Analysis of the electromagnetic impact of traction networks featuring reactive power compensation on pipelines

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Abstract. This paper presents a comprehensive numerical methodology for evaluating the electromagnetic interaction between traction power supply systems and nearby pipelines. Particular attention is given to the influence of reactive power compensation devices, which significantly affect current distribution and electromagnetic field characteristics. The developed model is based on phase-coordinate representation and enables accurate analysis under asymmetrical operating conditions. The investigated system includes a multi-source power network, traction substations, and a pipeline located parallel to a railway line. Simulation results show that the implementation of reactive power compensation leads to considerable variations in induced voltage levels, ranging from −14% to +31%. The proposed approach provides a universal tool for assessing electromagnetic compatibility in traction systems and can be applied to both existing and future high-voltage railway networks.

1 Introduction

Positioning metallic pipelines near electrified railway systems leads to a pronounced electromagnetic interaction. Traction networks generate time-varying electromagnetic fields that induce voltages in adjacent conductive structures, thereby posing safety risks and adversely affecting corrosion protection systems [1]. Considerable research has been dedicated to electromagnetic interference between power transmission lines and pipelines, placing special emphasis on the prediction of induced voltages and the characterization of

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current distribution [2–6]. Additional studies have examined alternating current interference, environmental influences, and fault conditions affecting electromagnetic coupling [7–11]. Despite these efforts, most available models assume symmetrical three-phase systems. In contrast, traction networks are inherently asymmetrical and operate under dynamic loading conditions, which significantly influence electromagnetic field distribution. Furthermore, modern traction systems increasingly incorporate reactive power compensation devices to improve efficiency and stabilize voltage levels. These devices alter current distribution and electromagnetic fields, but their impact on nearby pipelines is not sufficiently represented in existing models [12, 13]. The purpose of the present work is to establish a comprehensive modeling framework that takes these factors into consideration and facilitates accurate quantification of electromagnetic interference occurring between traction networks and pipelines.

Examination of the aforementioned studies leads to the following conclusions:

• Modeling the effects of power transmission lines and traction networks is critically important, as it is necessary for safeguarding personnel and reducing the detrimental impact of induced currents on electrochemical corrosion protection systems.

• Existing research on electromagnetic interference with pipelines predominantly addresses the effects arising from three-phase power transmission lines.

• A universal methodology for calculating the influence of traction networks is absent from the works reviewed.

Furthermore, reactive power compensation devices, which are commonly employed in AC traction networks, can alter the induced voltages and currents in pipelines. Nevertheless, these devices are frequently not fully considered in existing studies. This paper reports the findings of digital modeling conducted to assess the impact of traction networks on pipelines, with due attention to reactive power compensation.

2 Methodology

2.1 Physical background

The interaction between traction networks and pipelines is determined not only by electrical operating conditions but also by their spatial arrangement. Because traction systems are inherently asymmetrical, induced voltages can exceed allowable limits even during normal operation.

The induced voltage depends on:

- system operating mode;
- relative positioning of the pipeline;
- separation distance;
- length of parallel alignment.

Two primary mechanisms are involved:

- capacitive coupling caused by electric fields;
- inductive coupling resulting from alternating magnetic fields.

2.2 2Mathematical framework

The calculation of electromagnetic coupling is traditionally based on the Carson integral, which describes field propagation in conductive media.

However, classical analytical solutions are limited in accuracy for intermediate distances. To address this limitation, a numerical approach based on phase-coordinate modeling is employed. This method allows accurate representation of asymmetrical conditions and enables consistent evaluation across all spatial regions.

2.3 Computational approach

The developed methodology integrates:
- electric power system models;
- traction power supply systems;
- pipeline models;
- reactive power compensation devices.

The approach enables:
- simulation of steady-state and transient conditions;
- unified evaluation of induced voltages;
- analysis of complex system configurations.

3 Modeling results

The improved calculation method for determining operating parameters of complex electric power systems using phase coordinates allows for precise quantification of mutual electromagnetic interference across the near, intermediate, and far zones of the Carson integral. This approach employs asymptotic approximations for the near and far ranges, whereas the intermediate range is handled by directly evaluating the series expansion of the integral.

The traction network's electromagnetic influence was evaluated using the modeling methods and algorithms for traction power supply systems, which are realized in the Fazonord software package. The model includes both shunt and series compensation configurations (schematic diagrams in Figures 1 and 2). Simulations were carried out for the power supply system shown in Figure 3, consisting of an external network with four 220 kV lines and three traction substations (TS) that supply the catenary system (CS) of a double-track section. For clarity, Figure 3 illustrates the catenary system for only one track.

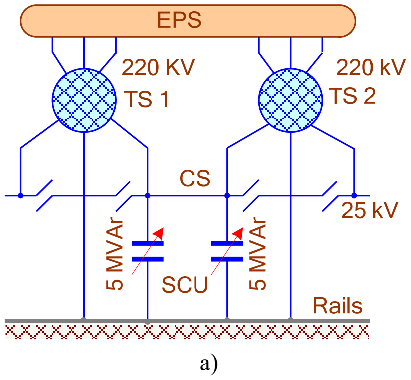


Fig. 1. Schemes for connecting shunt compensation units (SHCU): a) – at catenary system (CS); b) – at section pillar (SP)

The inter-substation zone model incorporated a 250 mm diameter pipeline positioned parallel to the railway at a distance of 50 m. Distributed grounding of the pipe was considered, with a conductivity of 0.05 S/km. Additionally, grounding electrodes were assumed to be installed at both ends of the pipeline, each having a ground resistance of 1 Ω.

Figure 4 presents a schematic diagram of the model for the traction network and pipeline system. Train traffic involving seven trains operating in both directions is illustrated in Figure 5, while Figure 6 shows the currents drawn by the electric locomotives.

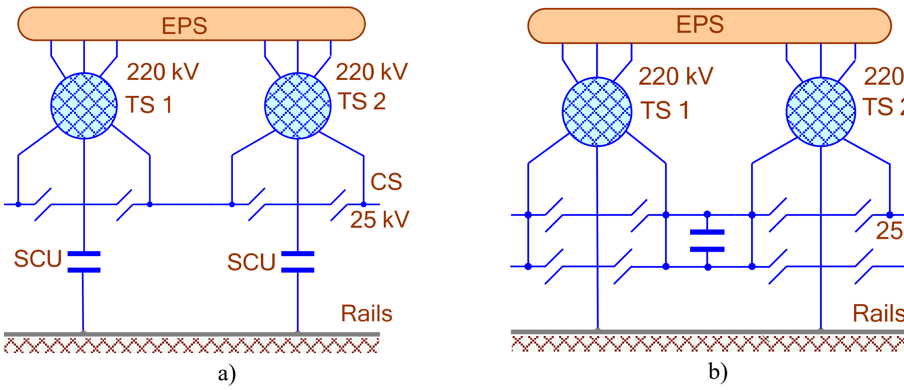


Fig. 2. Schemes for connecting series compensation units (SCU): a) – SCU in a rail feeder; b) – inter-track compensation unit

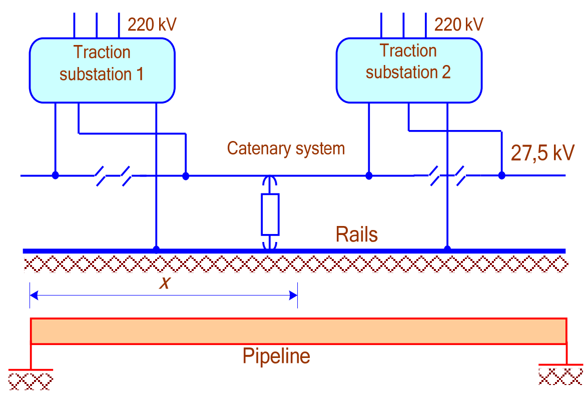


Fig. 3 Scheme of approaching traction network and pipeline

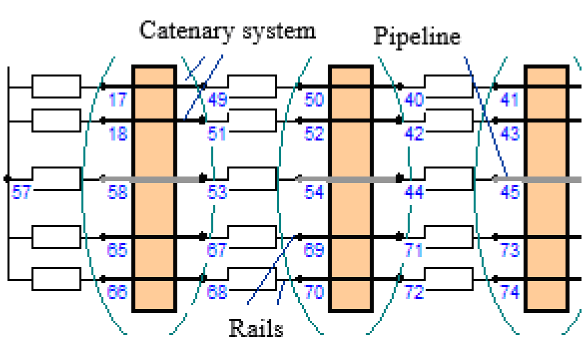


Fig. 4. Segment of the computational model diagram pertaining to the traction network and pipeline.

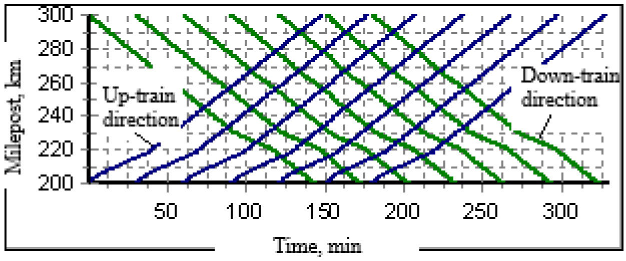
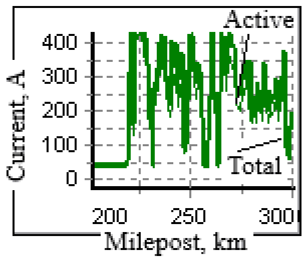


Fig. 5. Train traffic schedule: mileposts refer to distance markers placed along railway lines.



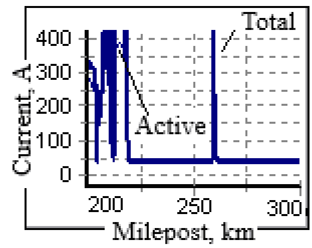


Fig. 6. Currents consumed by electric locomotives (a, b): a) – down trains weighing 6 300 tons; b) – up trains weighing 6 000 t.

The modeling of induced voltages and currents took into account the high harmonics produced by rectifying electric locomotives. The effective values were then calculated using the following expressions:

$$U_\Sigma = U_1\sqrt{1+\left(\frac{k_U}{100}\right)^2}\,;\; I_\Sigma = I_1\sqrt{1+\left(\frac{k_I}{100}\right)^2} \tag{1}$$

where k_U, k_I are total harmonic factors for voltage and current.

The modeling results are presented in Figures 7–11 and in Tables 1. Figure 7 shows the relation $U_\Sigma = U_\Sigma(t)$, obtained for the point corresponding to the coordinate x = 20 km. Figure 9 and 10 demonstrate the graphs $U_1 = U_1(t)$, $I_1 = I_1(t), U_\Sigma = U_\Sigma(t)$, $I_\Sigma = I_\Sigma(t)$, which correspond to the maxima of respective parameters.

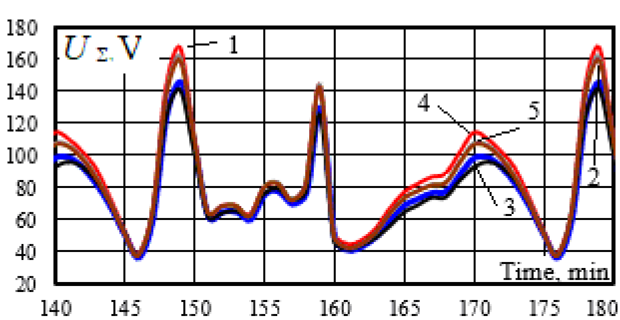
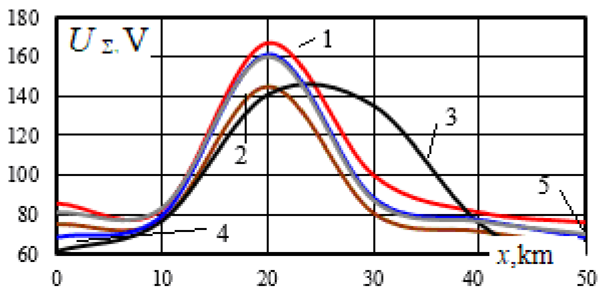
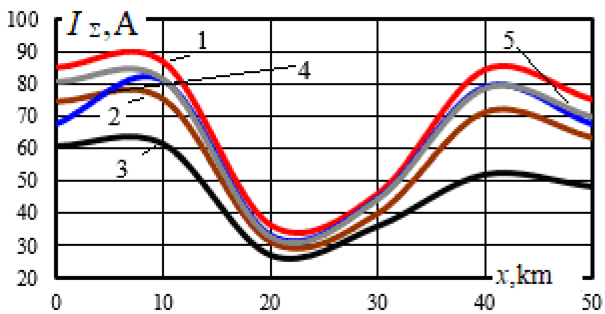


Fig. 7. Induced voltage as a function of time at coordinate x = 20 km under various compensation scenarios: 1 – inter-track compensation unit (CU); 2 – SHCU at traction substation; 3 – SHCU at section pillar; 4 – SCU in the rail feeder; 5 – no compensation



a)



b)

Fig. 8. Dependence of the maximum effective induced voltage (a) and current (b) on the x-coordinate.

Tables 1 depict the differences in maximum values of U_{Σ} for the scenarios with and without compensation. The specified parameters are illustrated in Figures 10 and 11. Figure 12 shows the coordinates of the points for the maximum differences U_{Σ} and I_{Σ}.

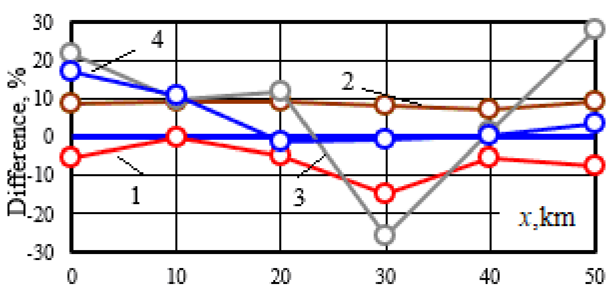


Fig. 9. Differences in maximum values of U_{Σ}: 1 – inter-track SCU; 2 – SHCU at TS; 3 – SHCU at SP; 4 – SCU in the rail feeder

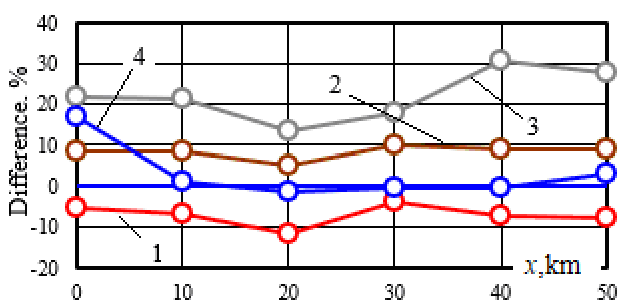
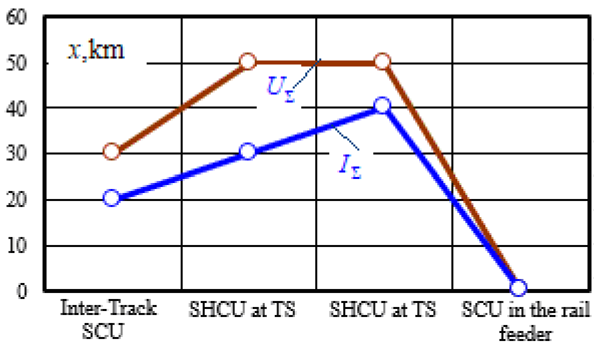


Fig. 10. Differences in the maximum values of I_Σ: 1 – inter-track SCU; 2 – SHCU at TS; 3 – SHCU at SP; 4 – SCU in the rail feeder

Table 1 Differences in the maximum values of U_Σ for the scenarios with and without compensation

Installation site	*x*, km					
	0	**10**	**20**	**30**	**40**	**50**
Inter-track compensation unit	–5.23	1.40	–4.82	–14.30	–5.31	–7.43
SHCU at TS	7.99	7.73	9.11	7.95	7.34	9.65
SHCU at SP	24,75	8,23	11,88	–54,81	1.92	30.88
SCU in the rail feeder	16.33	5.32	–1.09	–0.93	–0.26	3.53



Fig, 11. Coordinates of points of maximum differences for U_Σ and I_Σ

The obtained results permit the following conclusions:

• Reactive power compensation units induce changes in both the voltages induced on distinct pipeline segments and the currents flowing in the pipe.

• The installation of inter-track compensation units at x = 0, 20, and 30 km results in a reduction of peak UΣ values by 5% to 14%. At x = 10 km, UΣ rises by 1.4%, whereas IΣ falls by 4%–11%. These units, though not commonly employed, may prove useful when catenary currents differ substantially between tracks.

• The presence of SHCU at traction substations leads to increases in UΣ and IΣ of 7%–10% and 6%–11%, respectively.

• With SHCU positioned at the sectioning post, UΣ rises at all measurement locations except at x = 30 km, where a 55% decrease is observed. The currents flowing through the pipe increase by 17% to 34%;

• Connecting compensation units to the rail feeder causes U_Σ to increase at x = 0, 10, and 50 km, and to decrease at x = 20, 30, and 40 km. The variation in I_Σ follows a trend analogous to that of U_Σ.

4 Conclusion

A comprehensive modeling methodology for evaluating electromagnetic interaction between traction networks and pipelines has been developed. The study confirms that traction networks, characterized by inherent operational asymmetry, generate substantial electromagnetic interference in nearby pipelines. Importantly, reactive power compensation devices are shown to exert a strong influence on induced voltage levels, with effects that vary depending on device type and placement. Accurate assessment of these interactions is only possible through an integrated modeling framework that incorporates all system components, including supply networks, traction substations, catenary systems, rail return paths, compensation units, and pipeline grounding. The proposed methodology offers a practical and versatile tool that can be applied during the design, operation, and modernization of traction power supply systems. Its use enables the identification of hazardous zones, the optimization of compensation strategies, and the effective protection of pipelines from electromagnetic interference, thereby ensuring both personnel safety and electromagnetic compatibility.

This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.013-0001-C01.

References

1. A. Kryukov, H. Beloev, D. Seredkin, E. Voronina, A. Kryukov, I. Iliev, I. Beloev, K. Suslov, Modeling of Electromagnetic Fields Along the Route of a Gas-Insulated Line Feeding Traction Substations. Energies. **19(3),** 624 (2026)
2. L. Chen, Y. Du, Y. Liang, D. Zhuang, Z. Zhu, Z. Jiang, L. Zhang, Research on numerical modeling of AC interference from high-speed railway to nearby buried pipeline. Electric Power Systems Research. **228**, 110047 (2024). https://doi.org/10.1016/j.epsr.2023.110047
3. B. Milesevic, B. Filipovic-Grcic, T. Radosevic. Electromagnetic Fields and Induced Voltages on Underground Pipeline in the Vicinity of AC Traction System. Journal of Energy and Power Engineering. **8**, 1333-1340 (2014)
4. M. Hoger, M. Regula, P. Bracinik, A. Otcenasova. Influence of high voltage power lines on the propagation of stray currents from DC traction. Elektro. (2022). https://doi.org/10.1109/ELEKTRO53996.2022.9803410
5. C. Wang, S. Xu, W. Li, Y. Wang, G. Shen, S. Wang, Multi-physics coupled simulation and experimental investigation of alternating stray current corrosion of buried gas pipeline adjacent to rail transit system. Materials & Design. **247**, 113394 (2024).
6. Q. Tao, B. Suna, S. Bingran, Y. Tao, M. Yunfei, Y. Xinliang, Analysis of Electromagnetic Influence Between High-voltage AC Transmission Lines and Buried Oil and Gas Pipelines. in Proceedings of 2018 China International Conference on Electricity Distribution (CICED), Tianjin, China, 17-19 September (2018) https://doi.org/10.1109/CICED.2018.8592579
7. D. D. Micu, G. C. Christoforidis, L. Czumbil, AC interference on pipelines due to double circuit power lines: A detailed study. Electric Power Systems Research. **103**, 1-8 (2013). https://doi.org/10.1016/j.epsr.2013.04.00
8. A. Popoli, L. Sandrolini, A. Cristofolini, Reduction in the electromagnetic interference generated by ac overhead power lines on buried metallic pipelines with screening conductors. Electricity. **2**, 316–329 (2021). https://doi.org/10.3390/electricity2030019
9. X. Wang, Y. Wang, T. Sun, X. Yang, L. Yang, Y. Qi, Study of the coupling interference of high-voltage transmission lines on adjacent buried steel pipelines based on CDEGS. Electric Power Systems Research. **217**, 109125 (2023). https://doi.org/10.1016/j.epsr.2023.109125
10. G. Christoforidis, D. Labridis, Inductive Interference on pipelines buried in multilayer soil due to magnetic fields from nearby faulted power lines. IEEE Trans on Electromagnetic Compatibility. **47**(2), 254-262, (2005). https://doi.org/10.1109/TEMC.2005.847399

11. L. Qi, H. Yuan, L. Li, X. Cui. Calculation of Interference Voltage on the Nearby Underground Metal Pipeline due to the Grounding Fault on Overhead Transmission Lines. IEEE Transactions on Electromagnetic Compatibility. **55(5)**, 965–974, (2013). https://doi.org/10.1109/TEMC.2013.2240391
12. A. Popoli, A. Cristofolini, L.Sandrolini, Dataset for calculating the currents and voltages induced on underground pipelines by nonparallel overhead power lines. Data in Brief. **30**, 105643 (2020). https://doi.org/10.1016/j.dib.2020.105643
13. W. Mu, Z. Zhao, Y. Zhu, X. Lei, A rapid modeling for analysis the effect of transmission line to oil and gas pipeline. in Proceedings of 2016 Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC). Shenzhen, China, 17-21 May (2016). https://doi.org/10.1109/APEMC.2016.7522916