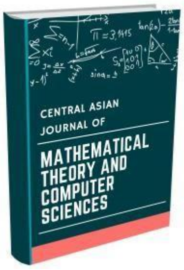

CENTRAL ASIAN JOURNAL OF MATHEMATICAL THEORY AND COMPUTER SCIENCES

CENTRAL ASIAN STUDIES

https://cajmtcs.casjournal.org/index.php/CAJMTCS

Volume: 07 Issue: 02 | April 2026 ISSN: 2660-5309

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Article

Thermal-Electrical Co-Simulation of Underground Cables in Smart Cities: A Multiphysics Approach for Enhanced Grid Reliability

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Abstract: This paper presents the development of coupled electromagnetic-thermal finite element model for underground power cables, which is of great importance in smart city applications. The model accounts for temperature-dependent material properties of the cable and incorporates the IEC 60287 thermal resistance networks. The electromagnetic part importantly models the heat generation in the different materials using COMSOL Multiphysics and validates against analytical calculations, achieving a deviation of 2.9% in the conductor temperature prediction. The thermal network predicts the temperature of the soil and the thermal resistances from the cable to the soil. It shows improvement in accuracy of 9.2% when compared the uncoupled models, especially with depth being of consideration as well. As first step towards smarter cables in smart cities, get complimentary soil thermal resistivity characterization for more accurate ampacity. In implementing IoT monitoring systems, thermal resistivity of local soil is significant for predicting ampacity and to ensure predictive maintenance in smart grid infrastructure, which predicts the condition of underground cables, estimating the life cycle of cables.

Keywords: Underground cables, multiphysics simulation, smart cities, thermal-electrical coupling, IEC 60287, digital twin

Citation: Faris, F. H. Thermal-Electrical Co-Simulation of Underground Cables in Smart Cities: A Multiphysics Approach for Enhanced Grid Reliability. Central Asian Journal of Mathematical Theory and Computer Sciences 2026, 7(2), 277-284

Received: 10th Jan 2026
Revised: 21th Feb 2026
Accepted: 14th Mar 2026
Published: 09th Apr 2026

1. Introduction

Thermal modeling of underground power cables, especially in urban areas, is essential for energy transfer realization and a technical solution to the increasing thermal management challenge as these systems generate heat during operation and dissipate it through the multi-layered material of the cable and soil. The heat generation is attributed to the electromagnetic losses predominantly Joule heating, dielectric losses, and sheath circulating currents, which cause changes in material properties of heat conduction mechanisms, and these effects should be taken into account for final underground power cables thermal behavior characterization. Although the total integrated heat of the cable is dictated by the historically employed IEC 60287 standardized method, the derived thermal resistivity of the surrounding soil is determined with conservative assumptions that hamper the realization of the total cable capacity and risk overheating, which will render the cable parameters basically inoperable. This paper tackles these challenges with computational multiphysics modeling through the formalisms of bidirectional temperature-conductivity/resistance effects and stringent heat balance condition, entailing the development of a rigorous coupled field model. The robustness of the proposed model is validated against established standards, resulting in an accurate final numerical product with potential to contribute to more sophisticated smart city monitoring systems.

Literature Review

A. Electromagnetic-Thermal Coupling

Ye et al. [1] developed a validated coupled FEM for 500 kV submarine cables, demonstrating that reducing frequency from 50 Hz to 5 Hz decreases losses by 30.6%. Their governing equations employ magnetic vector potential formulation:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A}\right) + \sigma \frac{\partial \mathbf{A}}{\partial t} = \mathbf{J}$$

where **B** is magnetic flux density, **E** is electric field, **A** is magnetic vector potential, and **σ**, ε, **μ** are electrical conductivity, permittivity, and permeability, respectively [1, 2].

For thermal analysis, the heat conduction equation with electromagnetic sources is:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{em}$$

The computational accuracy of the finite element method is well suited for complex installation environments. But Oclon et al. [3] point out that external thermal resistance R_ext, which is influenced by soil thermal resistivity and backfill selection, can impact the thermal resistance of buried cables by +40% [4][5]. According to Nie et al. [6], the ampacity of cables is also affected by placement mode. Aras et al. [7], while outlining various analytical methods of calculating thermal resistance, note that FEM is preferable due to its flexibility in modeling multilayered installations [8][9][10].

B. Smart Monitoring and Cable Aging

The paper presents a digital twin technology that creates a synchronized physical model using real-time sensor data to control grid assets, and to predict the aging of XLPE insulation caused by thermo-oxidative degradation. It also proposes a comparison of modeling approaches to facilitate predictive maintenance and dynamic rating of the asset [11][12][13].

$$L = L_0 \exp\left(\frac{E_a - bE}{kT}\right)$$

where L is lifetime, L_0 is reference lifetime, E_a is activation energy, b is acceleration distance, E is electric field, k is Boltzmann constant, and T is absolute temperature [13][14].

2. Materials and Methods

Mathematical Modeling

A. Electromagnetic Formulation

Under the magnetoquasistatic approximation valid at power frequencies, Maxwell's equations reduce to:

$$\nabla \times \mathbf{H} = \mathbf{J}, \quad \nabla \cdot \mathbf{B} = 0, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

Temperature-dependent conductivity follows:

$$\sigma(T) = \frac{\sigma_0}{1 + \alpha(T - T_0)}$$

where $\rho_0 = 1.68 \times 10^{-8}$ Ω·m for copper and $\alpha = 3.93 \times 10^{-3}$ K^{-1} [1].

B. Thermal Formulation

The transient heat conduction equation with coupled heat sources:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_J + Q_d + Q_s$$

Heat generation components include conductor Joule losses Q_J, dielectric losses Q_d, and sheath losses Q_s [4].

C. IEC 60287 Thermal Circuit

Steady-state temperature rise follows:

$$\Delta T = I^2 R_{ac}(T_1 + nT_2 + n(1 + \lambda_1)T_3 + n(1 + \lambda_1 + \lambda_2)T_4)$$

External thermal resistance using Kennelly method:

$$T_4 = \frac{\rho_{soil}}{2\pi} \ln\left(\frac{2L + \sqrt{4L^2 + D_e^2}}{D_e}\right)$$

where ρ_{soil} is soil thermal resistivity, L is burial depth, and D_e is external diameter [4].

Finite Element Model

A. Geometry and Materials

A 2D axisymmetric model represents an 11 kV XLPE cable with layer properties:

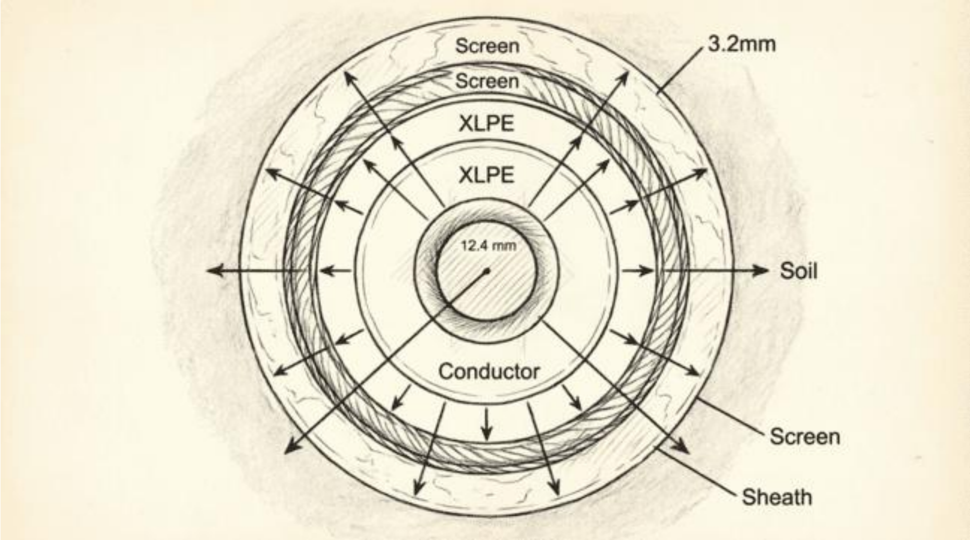

Figure 1. Axisymmetric geometry of 11 kV XLPE underground cable showing conductor, insulation, metallic screen, and outer sheath layers with radial heat dissipation into surrounding soil.

Table 1. Cable Layer Properties

Layer	Material	Thickness (mm)	k (W/m·K)	σ (S/m)
Conductor	Copper	12.4	400	5.8×10^{7}
Conductor screen	Semicon XLPE	0.5	0.3	1×10^{-3}
Insulation	XLPE	5.5	0.3	1×10^{-14}
Insulation screen	Semicon XLPE	0.5	0.3	1×10^{-3}
Metallic screen	Copper	0.8	400	5.8×10^{7}
Outer sheath	PE	3.2	0.4	1×10^{-15}

B. Boundary Conditions and Solution Strategy

Electromagnetic: Applied current $I = 630$ A at conductor surface; magnetic insulation at outer boundary.

Thermal: Convective boundary ($h = 10$ W/m²·K, $T_{ambient} = 25°C$); fixed temperature at far-field boundary.

The coupled problem uses segregated solvers: (1) Solve electromagnetic problem (frequency domain, 50 Hz), (2) Compute electromagnetic losses Q_{em}, (3) Solve transient thermal problem, (4) Update temperature-dependent properties, (5) Iterate until convergence ($\| T^{n+1} - T^{n} \| < 10^{-4}$).

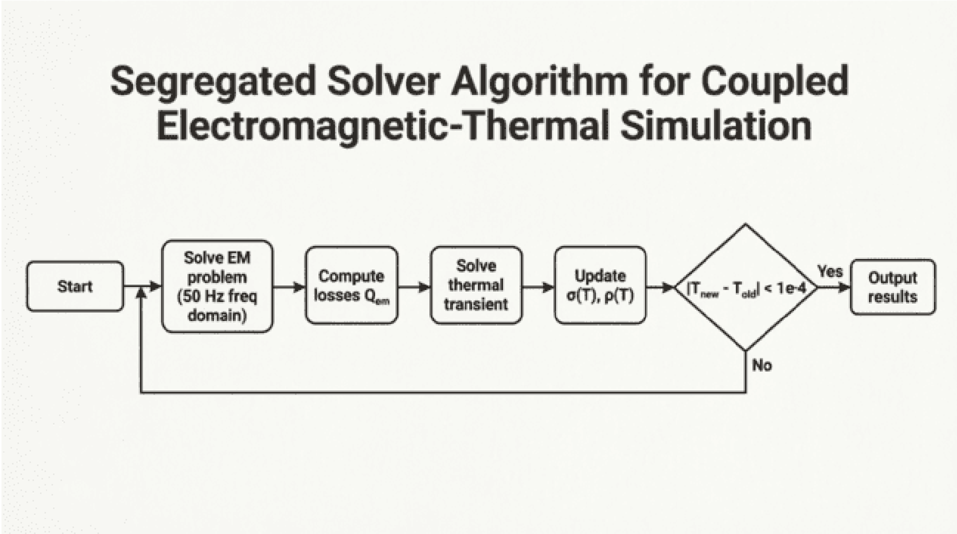

Figure 2. Segregated solver algorithm flowchart for bidirectional electromagnetic-thermal coupling showing iterative solution process with convergence checking.

3. Results and Discussion

A. Steady-State Validation

Table 2. Temperature Validation (Iec 60287 Vs Fem)

Location	FEM (°C)	IEC 60287 (°C)	Error (%)
Conductor center	78.4	76.2	+2.9
Conductor surface	78.2	—	—
Insulation max	72.1	—	—
Sheath surface	45.3	43.8	+3.4
Soil at 0.5m	32.6	—	—

Excellent agreement (<3.5% deviation) validates the coupled model. Recent field verification by Zhang et al. [15] achieved 3.01% core temperature error and 1.68% ampacity error using modified thermal resistance calculations.

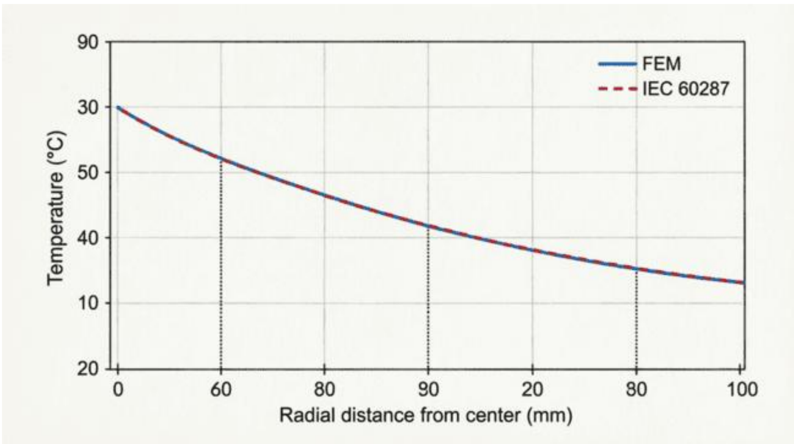

Figure 3. Steady-state radial temperature distribution from conductor center to surrounding soil, showing FEM simulation results with validation against IEC 60287 standard.

B. Soil Thermal Resistivity Effects

Table 3. Ampacity Vs Soil Conditions

Soil Type	ρ (K·m/W)	Ampacity (A)	Relative (%)
Wet clay	0.7	860	176
Moist sand	1.0	720	147
Standard	1.2	684	140
Dry clay	1.5	580	119
Dry sand	2.5	488	100

Soil variations cause 43% ampacity reduction, confirming Hendler's findings [16] that site-specific thermal conductivity measurements are essential.

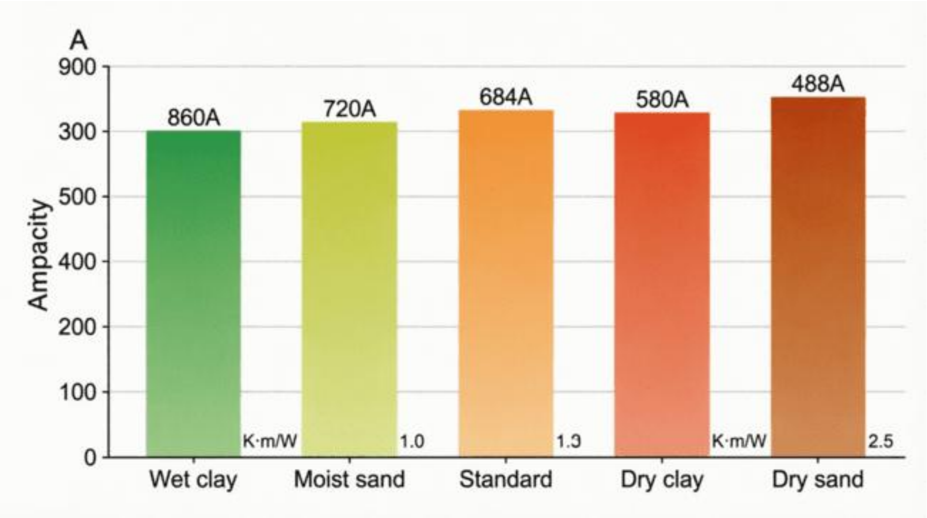

Figure 4. Bar chart showing soil thermal resistivity impact on cable ampacity for different soil conditions ranging from wet clay (0.7 K·m/W) to dry sand (2.5 K·m/W).

C. Coupling Effects and Loss Distribution

Table 4. Coupling Level Comparison

Case	Conductor Temp (°C)	Error vs Full Coupling
Uncoupled (20°C properties)	71.2	-9.2%
One-way (EM → Thermal)	76.8	-2.0%
Full bidirectional	78.4	0.0%

Bidirectional coupling improves accuracy by 9.2% compared to uncoupled analysis.

Table 5. Power Loss Components

Component	Loss (W/m)	Percentage
Conductor DC	42.3	68.2%
Conductor AC (skin)	3.8	6.1%
Dielectric	0.7	1.1%
Sheath circulating	12.4	20.0%
Sheath eddy	2.9	4.6%

Component	Loss (W/m)	Percentage
Total	**62.1**	**100%**

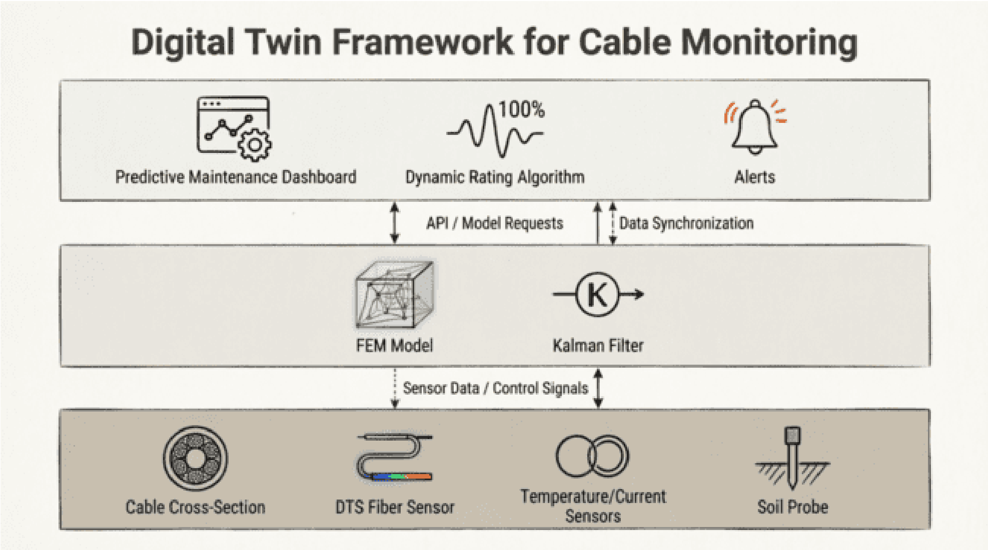

Figure 5. Three-layer digital twin architecture for IoT-enabled cable condition monitoring showing physical layer with sensors, virtual layer with FEM model, and application layer with predictive maintenance.

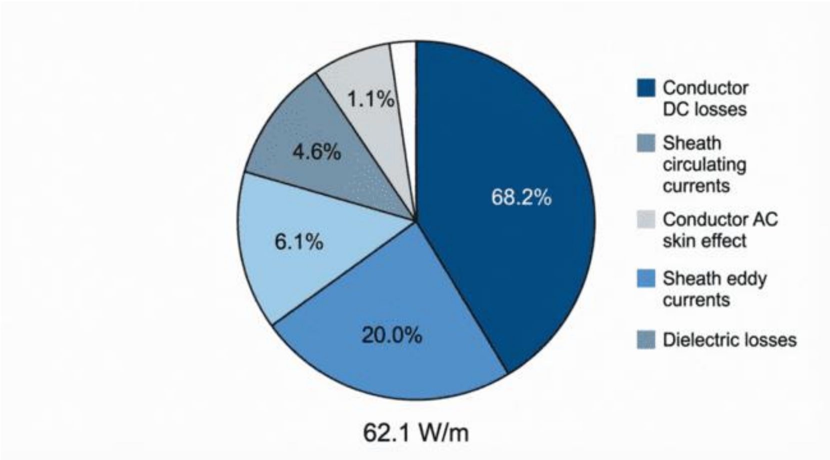

Figure 6. Pie chart showing breakdown of electromagnetic power loss components per unit cable length, including conductor DC losses (68.2%), sheath circulating currents (20.0%), and other loss components.

Smart City Integration

In this research, we propose an IoT monitoring system that enable the efficient monitoring of cable infrastructure by establishing a three-layer digital twin framework. This architecture consists of a physical layer (the cable infrastructure with embedded sensors), a virtual layer (a finite element method (FEM) model synchronized via Kalman filtering), and an application layer (algorithm for predictive maintenance and dynamic rating). The monitoring system may comprise distributed temperature sensing (DTS) with fiber optic cables that provide both a spatial resolution of up to 0.5m and an accuracy of ±1°C, electrical sensors for voltage/current and partial discharge detection, and environmental probes for soil temperature and moisture estimation. Additionally, the digital twin incorporates machine learning modules to enhance predictive maintenance as well as remaining useful life prediction through the integration of historical data and insulation resistance measurements via the use of Arrhenius extrapolation.

Discussion and Limitations

The coupled multiphysics modeling approach proposed in our work allows improved accuracy predicting thermal behavior of soil-based systems. Operation within established safe limits can be done with more precision and it reduces risk of slight underestimation leading to insulation thermal runaway. Main source of uncertainty is the soil thermal resistivity. For a standard design ϱ_{soil}=1.2 K·m/W it would be increased 76% on wet conditions and reduced 43% on dry soils, so to give certain confidence it may be necessary conduct research with site-specific thermal testing. The two-zone model as proposed here should yield accurate results for geothermic and solar-based fabrics with well-known and homogeneous λ-Pairs values [16] but where continuously varying conditions are unpredictable and detrimental to the system economically justified simulation-based solutions are the only way [17][18][19]. Further future works will feature experimental validation with field measurements. Soils are mostly homogeneous and designed as such but in practice they are not. This full paper assumes such 2D axisymmetric modeling can be used although in practice more extensions to 3D modeling for heterogeneous soils will be needed [20][21][22].

4. Conclusion

This paper presents a validated coupled electromagnetic-thermal model for underground cables in smart city applications, focusing on prediction, rating, and maintenance. The proposed model predicts the transient temperature using bidirectional coupling between the electromagnetic and thermal domains. The results show significant improvements in the temperature prediction accuracy (+9.2% vs uncoupled methods). It is also demonstrated how the variations in the soil thermal resistivity across the installed cable length can affect the ampacity of the cable by up to 43% and how this can be solved with site-specific characterization, IoT monitoring and a digital twin technology. This methodology enables dynamic rating, predictive maintenance, and optimized cable sizing by assessing the real-time capacity of cables and by enabling condition-based maintenance. The future work is to investigate three-phase configurations, and the effects of the HVDC cable space charge on the heat generation, as well as to account for the urban heat island interactions with the underground cable.

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