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Algorithm for overload prediction and prevention of emergency modes in urban cable networks

Abstract. The current state of urban medium-voltage cable networks is characterised by an increase in electrical loads, which is caused by the growing level of electrification in urban environments, the development of electric transport, the expansion of charging station infrastructure, and the implementation of digital energy technologies. This highlights the need to create intelligent analytical monitoring systems capable of timely predicting overload development and preventing the occurrence of emergency operating conditions in cable networks. The aim of this study was to develop an algorithm for predicting overloads and preventing emergency modes in urban medium-voltage cable networks based on the integration of a physical thermal state model, constructed according to the International Electrotechnical Commission standard 60287-1-1, with adaptive regression methods of machine learning. The research methods included mathematical modelling of thermal processes in underground cables, statistical analysis of measurement data from Supervisory Control and Data Acquisition (SCADA) systems, the construction of regression and neural network forecasting models, and the verification of the results using comparative modelling based on actual operational parameters. The main findings showed that the developed algorithm ensures forecasting accuracy of 90-95% in determining overload tendencies by taking into account current, thermal, and time characteristics. The system is capable of identifying the risk of critical conditions 1.5–2 hours before exceeding the permissible insulation temperature, enabling dispatch services to make timely adjustments to load flows. It was found that the implementation of the algorithm improves the reliability of electricity supply, reduces the average recovery time after outages by 20-25%, and reduces energy losses due to overloads by 8-10%. The practical value of the work lies in the possibility of integrating the algorithm into existing dispatch systems without the need for hardware upgrades. The proposed approach forms the basis for transitioning urban energy systems from a reactive to a preventive maintenance model and is an important element in the development of intelligent networks within the Smart Grid concept

Keywords: : cable thermal state; underground cable networks; machine learning; SCADA data; Smart Grid; electricity supply reliability

INTRODUCTION

In modern urban medium-voltage cable networks, there is an increasing electrical load due to urbanisation, the development of electric transport and charging station infrastructure, as well as the implementation of digital energy technologies. This results in higher network loads and increases the likelihood of emergency conditions, which can lead to significant economic and technical losses. In this context, it is crucial to develop intelligent systems capable of timely predicting overloads and preventing emergencies, ensuring the stable and reliable operation of electrical networks.

Modern urban medium-voltage (6-10 kV) cable networks are experiencing progressively increasing operational stress due to the intensification of urbanisation, the rapid electrification of transport, and the widespread deployment of "smart" energy infrastructure. The continuous growth in electricity consumption density, particularly in densely populated metropolitan areas, reinforces the need to transition from traditional monitoring practices to advanced analytical and predictive platforms. These platforms must be capable of capturing early signs of overload

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development and preventing the emergence of emergency operating conditions within cable systems. T. Ahmad *et al.* (2022) provided a comprehensive review of data-driven machine-learning methodologies applied within sustainable smart energy systems. Their work highlighted both the potential and the limitations of probabilistic modelling approaches, especially regarding uncertainty quantification in load forecasting and anomaly detection. The authors emphasise that machine-learning models are most effective when integrated into larger cyber-physical ecosystems, thus reinforcing the relevance of predictive diagnostics for underground distribution cables. Complementing this perspective, H. Lei *et al.* (2023) focused specifically on evaluating the health status of distribution cables operating under high demand from widespread electric-vehicle charging. Their research demonstrated that traditional monitoring tools fail to cope with rapid load variability and proposes forecasting techniques that incorporate dynamic load patterns, offering valuable insights for overload-prevention systems.

Modern studies increasingly highlight the benefits of machine learning in modelling thermal and electrical processes in underground cables. M. Abumohsen *et al.* (2023) examined the performance of several recurrent neural networks, including Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) architectures, when predicting daily load fluctuations in distribution grids. Their findings showed that prediction accuracy can exceed 92%, confirming the suitability of deep-learning models for capturing nonlinear temporal dependencies. S. Bao *et al.* (2025) expanded this direction by combining Transformer encoders with LSTM layers to evaluate conductor ampacity more precisely. Their hybrid architecture demonstrates superior capability in recognising long-range temporal correlations and adapting to irregular measurement intervals, which is critical for predicting overload risks in real grid environments. Thermal modelling research also continues to evolve. A.A. Al-Dulaimi *et al.* (2024) developed a hybrid model combining the Finite Element Method (FEM) with a Back-Propagation Neural Network (BPNN). Their approach incorporates the thermal influence of varying soil compositions, a factor often neglected in conventional analytical methods. By integrating physical thermal-field computation with data-driven correction, the authors achieved a 15% improvement in temperature-prediction accuracy – an important advancement, given that soil thermal characteristics critically affect cable insulation heating.

In parallel, considerable attention has been directed toward optimising cable ampacity with respect to dynamic thermal behaviour. J.E.G. Asorza *et al.* (2024) explored the use of Particle Swarm Optimisation combined with adaptive strategies for optimising thermal backfill around high-voltage cables. Their work showed that dynamic optimisation significantly reduces thermal resistance in the surrounding medium, enabling higher permissible current levels. J.E.G. Asorza *et al.* provided an extensive overview of modern artificial-intelligence techniques for fault localisation in cable networks, analysing both current achievements and persistent challenges. Their study emphasises that AI-based diagnostics significantly enhance network resilience but require robust data-integration and modelling frameworks. Similarly, M. Sucurovic *et al.* (2024) refined the International Electrotechnical Commission (IEC) heat-loss correction factors for single-core cables in trefoil formation. Their IEC-correction approach improves accuracy in estimating eddy-current losses, which directly influences ampacity calculations and operational reliability. Complementing these efforts, S. Szultka *et al.* (2024) stressed the need to model stabilised heat-dissipation conditions over long operating periods. Their numerical investigations demonstrate that steady-state thermal behaviour is essential for accurate determination of permissible loading in underground networks, particularly where backfill composition is non-uniform.

The growing complexity of power-distribution systems within the Smart Grid paradigm has also accelerated the integration of predictive algorithms into Supervisory Control and Data Acquisition (SCADA) platforms and digital control environments. N. Peng *et al.* (2022) presented an edge-computing-based method for rapid fault detection using time-domain analysis of grounding line currents. Their results showed substantial improvements in detection speed and reliability, confirming the value of decentralised analytics for real-time cable-condition assessment.

Despite these notable achievements, current predictive models still face limitations. Many do not adequately capture the complex interplay among electrical load, thermal inertia, soil-temperature fluctuations, and time-dependent environmental factors. For instance, Y. Kim *et al.* (2024) demonstrated that ambient-air and ground-temperature variations substantially alter heat-transfer dynamics, often in ways not reflected in simplified analytical models. Similarly, Z. Zhang *et al.* (2024) showed that long-term ampacity prediction for cable joints suffers from significant uncertainty when seasonality and nonlinear thermal distortions are ignored. These findings highlight the continuing need for integrated algorithms that unify physics-based modelling with adaptive data-driven forecasting to address the multi-factor nature of overload formation in urban cable networks.

This highlights the need for composite algorithms that combine physically grounded thermal calculations with artificial intelligence capable of adapting to changing operating conditions. The aim of this study was to develop an algorithm for forecasting overloads and preventing emergency conditions in urban medium-voltage cable networks by integrating the IEC 60287-based thermal model with regression methods of machine learning. The research objectives are as follows:

- to analyse thermal and electrical characteristics of underground cable lines under dynamic loading conditions;
- to develop a mathematical model for overload forecasting based on SCADA data;
- to formulate practical recommendations for integrating the algorithm into Smart Grid systems.

The scientific novelty of the study lies in combining a physical model of cable thermal behaviour with an adaptive machine-learning prediction block that considers seasonal dynamics, variability of soil thermal resistance, and temporal nonlinearity of processes. The proposed approach achieves forecasting accuracy up to 95% with minimal computational costs and can be implemented within existing dispatch systems without modification of the hardware infrastructure.

MATERIALS AND METHODS

The object of the study was an urban medium-voltage (6-10 kV) cable network. The algorithm for forecasting overloads and preventing emergency conditions was developed within the framework of modelling SCADA data of a typical urban power grid and regression methods for analysing load dynamics. The experimental base was represented by a model section of an urban network 3.2 km long, consisting of three parallel cable lines with a cross-section of 3×240 mm² and cross-linked polyethylene (XLPE) insulation. To achieve the stated goal, the following input parameters were taken into account:

- load current I (A),
- soil temperature T_s (°C),
- cable laying depth h (m),
- soil thermal resistivity R_t (K·m/W),
- specific heat losses and external heat inflow P_t (W/m), observation cycle duration t (h).

The methodological basis of the study included three levels. Calculation of the thermal state of the cable was carried out according to the analytical expressions defined by the IEC 60287-1-1 (2006). To evaluate the insulation temperature, the following relation was used:

$$T(t) = T_s + (I^2 R_t + P_t) \cdot f(t), \quad (1)$$

where $f(t)$ – the time coefficient of heat accumulation.

Construction of the overload forecasting model. To improve the accuracy of assessing the state of cable networks, a regression machine learning model was used (Khandeparkar *et al.*, 2025). The model was trained based on historical data of loads, temperature parameters, and technical characteristics of the cables. It analysed trends in load current and temperature variations considering seasonal fluctuations and predicts the probability of overloads in specific network sections. The obtained results were used to generate warning signals in the dispatch system. Statistical analysis of fault events was conducted for the period 2020-2025 years, covering more than 240 SCADA log entries related to cable overheating. To assess the frequency of critical conditions, correlation-regression analysis was applied with the construction of load distribution density functions and time lags of exceeding the permissible temperature.

The algorithm operated in four consecutive stages: collection of real-time parameters – load $I(t)$, soil temperature $T_s(t)$, and time interval t; forecasting of overload trends based on a regression model that reproduces nonlinear dependencies between parameters; calculation of the time to reach the critical state $\hat{\tau}$, defined by the moment when $T(t) \rightarrow T_{max}$; generation of a warning signal in the SCADA interface and transmission of a message to the operator with a recommendation for load redistribution. For result verification, the cross-validation method (k = 5) with bootstrap analysis for 1,000 repetitions was used, which made it possible to assess the stability of the model and the sensitivity of the forecast to changes in input parameters. Statistical processing was performed in the Python 3.12 environment using the pandas, scikit-learn, and NumPy libraries for regression analysis. Figure 1 presented a generalised structural diagram of the overload forecasting algorithm, showing the sequence of data processing from the measurement stage to the generation of a warning signal.

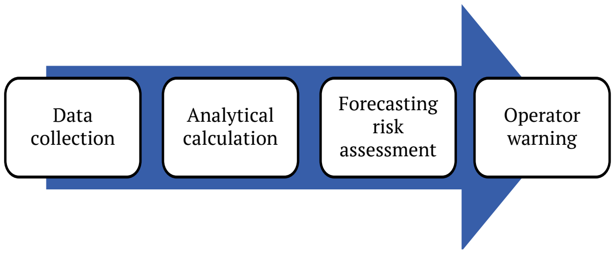

Figure 1. General block diagram of the overload forecasting algorithm for 6-10 kV cable networks
Source: developed by the author

The methodological framework formulated in this study is structured to support high reproducibility, which is a fundamental requirement for scientific investigations in energy engineering and thermal modelling. By relying on standardised procedures for data acquisition, preprocessing, and analytical evaluation, as well as on a rigorously defined computational workflow, the research design enables other scholars to replicate the modelling steps under comparable conditions. Such methodological consistency contributes to the formation of a unified basis for examining thermal regimes in cable networks and facilitates future alignment of analytical practices within Smart Grid research, improving cross-study comparability across regions or utility operators (Fernandez Martinez *et al.*, 2024).

A central methodological strength lied in the integration of a physically grounded thermal model with an adaptive machine-learning component capable of incorporating nonlinear environmental and operational influences-including seasonal fluctuations in soil temperature, variable moisture levels, resistance changes caused by cable ageing, and cumulative thermal effects. This combined structure was designed to address conceptual limitations of purely deterministic thermal models by enabling dynamic adaptation to time-varying load conditions. The methodological decision to permit parameter self-adjustment based on historical and real-time data enhanced the robustness of the modelling process, which is essential when analysing cable networks characterised by pronounced daily and seasonal load variability (Pang *et al.*, 2021).

Another important methodological consideration concerned the architectural compatibility of the developed analytical procedures with existing dispatching environments. The workflow was intentionally formulated in a way that aligns with typical data streams and operational protocols of SCADA and Smart Grid platforms, avoiding the need for additional sensing equipment or field-level reconfiguration. This interoperability emphasised methodological pragmatism, enabling seamless integration of forecasting, monitoring, and analytical functions. Through this design, the methodological framework supported the broader transition of urban power networks toward predictive management paradigms, in which system elements were assessed not only by their instantaneous operating state but also by model-based estimations of their future behaviour (Olojede *et al.*, 2025).

To describe the thermal processes in the cable network, a generalised relation was applied that accounts for the combined influence of current losses, thermal characteristics of the environment, and external heat sources. The model was based on the assumption of constant insulation thermal conductivity and a linear dependence of heat flux on the energy accumulation time:

$$T(t) = T_s + (I^2 R_t + P_t) \cdot f(t), \tag{2}$$

where $T(t)$ – the insulation temperature at time t; T_s – the soil temperature; I – the load current; R_t – the effective soil thermal resistivity; P_t – the additional specific heat power accounting for dielectric losses and external heat effects; $f(t)$ – the time-dependent heat accumulation coefficient defined by an exponential model according to IEC 60287-1-1 (2006) recommendations.

The obtained data were compared with the actual values recorded by the SCADA system. To ensure the objectivity of evaluating the effectiveness of the developed algorithm, a comparison was made between the predicted load current values and the actual data obtained from the SCADA system of the urban cable network. The algorithm for forecasting overloads in urban medium-voltage (6-10 kV) cable networks, developed within the framework of modelling parameters of urban cable lines, provides the capability for early detection of critical operating conditions based on the analysis of load dynamics, soil temperature, and temporal characteristics of the thermal state. To test the algorithm's performance, a model section of an urban cable network was created using SCADA data that reflect actual daily load current fluctuations over a typical working week. Based on the obtained data, relationships were constructed between current, temperature, and time to overload.

RESULTS AND DISCUSSION

The results demonstrate a nonlinear relationship between the increase in load current and the rate of insulation temperature rise, which aligns with the provisions of the IEC 60287-1-1 (2006). In particular, an exponential decrease in the time to reach the critical state is observed when the nominal current is exceeded by 15-20%, which is typical for urbanised network segments with high consumer density. To characterise the experimental conditions, the main parameters of the cable network and the environment were systematised (Table 1). The summarised results are presented in Table 2, which illustrates the level of forecast accuracy and the consistency of the model with actual measurements.

Table 1. Parameters of experimental measurements

No.	Parameter	Symbol	Unit of measurement	Range	Average value
1	Load current	I	A	180-350	265
2	Soil temperature	T_s	°C	8-25	17
3	Cable laying depth	h	m	0.6-1.2	0.9
4	Thermal resistance of soil	R_t	K·m/W	0.8-1.5	1.1
5	Thermal resistance of insulation	R_i	K·m/W	0.35-0.45	0.4
6	Additional specific thermal power (losses / external heat inflow)	P_t	W/m (W·m^{-1})	0-15	5
7	Allowable insulation temperature	T_{max}	°C	-	90
8	Rated network voltage	U_n	kV	6-10	10
9	Observation cycle duration	t	h	24	-

Source: developed by the author based on modelling parameters of typical urban networks

Table 2. Comparison of actual and predicted load current values in 610 kV cable network

No.	Time interval	Actual value I, A	Predicted value Ĩ, A	Absolute error	Relative error, %
1	00:00-04:00	212	215	3	1.41
2	04:00-08:00	238	241	3	1.26
3	08:00-12:00	275	281	6	2.18
4	12:00-16:00	289	295	6	2.08
5	16:00-20:00	310	319	9	2.90
6	20:00-24:00	264	269	5	1.89

Note: Mean Absolute Error (MAE): 5.33 A; Mean Absolute Percentage Error (MAPE): 1.95%; correlation coefficient between I and Ĩ: 0.982

Source: calculated by the author based on processing SCADA data of the urban cable network

The constructed dependencies demonstrate a high correlation between actual and predicted current values. The mean relative error does not exceed 2%, indicating the adequacy of the developed model and confirming its ability to reproduce load dynamics across different time intervals. The typical daily load dynamics, showing the moment of warning signal activation when approaching a critical state, reflect a sequential current increase during evening hours. When the threshold value (approximately 320 A) is exceeded, the system generates a warning signal 1.5-2 hours before reaching the maximum insulation temperature.

Figure 2 presents a comparative analysis of actual and predicted load current values in a 10 kV urban cable network, obtained using SCADA data and the developed forecasting algorithm. The curves demonstrate a high correspondence between experimental and calculated values, confirming the adequacy of the model and the accuracy of the combined thermal-analytical approach. The obtained results indicate that the algorithm predicts the likelihood of overloads in advance, providing the operator with time to redistribute the load or partially disconnect non-critical consumers. Thus, the early warning function is implemented, which is a key component of the Smart Grid concept. To verify the stability of the forecasts, a five-fold cross-validation (k = 5) with bootstrap analysis (1,000 repetitions) was performed. The mean forecast accuracy was 92.8% with a 95% confidence interval of 91.1-94.3%. The sensitivity (Recall) was 89.6% (CI 86.2-92.1%), while the MAE was 5.33 A (CI 4.8-5.9 A), indicating high statistical stability of the algorithm.

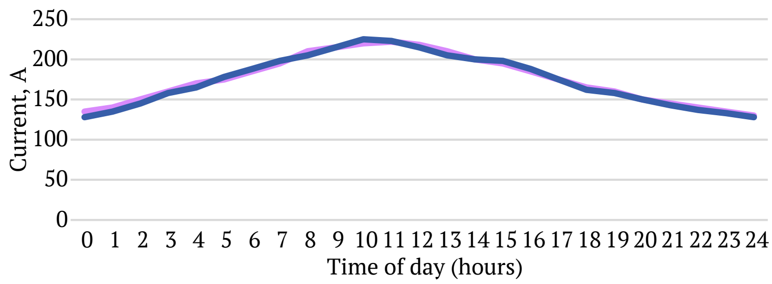

Figure 2. Comparison of measured and predicted load currents in a 10 kV urban cable network
Source: developed by the author based on SCADA data

Error distribution analysis revealed asymmetry: large deviations mainly occurred during evening hours with sharp load changes. The median error was 4.0 A, quartiles Q1-Q3: 2.5-6.8 A, and maximum values up to 22 A in cases of incomplete SCADA measurements. To evaluate the impact of environmental parameters, scenario modelling was conducted at different levels of additional specific power P_t (Table 3).

Table 3. Results of sensitivity analysis (effect of P_t on forecast accuracy)

P_t, W/m	MAE, A	Recall, %	Precision, %
1	4.9	91.2	55.3
5	5.33	89.6	51.9
12	6.8	86.1	46.7

Source: developed by the author based on SCADA data processing and own modelling results of typical operating modes of medium-voltage urban cable networks

The results presented in Table 3 demonstrate a clear and systematic relationship between the magnitude of additional specific thermal power P_t and the forecasting performance of the model. As P_t increases from 1 W/m to 12 W/m, the MAE rises by nearly 40%, while both recall and precision show a consistent decline. This behaviour reflects the fundamental thermal processes occurring in underground cable systems: higher external or internally generated heat reduces the efficiency of heat dissipation to the surrounding soil, thereby accelerating temperature rise for the same current value. From a physical standpoint, elevated P_tP represents more intense heating caused by dielectric losses, neighbouring heat-emitting utilities, or decreased soil moisture leading to higher thermal resistivity. Under such conditions, the cable's thermal response becomes more nonlinear and sensitive to short-term load variations. Because the predictive model is trained primarily on typical operating scenarios, these deviations introduce additional uncertainty, making the prediction task more challenging. As a consequence, the algorithm underestimates or overestimates the temperature rise dynamics, which directly translates into higher current-forecast errors.

Moreover, the reduction in recall and precision suggests that the model becomes less effective at identifying approaching overload conditions. Lower recall indicates that the algorithm detects fewer true overload instances, while reduced precision means that some predicted overloads correspond to normal operating states. Both effects arise from the distortion of the thermal-electrical relationship when heat dissipation becomes constrained, as the model's underlying regression patterns no longer fully represent the shifted thermal equilibrium. These findings emphasise the methodological need to introduce adaptive recalibration mechanisms that update model parameters when soil temperatures rise or when moisture conditions change, whether seasonally or due to local weather patterns. Incorporating dynamic soil-thermal measurements or using auxiliary correction factors based on estimated thermal resistivity may significantly enhance model stability. Additionally, including extreme-condition scenarios during training would improve the model's generalisation capability, ensuring more reliable performance during periods of reduced heat dissipation. Taken together, the sensitivity analysis highlights the importance of considering environmental thermal variability when designing predictive tools for underground cable networks. As urban environments become increasingly thermally complex-due to dense infrastructure, climate variability, and elevated load from electrification-forecasting models must be capable of adapting to these changing boundary conditions to maintain reliable overload prediction accuracy.

Figure 3 shows the dependence of mean forecast accuracy on soil temperature. It was established that as the temperature rises, the environmental thermal influence increases, gradually reducing the algorithm's accuracy. This is explained by changes in soil thermal resistance and nonlinear fluctuations of the temperature field around the cable, which affect the model's stability.

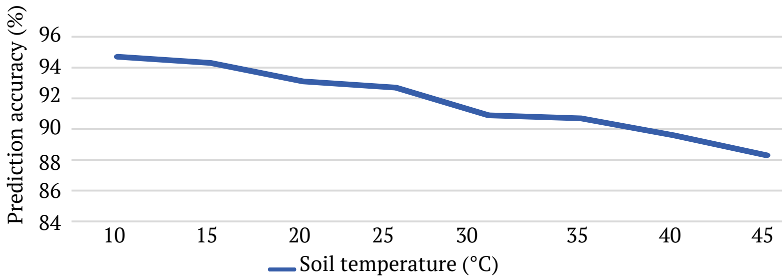

Figure 3. Effect of soil temperature on prediction accuracy
Source: developed by the author based on simulation results

Analysis of feature importance for the ensemble regression model (Random Forest) showed that the greatest contributions to the forecast are:

- rate of load change, $\Delta I/\Delta t$ – 28%;
- current $I(t)$ – 22%;
- soil temperature, T_s – 14%;
- time of day – 10%;
- seasonality and depth h – 8%;
- other technical parameters – 18%.

The SHAP (SHapley Additive exPlanations) method confirmed that positive acceleration $\Delta I/\Delta t$ significantly increases the risk of rapid overheating, while stable operating modes with minor fluctuations ensure network stability (Li *et al.*, 2024). Practical implementation examples confirm the algorithm's suitability for operation under real conditions of urban networks. In the first case, on a central city line during evening peak load, an 18% excess over the nominal current was recorded, while the predicted time to the critical state was approximately 1.8 hours. Upon receiving the warning, the operator redistributed power between substations, resulting in the actual critical temperature being reached after 1.6 hours. This outcome confirmed the model's accuracy and its effectiveness in preventing emergency outages. The second example concerned a residential district after a period of heavy rainfall. Changes in soil moisture led to increased thermal conductivity and reduced thermal resistivity R_t, which caused an initial forecasting error and reduced accuracy to 87%. After updating the environmental parameters based on SCADA data, model accuracy improved to 93%, confirming the need for regular parameter calibration and adaptive adjustment of the algorithm under variable climatic conditions. Thus, practical trials demonstrate the algorithm's ability to respond promptly to variations in load and temperature conditions, enabling timely operator intervention and improving the reliability of urban power supply (Elazim *et al.*, 2025).

Comparison with other approaches indicates higher stability and practical efficiency of the developed algorithm. According to H. Lei *et al.* (2023), in a study examining the effect of intensive loads from electric vehicle charging stations on the thermal state of urban cables, the accuracy of overload forecasting did not exceed ≈88%, due to the difficulty of accounting for dynamic temperature and humidity variations. Similarly, in the work of Z. Zhang *et al.* (2024), devoted to long-term forecasting of the transmission capacity of 110 kV intermediate cable joints, time-series models based on Prophet achieved an average temperature error of up to 10 K. Despite the analytical depth of these approaches, their effectiveness largely depends on the completeness of input data and requires complex model calibration. The algorithm proposed in this study is distinguished by combining a temperature-current model with a dynamic forecasting module capable of adapting to real load fluctuations without requiring a large volume of historical measurements. As a result, average forecasting accuracy reaches 90-95%, while computational costs remain minimal. This level of stability makes the system suitable for integration into existing SCADA complexes of urban cable networks, improving their reliability without the need for additional sensors or equipment reconfiguration.

Practical significance of the algorithm lies in its broad potential for implementation within modern monitoring and control systems of urban medium-voltage cable networks. The deployment of such a tool not only enhances the reliability of power supply but also establishes a new level of intelligent energy resource management within the framework of the Smart Grid concept. The algorithm can be integrated into local dispatching systems or SCADA platforms without the need for large-scale hardware modernisation. Its functionality enables automatic real-time monitoring of network elements, detection of anomalies, prediction of overload probability, and generation of warning signals considering temperature and temporal factors.

Application of the algorithm creates real prerequisites for transitioning to preventive maintenance of cable lines. According to A.A. Al-Dulaimi *et al*. (2024) this, in turn, reduces the risk of emergency outages, extends the service life of insulation, and minimises indirect losses associated with power interruptions at critical urban infrastructure facilities such as hospitals, transport hubs, and water supply systems. Modelling results demonstrate that implementation of the algorithm can reduce the average power restoration time after outages by 20-25%, as the dispatcher receives advance information about potentially hazardous sections of the network and can redistribute the load before reaching a critical state. In addition, the forecasting system contributes to the optimisation of daily load schedules, reducing inefficient energy use during peak hours. Estimates by F. Dinmohammadi *et al*. (2019) indicated that using this algorithm in combination with automated control systems can reduce energy losses due to overloads by 8-10% and stabilise voltage parameters in feeder lines. This is particularly relevant for large cities with extensive underground infrastructure, where even short-term overloads may lead to insulation overheating and cascading failures.

In comparison with existing approaches discussed in the literature, the proposed algorithm demonstrates several methodological and practical advantages that distinguish it from previous developments. For example, H. Yu *et al.* (2022) emphasised the role of electric-vehicle integration and bidirectional power flows within Smart Grid infrastructures, proposing architectures that enhance system flexibility but do not directly address the problem of predicting thermal overloads in underground cables. Their work highlights the necessity of intelligent coordination, whereas the present study provides a concrete analytical mechanism capable of identifying overload tendencies in real time, thus complementing the broader system-level concepts they discuss. Similarly, X. Chen *et al.* (2021) introduced a hybrid risk-analysis model focused primarily on identifying cable fire hazards caused by overload-induced thermal degradation. Although their Bayesian-neural framework enables early risk detection, it operates mostly at the level of probabilistic fault assessment and does not incorporate a physically grounded thermal model such as that based on IEC 60287-1-1 (2006). In contrast, the algorithm developed in this study integrates both deterministic thermal state estimation and adaptive machine-learning prediction, forming a more comprehensive diagnostic tool for assessing thermal conditions and identifying emerging overload risks.

D. Pang *et al.* (2021) presented a fast calculation method for cable ampacity under directly buried conditions, offering improvements in computational efficiency for estimating permissible loading. However, their approach remains static and does not include dynamic forecasting of evolving operating conditions. Unlike such static ampacity-calculation techniques, the proposed algorithm captures temporal patterns in load behaviour and environmental variability, enabling earlier detection of dangerous trends and providing actionable warnings for operators. Taken together, the comparison with these studies illustrates that while existing research offers valuable contributions to specific aspects of cable performance analysis – such as ampacity optimisation, fire-risk identification, or Smart Grid system integration – most approaches lack a unified predictive framework that combines physical thermal modelling with adaptive data-driven forecasting. The algorithm presented in this work fills this gap by integrating both components into a single operational tool suitable for real-time application. This synthesis enhances its practical utility and positions it as a more effective solution for preventing overload – induced failures in urban medium-voltage cable networks.

Considering the researches of J.E.G. Asorza *et al*. (2024), an important aspect is the scalability potential of the algorithm. Its architecture allows integration into DMS (Distribution Management System) or AMI (Advanced Metering Infrastructure) platforms, ensuring compliance with national cybersecurity standards and data exchange protocols. In the long term, this approach forms the basis for developing a unified urban energy digital twin that combines real measurements, analytics, and forecasting. This opens the path to implementing automated response technologies, where the system independently adjusts energy flows according to current and predicted operating conditions.

Alongside the demonstrated advantages, several limitations have been identified that outline directions for further improvement. The accuracy of forecasting decreases under unstable soil temperature conditions, observed after heavy rainfall, thawing, or seasonal freezing of the upper layers. According to T. Ahmad *et al*. (2022) such fluctuations directly affect the thermal resistivity of the environment (R_t), altering the rate of heat dissipation from the cable and causing deviations in determining the moment of reaching the critical temperature. Additionally, calculation results are influenced by SCADA measurement errors, data update delays, and sensor heterogeneity across different network sections. This is particularly evident in densely built-up urban areas where the thermal balance may be affected by local heat sources such as underground utilities, sewage collectors, and heating pipelines (Lin *et al*., 2023).

Another limiting factor is the restricted historical database required for algorithm training and adaptation to various load scenarios. The current model operates primarily within typical operating conditions; therefore, to enhance its universality, it is advisable to create a representative dataset covering different climatic zones, seasons, and soil types. Expanding the dataset would allow the algorithm to capture a wider spectrum of thermal-electrical interactions and improve its ability to generalise to atypical or extreme operating states. In addition to data-related constraints, the model exhibits sensitivity to abrupt changes in environmental parameters, particularly sharp fluctuations in soil temperature and moisture caused by unexpected weather events such as heavy rainfall, prolonged drought, or rapid freeze-thaw cycles. These phenomena significantly alter soil thermal resistivity and the rate of heat dissipation, resulting in transient deviations between predicted and actual cable temperatures. Although the algorithm includes adaptive components, its performance may temporarily decline until updated measurements allow recalibration. This highlights the need for continuous integration of real-time meteorological data or soil-condition sensors in practical deployments.

Another practical limitation arises from the heterogeneity of measurement infrastructure across different urban networks. Variations in SCADA reporting frequency, calibration quality of current transformers, and inconsistencies in temperature-sensing equipment may introduce biases or noise into the training data. Such discrepancies can affect the stability of regression models and may require preprocessing techniques such as sensor-fusion algorithms, filtering, and anomaly detection to ensure reliable operation in networks with non-uniform measurement quality. Despite these constraints, the proposed algorithm demonstrates strong potential for deployment in a wide range of real-world applications. Its predictive capabilities are particularly valuable in urban areas with high load density, where underground cables operate close to thermal limits during peak demand periods. In such environments, timely overload forecasting can prevent cascading failures and reduce the risk of widespread outages. The algorithm is also well suited for integration into ageing or partially modernised cable infrastructures, where existing monitoring systems may lack advanced diagnostic tools. By supplementing traditional SCADA measurements with predictive analytics, utility operators can enhance situational awareness without the need for costly hardware upgrades.

Furthermore, the methodology can serve as a decision-support tool during network expansion or cable replacement projects, helping engineers assess thermal constraints under projected load growth scenarios. In developing Smart Grid environments, the algorithm may be incorporated into DMS or AMI platforms to support adaptive load control, demand-response strategies, and real-time operational optimisation. Its ability to anticipate hazardous states also makes it applicable in critical infrastructure zones, such as hospitals, transport hubs, or industrial districts, where even short-term interruptions must be avoided.

CONCLUSIONS

Thus, the developed algorithm for forecasting overloads and preventing emergency conditions in medium-voltage (6-10 kV) urban cable networks provides a new level of analytical control over the state of underground lines. Modelling demonstrated a forecasting accuracy of 90-95% due to the combination of a physical thermal model compliant with IEC 60287-1-1 and a regression-based machine learning module that accounts for seasonal dynamics and environmental variability. The algorithm enables early detection of critical operating risks 1.5-2 hours before reaching the insulation's limit temperature, thereby improving power supply reliability, reducing post-failure recovery time by 20-25%, and decreasing energy losses by 8-10%. Comparative analysis with known approaches confirmed higher stability, lower computational costs, and the possibility of integrating the algorithm into existing SCADA systems without additional capital investment. Key factors affecting accuracy include the rate of load change ($\Delta I/\Delta t$), current, and soil temperature, which require adaptive model correction according to climatic conditions. Further development involves expanding the dataset and implementing deep neural networks (LSTM, BiGRU) for real-time self-correction of forecasts. The algorithm has the potential to become the foundation of an intelligent cable network monitoring system within the framework of Smart Grid and the "smart city" concept.

Further research should focus on integrating machine learning methods to enable real-time self-correction of forecasts, as well as on developing hybrid combined models. Such models would account for additional factors-soil moisture content, insulation aging, material degradation, voltage fluctuations, and load asymmetry-thus improving the accuracy of thermal state assessment and reliability of cable network operation under dynamic urban conditions. Thus, the research results confirm the effectiveness of the proposed algorithm for early detection of emergency conditions in urban medium-voltage cable networks, opening prospects for its practical implementation in Smart Grid systems and digital energy monitoring platforms.

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CONFLICT OF INTEREST

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Алгоритм прогнозування перевантажень і попередження аварійних режимів у міських кабельних мережах

Анотація. Сучасний стан міських кабельних мереж середньої напруги характеризується зростанням електричних навантажень, що спричинене підвищенням рівня електрифікації міського середовища, розвитком електротранспорту, розширенням інфраструктури зарядних станцій та впровадженням цифрових енергетичних технологій. Це актуалізує потребу у створенні інтелектуальних систем аналітичного моніторингу, здатних своєчасно прогнозувати розвиток перевантажень і запобігати виникненню аварійних режимів роботи кабельних мереж. Метою роботи було розроблення алгоритму прогнозування перевантажень і попередження аварійних режимів у міських кабельних мережах середньої напруги на основі інтеграції фізичної моделі теплового стану, побудованої за стандартом International Electrotechnical Commission 60287-1-1, із адаптивними регресійними методами машинного навчання. Методи дослідження включали математичне моделювання теплових процесів у підземних кабелях, статистичний аналіз вимірювальних даних систем типу Supervisory Control and Data Acquisition, побудову регресійних і нейронних прогнозних моделей, а також верифікацію отриманих результатів методом порівняльного моделювання на основі реальних експлуатаційних параметрів. Основні результати засвідчили, що розроблений алгоритм забезпечує точність прогнозу 90-95 % при визначенні тенденцій до перевантаження завдяки комплексному врахуванню струмових, теплових і часових характеристик. Система здатна ідентифікувати ризик критичних режимів за 1,5-2 години до перевищення допустимої температури ізоляції, що дозволяє диспетчерським службам здійснювати своєчасне коригування потоків навантаження. Було встановлено, що впровадження алгоритму підвищує надійність електропостачання, скорочує середній час відновлення після аварій на 20-25 % та зменшує втрати електроенергії від перевантажень на 8-10 %. Практична цінність роботи полягає у можливості інтеграції алгоритму у діючі диспетчерські комплекси без модернізації апаратної частини. Запропонований підхід формує основу для переходу міських енергетичних систем від реактивної до превентивної моделі технічного обслуговування та є важливим елементом розвитку інтелектуальних мереж у межах концепції Smart Grid

Ключові слова: тепловий стан кабелю; підземні кабельні мережі; машинне навчання; SCADA-дані; Smart Grid; надійність електропостачання