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Mitigating Influenced Voltages on Pipelines Adjacent to Overhead Lines: An Analysis of different Fault Situations

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Abstract:

Pipelines designed for the transportation of oil, natural gas, or hydrogen often run parallel to high voltage overhead lines for extended distances. Modern protective measures such as polyethylene coating and active corrosion prevention are used to extend their expected lifetime. Short-circuits, lightning currents, and switching transients on overhead transmission lines (OHTL) can lead to substantial induced voltages on pipelines. To avoid potentially lethal over-voltages, pipelines are grounded at regular intervals. However, traditional grounding methods, involving deep drillings or extensive flat earth electrodes, can be prohibitively expensive. This paper employs a bespoke software tool to calculate pipeline over-voltages, optimizing the placement of grounding points. Simulations are conducted to assess potential changes in pipeline voltages during short-circuit and lightning conditions, particularly when AC overhead lines are upgraded to DC applications.

Keywords: Pipeline Voltages, Overhead Lines, AC, HVDC, Lightning

1 Introduction:

Growing energy demands prompt investments in upgrading overhead transmission lines (OHTL) and expanding oil and gas pipeline (OGP) networks. Sharing energy routes for extended distances (Figure 1), OHTLs and OGPs coexist, with the not perfectly balanced magnetic field of AC transmission lines inducing electromagnetic forces on buried pipelines. European standards dictate a maximum AC r.m.s. voltage of 60 V against ground, necessitating multiple pipeline groundings. Modern OGPs are well isolated by polyethylene coating for corrosion protection reason (Figure 2). This worsens the pipeline grounding situation resulting in higher needs for earthing. Even higher electric potentials are induced in a pipeline when the OHTL is affected by short circuit currents or lightning strikes. For such short time transients' higher limits apply in the standards. Unfortunately, the different organizations do not recommend same values (see Table 1). Changes in energy route configurations mandate a thorough check of induced pipeline voltages and potential improvements in grounding, crucial not only for new constructions but also for capacity upgrades.

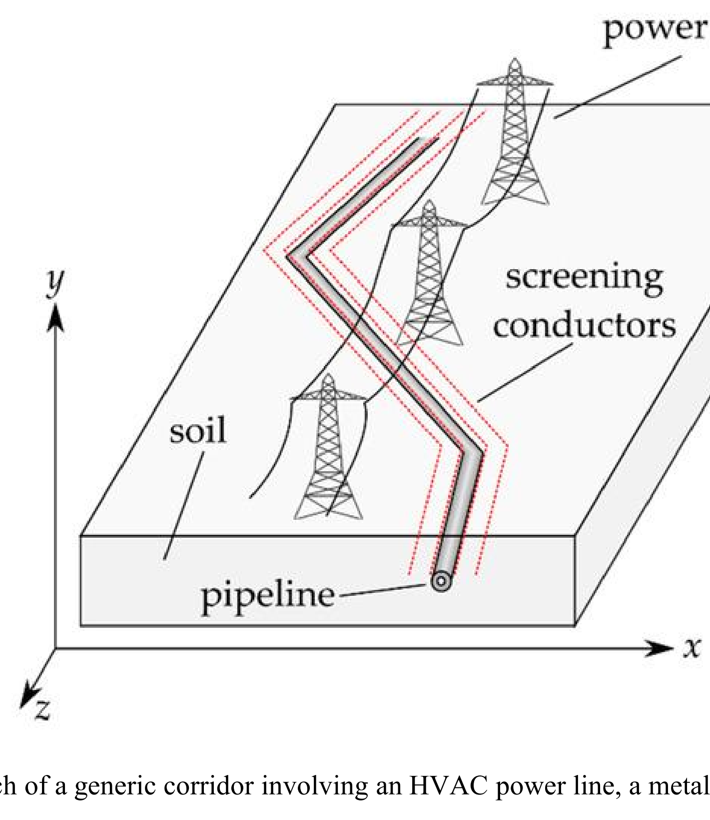

Figure 1: Sketch of a generic corridor involving an HVAC power line, a metallic pipeline buried in the soil, and several screening conductors, buried in the soil above the pipeline [16]

Figure 2: Pipeline insulation for corrosion protection [protectionengineerings.com]

Table 1: Limits for short term overvoltage's on pipelines

Standard	Limits for short term overvoltage's
TE 30 [4]	2000V
EN 50443 [3]	1500V
TE 7 [5]	1000V

DC overhead lines can induce voltages on Oil and Gas Pipelines (OGPs). Under stationary currents, the induced potential due to inductive coupling is primarily caused by the current ripple, which is less than 3% and therefore considered negligible. For buried pipelines, capacitive coupling also does not necessitate consideration. However, the scenario changes in the event of an earth fault or lightning phenomena on the DC line as the resulting transient currents are much higher. It is important to note that explicit standards for calculating the influence of DC Overhead Transmission Lines (OHTLs) on pipelines are currently nonexistent.

Whenever there is a modification in the configuration of an energy route, it is essential to examine the limits of induced pipeline voltages for all operational modes. Grounding of the pipeline may need to be enhanced accordingly. This requirement is not only applicable when constructing a new OHTL or OGP but also when increasing the current rating. The focus of this paper is on the situation involving the upgrading of a 380kV AC transmission line with an additional DC system.

2 Induced Potential on Buried Pipeline by OHTL Currents and Faults:

This section outlines the calculation principles for induced voltages on buried conductors, utilizing a self-programmed software tool based on the ITU model [1] derived from Carsons model [2]. Commercial software, such as CDEGS, effectively addresses scenarios where the current frequency on the Overhead Transmission Line (OHTL) is 50 or 60 Hz. However, when dealing with lightning or switching transients that involve high-frequency components, some researchers utilizing this software have reported exceedingly high induced voltages [12-13]. These outcomes prove challenging to explain easily. Consequently, we employ a self-programmed software based on the ITU model [1] to obtain results in a different manner. The calculation method relies on the following equations (eq. 1 - 4) and is illustrated in **Figure 3.** For rapid transient currents on the OHTL, the skin effect component δ (eq. 4) restricts induced pipeline voltages to reasonable values when considering the relevant frequency of the transient currents.

The buried pipeline is conceptualized as a transmission line with longitudinal Electromotive Force (EMF) sources (see **Figure 4** and **Table 2**). Here, Uij is the sum of the counter electromotive forces along a considered segment. In this pipeline model, the complex line-to-ground resistance Z_E must be individually calculated for each segment based on its pipeline geometry, insulation, soil resistance, and potential grounding at that point. The loop current I_i can be determined through the inversion of the system.

$$E^{'}[\frac{V}{kA \cdot km}] = 1{,}4 \cdot \sqrt{A^2 + B^2 - A \cdot B)} \tag{1}$$

$$A = ln\frac{\delta}{y_0^2+a^2} \cdot ln\frac{(y_0-y_2)^2+x_2^2}{(y_0-y_1)^2+x_1^2} + 22 \cdot\ ln\frac{(a-x_2)^2+y_2^2}{(a-x_1)^2+y_1^2} \tag{2}$$

$$B = ln\frac{\delta}{y_0^2+a^2} \cdot ln\frac{(y_0-y_3)^2+x_3^2}{(y_0-y_1)^2+x_1^2} + 22 \cdot\ ln\frac{(a-x_3)^2+y_3^2}{(a-x_1)^2+y_1^2} \tag{3}$$

$$\delta{=}658{\cdot}\rho f \tag{4}$$

where:

E' = Induced voltage per km and kA

f = Frequency of the TL current (Hz)

ρ = Soil's Resistivity in Ohm (m)

δ = Skin effect component

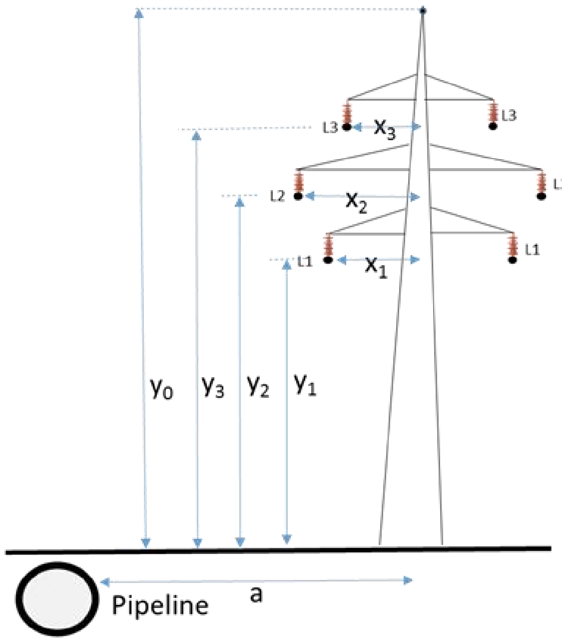

Figure 3. Geometry for ITU model calculation

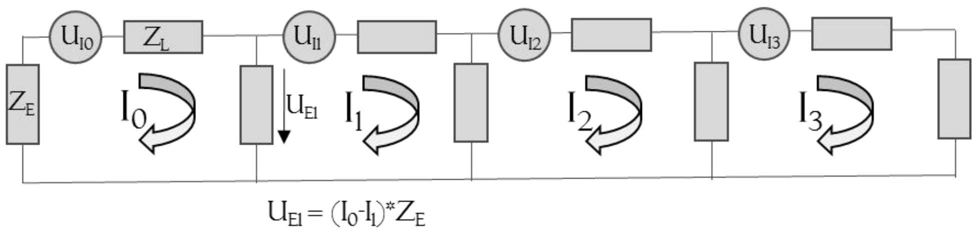

Figure 4. Calculation model for the pipeline voltage (comp. [5])

Table 2. Calculation model for the pipeline voltage

	I_0	I_1	I_2	I_3
U_{I0}	$Z_L+Z_E+Z_E$	$-Z_E$		
U_{I1}	$-Z_E$	$Z_L+Z_E+Z_E$	$-Z_E$	
U_{I2}		$-Z_E$	$Z_L+Z_E+Z_E$	$-Z_E$
U_{I3}			$-Z_E$	$Z_L+Z_E+Z_E$

3 Fault Current Modelling:

Transient signals, such as lightning and DC fault currents, are approximated using linear current ramps with constant di/dt. **Figure 5** illustrates the approximation of a lightning current with a magnitude of 10 kA striking a power line. In this scenario, the worst case is assumed, wherein no back flashover is taken into account, and the lightning protection is categorized as class III with the use of an earth wire. While lightning strikes impacting the overhead grounding wire may exhibit significantly higher amplitudes, their current is directed to the ground at each pole [12]. Consequently, the resulting geometrical length, associated with substantial current, is much shorter compared to lightning currents flowing through a live conductor. This, in turn, leads to smaller induced potentials on the OGP.

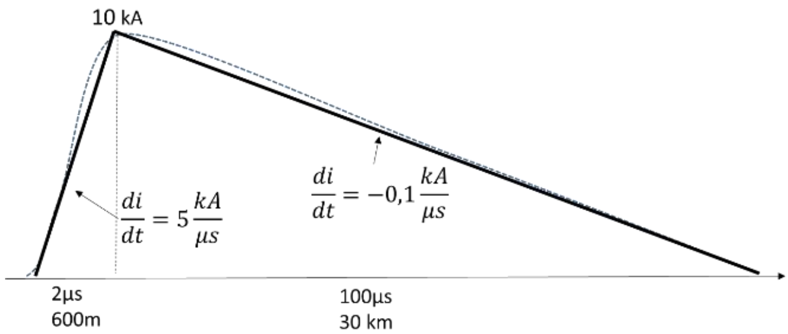

Figure 5. Simplified lightning current on OHTL in black and measured in blue

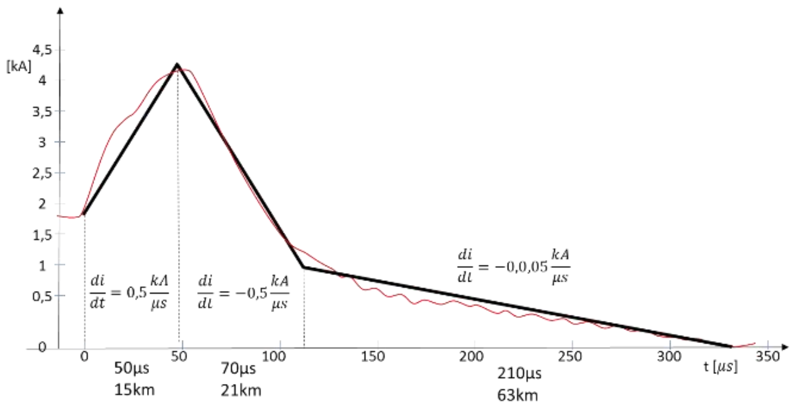

Figure 6. Simplified DC line to earth fault current in black and measured in red

Moving on to **Figure 6**, it presents the current approximation for a DC line-to-earth fault in close proximity to a converter station, showcasing the worst-case scenario as reported in [7]. It's worth noting that other events on HVDC lines, such as circuit breaker operations, exhibit lower rise times and generate reduced induced voltages [8-10].

4 Characteristics of OHTL and Pipelin and Simulation Results:

To provide realistic results, the paper selects a real-life scenario involving a 380 kV OHTL running parallel to a DN1200 gas pipeline for 31 km (**Figure 7**). The transmission line is modeled based on standard lattice tower geometry (2 circuits in barrel shape), and the steel pipeline material characteristics are defined as following; (ρ=0,16 μΩ·m; μr=200) with a 3 mm PE insulation (ρ=1 MΩ·m).

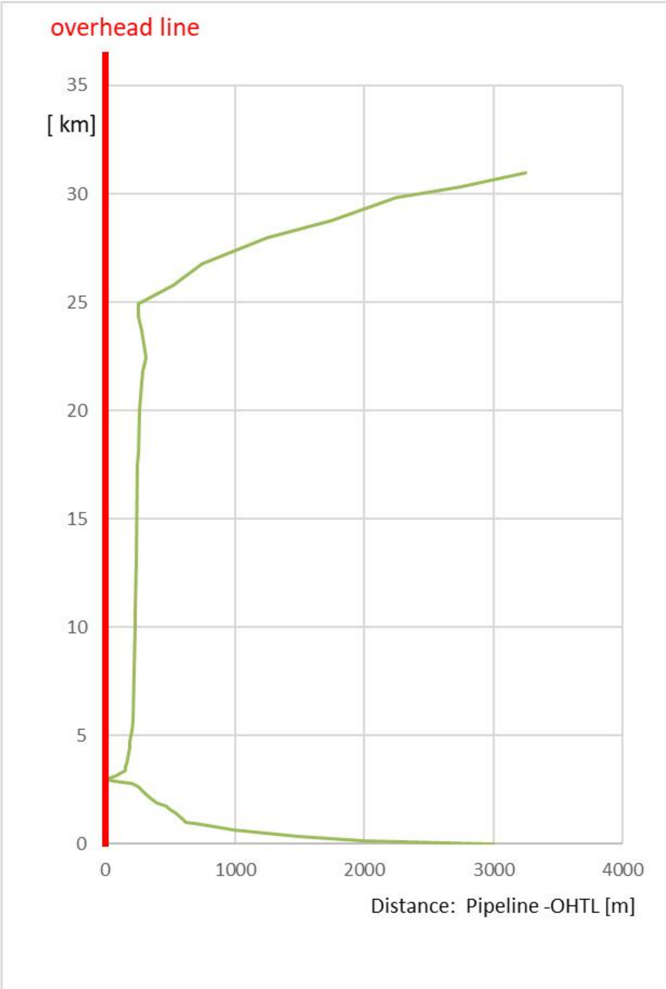

Figure 7: Separation between of Pipeline and OHTL

The resulting pipeline potentials for the rated current of 3,4 kA are shown in **Figure 8**. Without grounding the pipeline voltage to earth would reach a magnitude of 120 V. This is significant above the 60 V limit of EN 50443. With 2 optimized grounding points (4 Ω at 2 km and 3,5 Ω at 25 km) the voltage stays within acceptable limits.

In the event of a short circuit to earth, the examined Overhead High-Tension Line (OHTL) can experience a maximum short-circuit current of 13.2 kA, with the expectation that it will be cleared in less than 1 second. For such brief occurrences, EN 50443 permits a maximum potential rise to 1500V. The calculation results for such an event are depicted in **Figure 9**. Once again, the maximum voltage significantly exceeds the limit if the pipeline remains ungrounded. Optimized earthing points (0.5 Ω at 2 km, 0.5 Ω at 25 km, and 20 Ω at km 31) prove effective in keeping the voltage within acceptable limits.

The grounding requirements derived from these lightning calculations are more stringent than those stemming from the rated thermal current case mentioned earlier. A calculation incorporating these three earthing points demonstrates that the potential also remains below 60V at the 3.4 kA rated current.

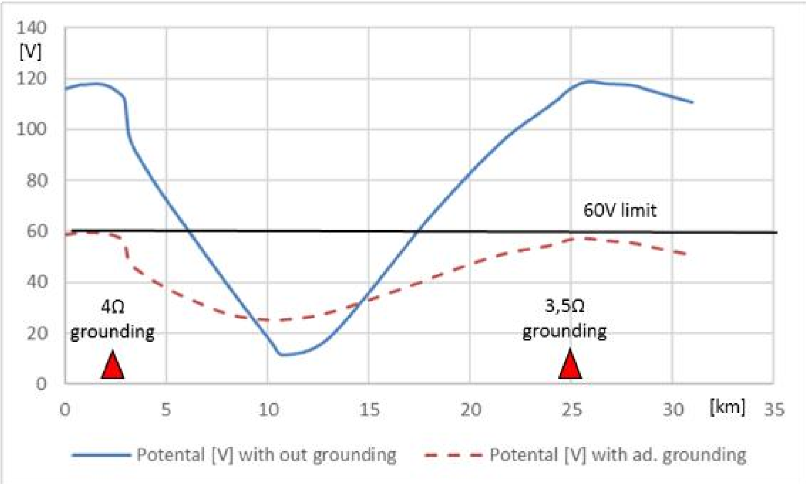

Figure 8. Pipeline potential at 3,4 kA rated thermal current limit

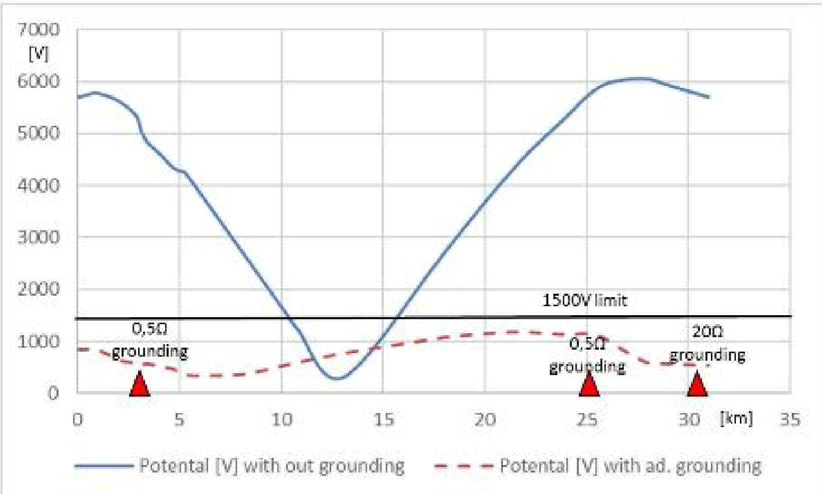

Figure 9. Pipeline potential at 13,2 kA short circuit current

Currents induced by lightning events on live wires of the Overhead High-Tension Line (OHTL) exhibit significantly faster current rise times. Some researchers report results in the range of 100 to 500 kV for the pipeline voltage [10-11], given that the induced voltage is proportional to the product of di/dt and the mutual impedance between OHTL and OGP. However, this mutual impedance is not constant across different frequencies (compare with skin effect equation 4). This variability is not consistently modeled in the literature, leading to notable changes in results. In the calculations presented in this paper, the lightning current is segregated into its frequency domain components and represented by their median frequency. This approach yields the results shown in **Figure 10**, where voltages remain well below the 1500 V limit. No additional grounding for the pipeline is required for lightning strikes. This outcome aligns more closely with the observed behavior in existing pipelines. An overvoltage of a few hundred kV on the pipelines could potentially lead to a breakdown of the 3 mm PE insulation, although such occurrences are rarely reported. Additional measurements are needed to validate these results.

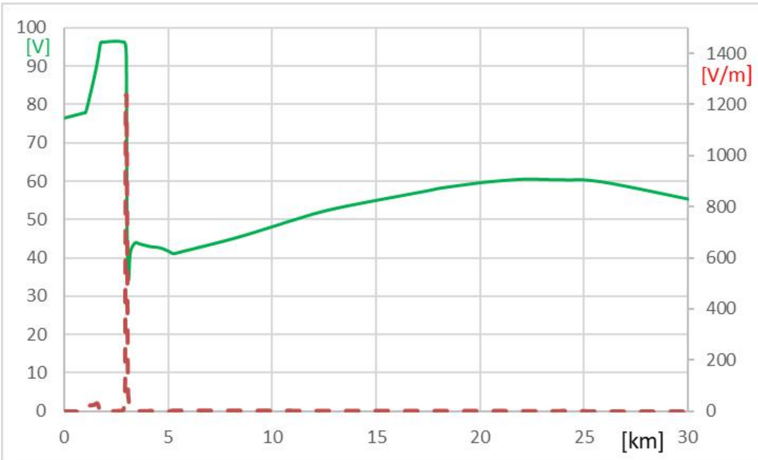

Figure 10. Induced pipeline Potential from 10 kA lightning current hitting the OHTL without any pipeline grounding and the induced electrical field in red.

HVDC transmission lines are employed to enhance power capacity, particularly for long-distance transmissions. For both economic considerations and public acceptance, existing AC lines are occasionally upgraded with DC systems. In such instances, it becomes crucial to investigate their impact on nearby pipelines. The induced pipeline voltage during steady-state operation, with less than 3% ripple, is minimal. However, in the event of a line-to-earth fault, currents can escalate rapidly, leading to an induced overvoltage on the pipeline. **Figure 11** illustrates the resulting overvoltage from a DC line-to-earth fault. Although the resultant potential is much higher compared to the lightning event described earlier, it remains at 420 V—well below the 1500 V limit.

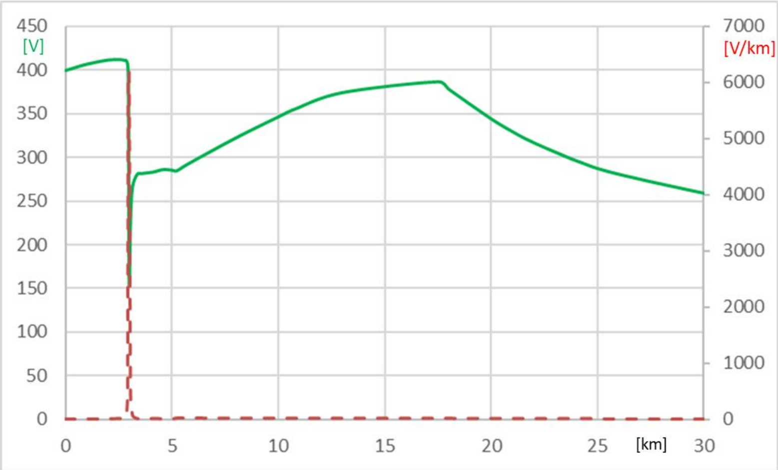

Figure 11. Pipeline potential resulting from a DC line to earth fault in green without any pipeline grounding and the induced electrical field in red.

6 Conclusion:

The voltages induced on buried pipelines by faults like short-circuits or lightning strikes on Overhead High-Tension Lines (OHTLs) can be accurately calculated using the ITU model in the following scenarios:

• 50/60 Hz rated currents

• 50/60 Hz short-circuit currents

• Currents from lightning events

• Currents from DC line-to-earth failures

Additionally, the self-developed calculation program can optimize the number of required grounding points. This optimization not only helps in cost savings for new installations but also assesses scenarios for the power upgrade of existing overhead transmission lines. The results presented in this study suggest that:

- The grounding requirements arising from an AC short-circuit event pose the most significant challenges
- And often restrict induced voltages during normal operational conditions to satisfactory values.
- Induced voltages from lightning events or DC line-to-earth failures, as reported here, are notably lower than those documented at other points [10-11].
- In most instances, induced voltages from lightning and DC events will likely remain within allowed limits even without grounding. However, further measurements are essential to substantiate this last conclusion.

Even if computational effort is significant, al these models are limited in their precision as Carson's model [2] is not precise. Modern OHTL have sometimes up to 3 earth or fiberoptic support wire acting as current reduction loops limiting the influenced voltage and are not well model by Carson.

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