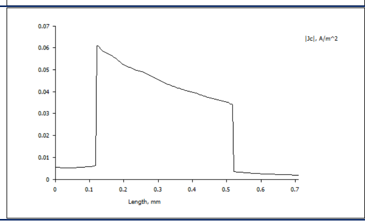
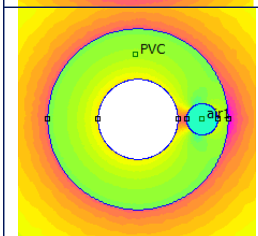	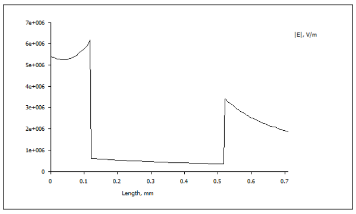	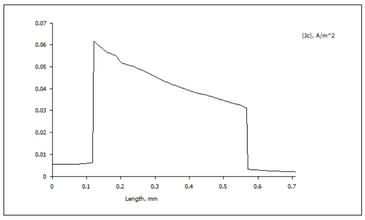
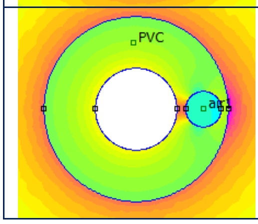	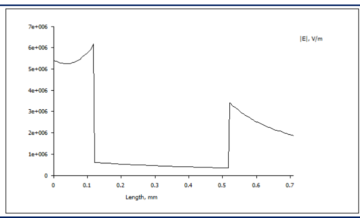	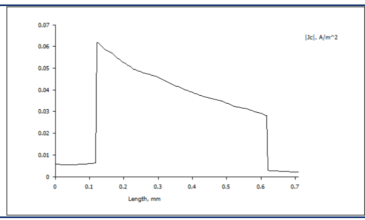

From the analysis of the results presented in Table 1 regarding the electromagnetic behavior of an electrical cable with defects in the PVC insulation in the form of a weakly ionized air cavity, a series of results are observed, which we will highlight below. The presence of the void causes an increase in the electric field near the void from the conductor side to over 6 kV/mm, exceeding the air discharge threshold, which is approximately 3 kV/mm. This amplification of the electric field at the defect leads to an increase in the conduction current density by more than 10 times. Under these conditions, repetitive partial discharges could occur. Repetitive partial discharges do not immediately cause electrical failure in the cable, but they can locally carbonize the void walls, gradually degrade the PVC insulation, propagate a crack or expand the void, and eventually lead to complete failure (flashover).

4. CONCLUSIONS

This paper presents a solution for using the "Current Flow" mode in FEMM (Finite Element Method Magnetic) to study the influence of defect size in the dielectric of electrical cables and a method for optimizing this solution using LUA code.

A series of simulations were then performed with the optimized solution under conditions of partial discharge occurrence in the air-filled defect. An increase in the electric field near the defect toward the conductor was obtained, exceeding the air's breakdown strength, which led to a more than 10-fold increase in the conduction current density, indicating the formation of a conductive channel in the dielectric. This regime is detrimental to insulation and directly affects the medium and long-term reliability of the cable, with an increased risk of progressive dielectric failure (puncture).

The solution can be adapted with minimal effort to other studies on defects in electrical cables, requires little material investment because the FEMM package is free, and is very helpful in risk assessment for electrical cable design.

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