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# Parametric Analysis of Conductive Coupling of Transmission Line Tower Grounding and Pipeline in Multilayer Soil

***Abstract**. Faults in electric power system may give rise of coating stress voltages on nearby pipelines due to mutual electromagnetic coupling. To prevent hazardous situations, accurate modelling of the electromagnetic interactions between such systems is required. In this paper, we perform parametric analysis of the effects of multilayer soil and of the effectiveness of different mitigation techniques in reducing coating stress voltages on a short pipeline section due to conductive coupling. Analyses are performed using full-wave electromagnetic model, based on the method of moments.*

***Streszczenie.** Awarie w systemie elektroenergetycznym mogą powodować wzrost napięć naprężeniowych powłok na pobliskich rurociągach w wyniku wzajemnego sprzężenia elektromagnetycznego. Aby zapobiegać niebezpiecznym sytuacjom, wymagane jest dokładne modelowanie oddziaływań elektromagnetycznych między takimi systemami. W tym artykule przeprowadzamy analizę parametryczną wpływu wielowarstwowego gruntu i skuteczności różnych technik łagodzenia w zmniejszaniu napięć naprężeń powłoki na krótkim odcinku rurociągu z powodu sprzężenia przewodzącego. Analizy przeprowadzane są z wykorzystaniem pełnofalowego modelu elektromagnetycznego, opartego na metodzie momentów. (**Analiza parametryczna przewodzącego sprzężenia uziemienia słupa linii przesyłowej i rurociągu w glebie wielowarstwowej** )*

**Keywords:** Conductive coupling, electromagnetic model, interference, method of moments, mitigation, pipeline.
**Słowa kluczowe:** Sprzężenie przewodzące, model elektromagnetyczny, interferencja, metoda momentów, łagodzenie, rurociąg.

## Introduction

Faults in electric power system may give rise of coating stress voltages on nearby pipelines due to mutual electromagnetic coupling. Excessive voltages may endanger people and disrupt pipeline system safety and reliability. To prevent hazardous situations, safety analysis require accurate modelling of the electromagnetic interactions between such complex systems [1, 2].

In this paper, we perform parametric analysis of the conductive coupling of tower grounding of a high voltage (HV) transmission line to short sections of buried and well insulated metallic pipeline. The objectives of the analysis are: 1) to determine the effects of the multilayer soil on the increase and distribution of soil potentials near the grounding system to which the pipeline may be exposed; 2) to analyse the effectiveness of some typically used mitigation methods for reducing the coating stress voltages of pipeline.

Analysis are performed by full-wave electromagnetic model, based on the method of moments (MoM), that enables precise modelling of both systems and accurately accounts for the electromagnetic coupling in presence of multilayer soil [3 - 5].

## Description of the analyzed problem

As interfering system we consider tower grounding of a HV transmission line, with horizontal electrodes buried at depth of 0.8 m. As interfered system we consider short metallic pipeline, with minimum length of 1 km that is well insulated from the surrounding soil by PE insulation and terminated at both ends by insulating joints. The pipeline is buried at depth of 1.5 m in a two-layer soil. The upper soil layer has conductivity $\sigma_1$ = 0.01 S/m and a thickness of 1 m (for a case where pipeline and tower grounding are in same layer) or 2 m (for a case where pipeline and tower grounding are in different layers). Three different alternative values of the conductivity $\sigma_2$ of the lower layer are considered, that are also expressed in terms of the reflection coefficient $K$ [6]: 0.19 S/m ($K$ = –0.9), 0.01 S/m ($K$ = 0), and 0.000526 S/m ($K$ = 0.9), where:

$$K=\left(\sigma_1-\sigma_2\right)/\left(\sigma_1+\sigma_2\right) \tag{1}$$

Since the interfered system is buried pipeline, following the guidelines provided in [1], only the effects of conductive and inductive coupling are of particular interest, while the effects of capacitive coupling are negligible. In this paper we focus the analysis on the conductive coupling, which is related to the effects of elevated soil potentials due to dissipated current from nearby grounded structures of the power system during fault conditions. More details of the interfering and interfered systems are provided on Fig. 1.

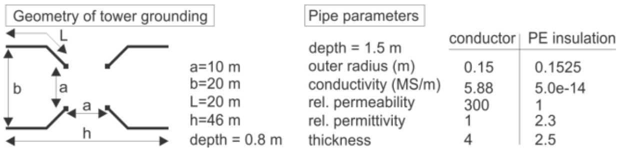

Fig.1. Parameters of interfering and interfered system.

## Effects of multilayer soil on elevated potentials

In the following analysis, we consider that the minimal horizontal distance between tower grounding electrodes and pipeline is varied between 2 m, 10 m and 20 m. According to [1], such distances correspond to the minimum allowed (for 2 m) and the maximum separation distances (for 20 m) that require analysis of conductive coupling to pipeline. Fig. 2 shows the maximum values of soil potentials surrounding the insulated pipeline, with respect to remote earth. In this analysis other coupling mechanisms are neglected so the pipeline can be considered to be at 0 V of potential and therefore calculated potentials will correspond to the coating stress voltages when the pipeline is subjected to conductive coupling. Calculated voltages are normalized to 1 A current that is injected in the grounding electrodes.

Results show that resistivity of the deeper soil layer have strong influence on the coating stress voltages as they increase with the increase of the deeper soil resistivity. Significant increase of coating stress voltages is observed when pipeline is within the more resistive soil layer. The assumption of homogeneous soil related either to the characteristics of the upper or deeper soil layer, or to the mean value of layered soil resistivity, will lead to erroneous results and substantial underestimation or overestimation of the calculated voltages. Therefore, accurate modelling of layered soil is required for proper risks assessment.

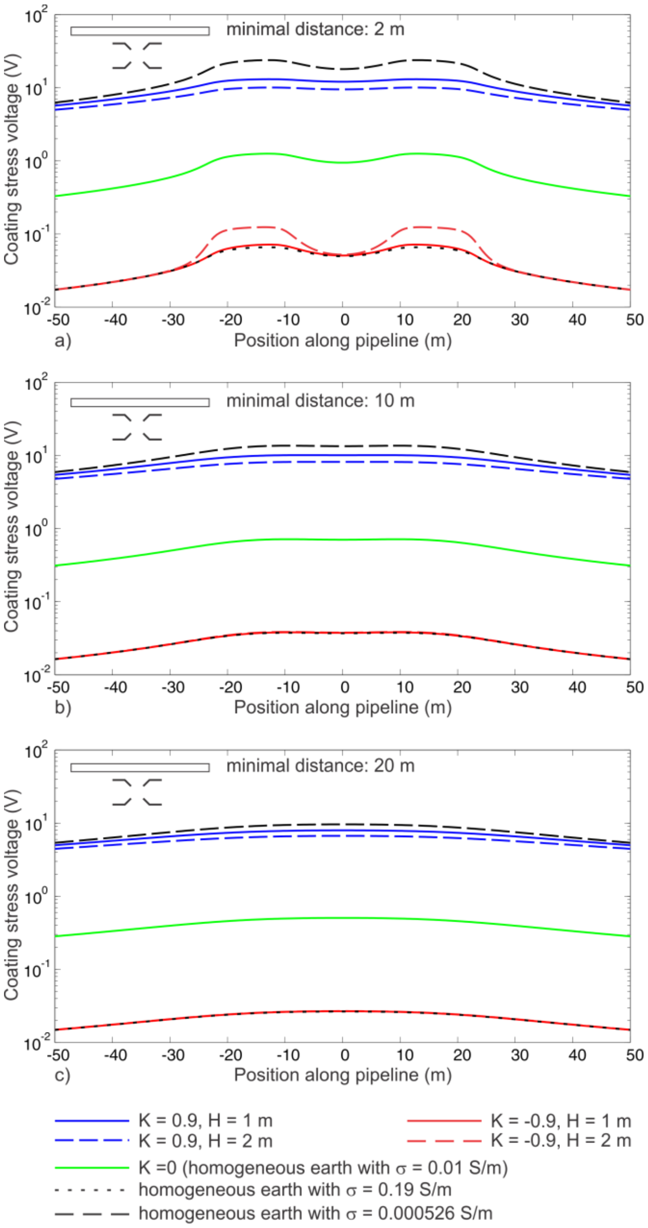

Fig.2. Effects of multilayer soil on coating stress voltage due to conductive coupling for minimal horizontal separation between pipeline and tower grounding of: a) 2 m; b) 10 m; c) 20 m (normalized values per dissipated current of 1 A through the tower grounding)

### Effects of multilayer soil on soil ionization

When high intensity currents are dissipated through small-sized grounding such as tower grounding electrodes, despite of the local increase of soil potentials, strong electric field surrounding the grounding electrodes may also appear. The zone where the intensity of the electric field is above a critical strength (here we consider $E_{cr}$ = 300 kV/m) can be considered as ionized and arcing from the electrodes within the ionized soil may appear. Hazardous situation may appear if such ionized channel is attached to the metallic pipeline, leading to possible successive discharge of high intensity fault currents into the pipeline.

In this analysis we calculate the electric field within soil for the minimal horizontal separation distance of 2 m between pipeline and the tower grounding. Fig. 3 shows the spatial distribution of electric field surrounding the pipeline along a profile perpendicular to the pipeline. The electric field values are normalized for current of 1 A that is dissipated through the tower grounding. For better clarity of the results, only the variations of the electric field within the range 0.1 – 2 V/m are displayed for all scenarios.

Results show that the risk of entering the pipeline into ionized zone of soil is increasing with the increasing resistivity of deeper soil layer. Similarly to the previous observations, such risk increases when pipeline is within the more resistive soil layer. For example if we consider that entire lightning current with intensity of 200 kA (attributed to first lightning stroke with $T_1$ / $T_2$ = 10/350 μS) is discharged through the tower grounding electrodes, then the pipeline may enter in the ionized zone when K = 0.9, but only when pipeline is within the more restive layer. The most hazardous situation is observed for homogeneous soil with σ = 0.000526 S/m, i.e. when grounding electrodes and pipeline are at small distance and within highly resistive soil.

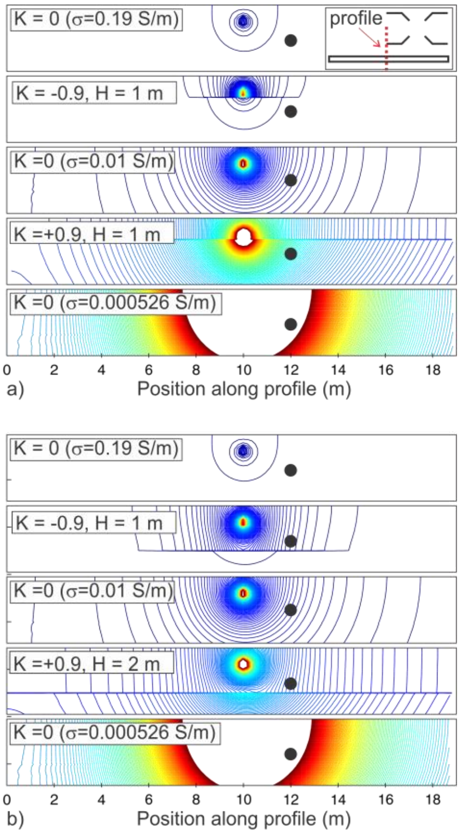

Fig.3. Effects of multilayer soil on the intensity of electric field in the soil for two scenarios: a) grounding electrodes and pipeline in different soil layers; b) grounding electrodes and pipeline within same layer (normalized values per dissipated current of 1 A through the tower grounding)

### Mitigation of conductive coupling

In this section the full-wave electromagnetic model is used to accurately model some typical mitigation methods and estimate their effectiveness in reduction of the effects of conductive coupling. The use of gradient control wire, buried parallel and close to the pipeline between the pipeline and tower grounding electrodes, is a preferred method for dealing with conductive coupling. In such configuration, bare zinc ribbon or copper wire is attached to the pipeline directly or by dc decoupling device, for the latter [7, 8]. Another variant is the use of gradient control wire detached from the pipeline [9]. In this paper we analyze the effectiveness of both methods in different scenarios.

As interfering system we consider grounding electrodes of transmission line tower that have 10 m minimum horizontal separation from the short pipeline section. For simplicity, in these analysis we consider only homogeneous earth with $\sigma$ = 0.01 S/m. We also assume that grounding system is energized by fault current with intensity of 1 A, so the results provided in Fig. 4 and Fig. 5 can be considered as normalized values of soil potentials, pipe potentials and coating stress voltages for the different mitigation methods.

Fig. 4a shows scenario where 1 km pipeline section, that is well insulated from the surrounding earth by PE coating and has no electrical continuity with the rest of pipeline due to the use of insulating joints, enters the zone of elevated soil potentials from the energized tower grounding system. Since leakage currents through PE insulation and insulating joints are negligible, in absence of other coupling mechanisms, the pipe potential over entire length is raised to a value that is equal to mean value of the soil potential along the pipeline's entire length. The coating stress voltage is calculated as a potential difference between the pipeline and surrounding earth, and follows a similar pattern as the variation of the soil potentials over the pipeline length.

Fig. 4b shows scenario where 100 m FeZn ribbon connected to pipeline is laid in the same trench with the pipeline, between the pipeline and the tower grounding electrodes, at a distance of 0.4 m from the pipeline center.

In this case, the gradient control wire receives the mean value of the soil potential over entire wire length and transfers that potential to the pipeline. The pipe potentials are significantly raised compared to the scenario in Fig. 4a and approach the value of the soil potentials near the tower grounding electrodes, therefore providing substantial protection of the coating in vicinity of the grounding electrodes. However, in short pipeline sections, elevated pipe potentials remain nearly constant along entire length, leading to high coating stress voltages outside the zone of conductive interference. Fig. 4b shows that such mitigation to short pipeline section can lead to even hazardous situation, where substantial coating stress voltages are distributed over large portion of the pipeline.

In the third scenario analyzed in Fig. 4c, the FeZn ribbon is detached from the pipeline. In such configuration, the FeZn ribbon that is in direct contact with soil is energized in the zone of conductive influence and expels this energy outside this zone, over the entire wire length. The leakage currents surrounding the FeZn ribbon contribute in equalizing the soil potentials surrounding the pipeline, especially in the zone near the grounding electrodes. The pipe potentials remain the same as in the scenario in Fig. 4a since the energy in the system remains the same, while it is differently distributed due to the presence of FeZn ribbon. Results show that mitigation method seems to be most favorable in reducing the coating stress voltages.

The efficacy of the analyzed mitigation methods, with respect to the FeZn ribbon length is provided in Fig. 5. Results show that the use of 200 m ribbon detached from the pipeline is most effective in reducing the coating stress voltages. It should be considered that the length of the parallel approaching between pipeline and tower grounding is nearly 46 m therefore the FeZn ribbon significantly extends outside the zone of strong conductive influence.

Extensive analyses, not provided in this paper, have shown that other mitigation methods are not efficient as the method in Fig. 4c.

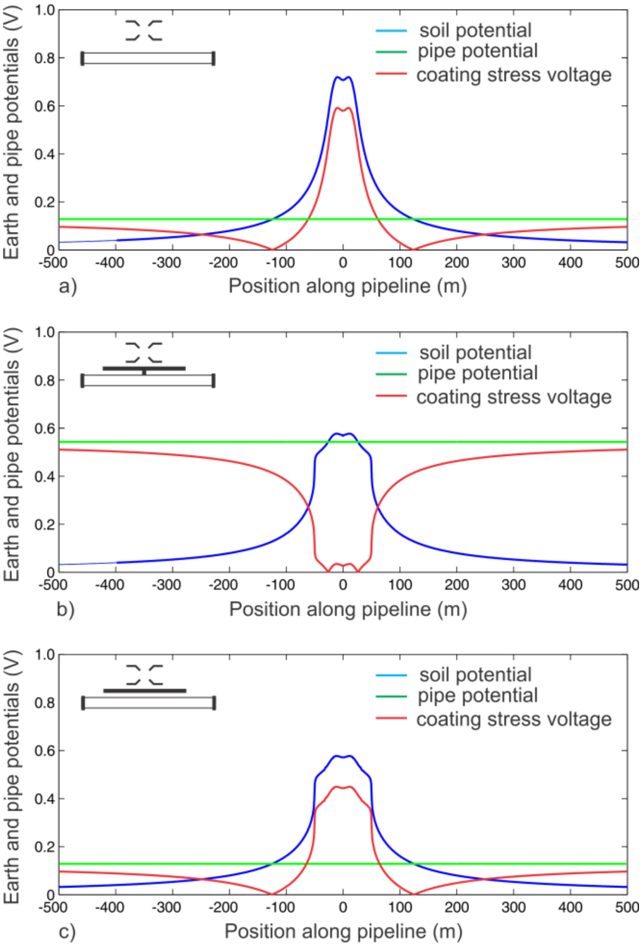

Fig.4. Soil potential, pipe potential and coating stress voltage in three scenarios:a) without using mitigation, b) with 100m FeZn ribbon in the same trench with pile and connected to pipe, c) with 100 m FeZn ribbon detached from pipe (normalized values per dissipated current of 1 A through the tower grounding)

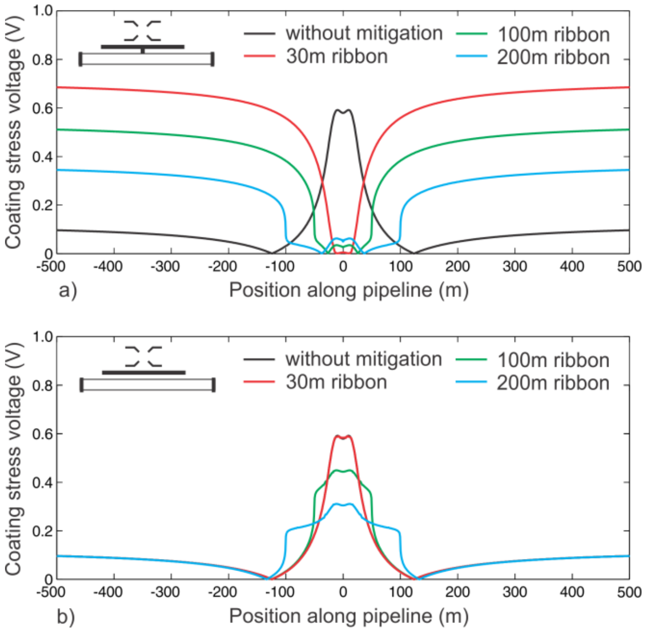

Fig.5. Coating stress voltages for different lengths of FeZn ribbon for two scenarios:a) FeZn ribbon attached to pipeline, b) FeZn ribbon detached from pipeline (normalized values per dissipated current of 1 A through the tower grounding)

## Effectiveness of the mitigation for different pipe lengths

The effectiveness of the analyzed mitigation methods for conductive coupling is compared for three pipeline lengths: 1 km, 2 km and 5 km, considering attached or detached FeZn ribbon with length of 200 m. The other electrical and geometrical parameters of the systems are maintained as the ones described in the previous section.

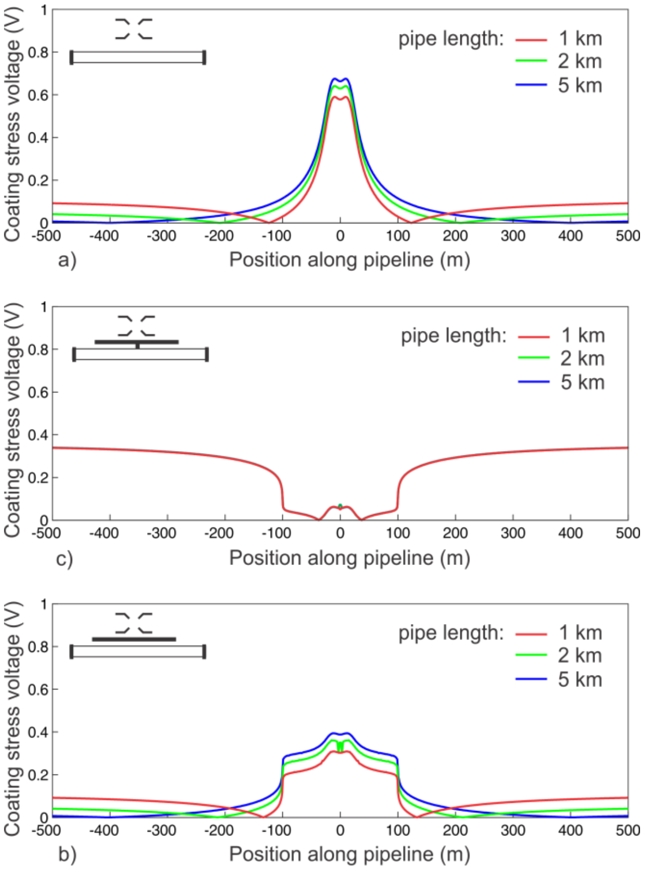

Fig.6. Variation of coating stress voltages with respect to pipeline length for three scenarios:a) without using mitigation, b) with 200m FeZn ribbon in the same trench with pile and connected to pipe, c) with 200 m FeZn ribbon detached from pipe (normalized values per dissipated current of 1 A through the tower grounding)

Results of the analysis are provided in Fig. 6, for three different scenarios. In the first scenario in Fig. 6a, with the increase of the pipeline length, larger portion of the pipeline extends beyond the zone of conductive interference and the mean value of soil potentials along its length is reducing. Since the distribution of soil potentials remains almost constant regardless of the pipe length, the reduction of the pipe potentials leads to increasing coating stress voltages with the increasing pipeline length.

The scenario in Fig.6 c, with detached FeZn ribbon from the pipeline, provides better reduction of the coating stress voltages compared with the scenario in Fig. 6b, with attached FeZn ribbon to pipeline. Although the coating stress voltages in Fig. 6c increase with increasing pipeline length, considering the results in Fig. 6a, it can be observed that the reduction factor of coating stress voltages and therefore the efficiency of this mitigation method remain constant regardless of the pipeline length. One approach to deal with the increasing coating stress voltages is to further increase the length of detached FeZn ribbon with the increase of the pipeline length.

## Conclusions

In this paper, we have analysed the effects of multilayer soil on the coating stress voltages on pipelines, which can be induced due to conductive coupling with HV transmission line tower grounding in fault conditions. We have also analysed the effectiveness of some commonly used mitigation techniques for dealing with conductive coupling.

Analysis show that coating stress voltages are strongly affected by the characteristics of the multilayer soil, and that severity of the induced voltages is proportionally related to the specific resistivity of the deeper soil layers. However, accurate calculation of these voltages requires proper treatment of the characteristics of the multilayer soil, and the use of simplified model of uniform soil can introduce significant error in the calculated voltages.

The obtained results for the analysed scenarios show that the use of FeZn ribbon buried parallel and close to the pipeline between the pipeline and tower grounding electrodes, which is detached from the pipeline and spans beyond the interfering zone, can serve as simple and optimal protection method for dealing with the conductive coupling. However, analyses also show that optimal design of such mitigation requires case-specific and accurate modelling of the electromagnetic interactions between the coupled systems.

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