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DEVELOPMENT OF A FUZZY LOGIC SYSTEM FOR PREDICTING 10 KV LINE WEAR

The article addresses the problem of improving the accuracy of assessing the technical condition of 10 kV overhead power lines, a significant proportion of which in the distribution networks of CIS countries are operated beyond their standard service life and are characterized by a high level of physical wear. Traditional diagnostic methods based on standard service life and visual inspection do not allow reliable consideration of heterogeneous and partially uncertain factors such as the age of the line, the type of poles, and the time elapsed since major overhauls were carried out. This study proposes an intelligent system for predicting the wear of 10 kV overhead power lines based on fuzzy logic methods. The developed model includes the definition of input linguistic variables, the construction of membership functions, the formation of a rule base, and the determination of the predicted wear value using a defuzzification method. To verify the effectiveness of the proposed approach, statistical data from the distribution networks of one region were used. A comparison of the model predictions with actual operational assessments demonstrated good agreement, confirmed by the calculated performance indicators mean absolute error, root mean square error, and coefficient of determination. The developed system can be used to improve diagnostic accuracy, optimize maintenance scheduling, and enhance the reliability of distribution power networks.

Keywords: overhead power lines, fuzzy logic, line wear prediction, intelligent forecasting system, distribution networks.

Introduction

Overhead power lines with a voltage level of 10 kV represent a key component of distribution electrical networks and provide the majority of electricity supply to cities and populated areas [1]. A significant share of technological disturbances, emergency outages, and interruptions of power supply is associated with these lines [2].

In the CIS countries, a similar situation is observed regarding the technical condition of 6-10 kV overhead lines: most of these lines were constructed in the 1960s-1980s and have significantly exceeded their standard service life. According to industry assessments, the average level of physical wear reaches 60–80 %, while the proportion of networks that have been in operation for more than 30–40 years accounts for more than half of their total length [3]. The rate of modernization of distribution networks remains insufficient: newly constructed or fully reconstructed lines generally do not exceed 10–15 % of the existing infrastructure, which does not compensate for the natural aging process. Despite the use of durable reinforced concrete poles, the high wear of conductors, insulators, and fittings leads to an increase in failure rates [4; 5].

Thus, the following trends are characteristic of the distribution networks of CIS countries: a high average wear of operating lines; insufficient rates of network renewal; significant exceedance of the standard service life; and an increased frequency of technological disturbances caused by the aging of structural components [6]. The wear of 10 kV overhead lines significantly affects the reliability of power supply and increases the number of electricity interruptions [7; 8; 9].

An analysis of the condition of overhead lines shows that the degree of their wear is determined by a combination of heterogeneous factors, including the age of the structures, the type of poles, the frequency of major overhauls, climatic impacts, the condition of fittings, and others. A significant part of these factors is qualitative in nature and does not have strict quantitative boundaries: it is impossible to clearly determine at what point a line should be considered "old" or how "recent" a repair should be considered. This complicates the application of traditional assessment methods based on standard service life or visual inspection, since they poorly account for uncertainty, incomplete data, and the nonlinear relationships between parameters.

Under such conditions, the application of fuzzy logic methods represents a promising approach, as it allows the description of multifactor processes under conditions of vague boundaries and uncertainty. The use of linguistic variables (such as "young line", "wooden pole", "repair performed long ago", etc.) enables the formalization of expert knowledge and improves the accuracy of predicting the technical condition of complex engineering systems [10].

In this study, an intelligent system for predicting the wear of 10 kV overhead power lines based on fuzzy logic is proposed. The system includes the definition of input linguistic variables (such as line age, pole type, information on major overhauls, and others), the formation of corresponding term sets, the construction of a rule base, and the calculation of the output variable – the predicted level of wear expressed as a percentage. Based on statistical data from a power distribution company, the model is trained, verified, and its predictive accuracy is compared with existing methods used for assessing the technical condition of overhead lines.

The development of such a system will improve the accuracy of diagnostics and wear prediction for 10 kV overhead power lines, optimize the planning of maintenance activities, and reduce the probability of emergency outages in distribution networks.

Materials and Methods

This section describes the source materials and the methods used to develop an intelligent system for predicting the wear of 10 kV overhead power lines based on fuzzy logic.

Fuzzy logic represents an approach to modeling processes under conditions of uncertainty and vague boundaries, allowing expert knowledge to be incorporated through the use of linguistic variables (e.g., "young line", "wooden pole", "repair performed long ago"). This method is particularly relevant for assessing the technical condition of complex engineering systems such as overhead power lines, where classical deterministic models often prove insufficiently accurate.

The study includes a description of the initial data, the selection of input and output variables, the development of a model based on expert rules, the software implementation using Python, as well as the visualization of membership functions and wear prediction results.

Statistical data on 80 overhead power lines with a voltage level of 10 kV from a regional distribution company (Astana, 2024) were used to construct the model.

The model was implemented using Python and the scikit-fuzzy library based on the Mamdani fuzzy inference system. The centroid (center of gravity) method was used for defuzzification. The model development included the following stages [10].

1. Definition of linguistic variables: each input variable is described by corresponding terms using Gaussian, trapezoidal, and triangular membership functions.

The proposed model contains six input linguistic variables: Age, RepairAge, Support, Wire Type, Chains, and Length. The output variable is Wear (percentage of wear).

For example, the linguistic variable Length (line length) is represented by three terms: Short, Medium, and Long. The variable range is [0; 6] km, and Gaussian membership functions (gaussmf) were applied. The parameters of the membership functions are defined as follows: Short: σ=1, c=1; Medium: σ=1, c=3; Long: σ=1, c=5. This configuration makes it possible to smoothly represent the degree to which a line can be considered "short," "medium," or "long," taking into account the fuzzy boundaries between categories. Figure 1 illustrates the visualization of the membership functions for the variable Length.

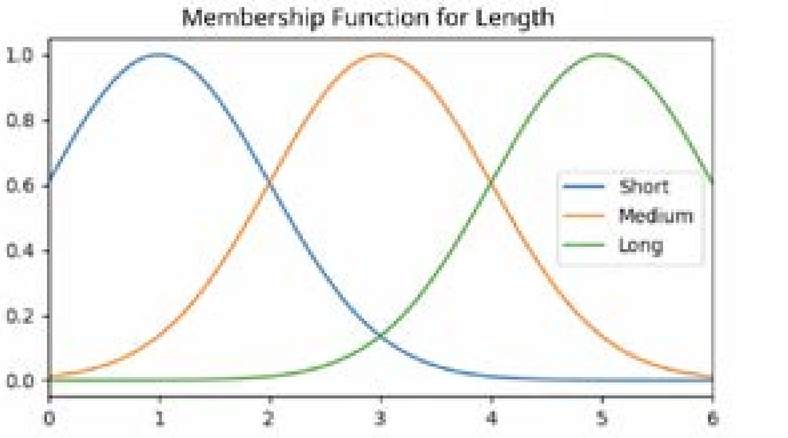

Figure 1 – Membership functions of the linguistic variable Length

2. Construction of the rule base: the expert rule base consists of 61 rules that account for combinations of input variables. An example of a rule is: IF Age = Very Old AND RepairAge = Very Old Repair AND Support = Wood THEN Wear = Very High.

3. Rule aggregation: the maximum method is used to combine the membership values obtained from each rule.

4. Defuzzification: the centroid method is applied to obtain a numerical value of the predicted line wear:

$$Z = \frac{\sum_i \mu_i(x) \cdot z_i}{\sum_i \mu_i(x)}, \tag{1}$$

where $\mu_i(x)$ – the degree of activation of the i-th rule for the given input data;
z_i – the output value corresponding to that rule;
Z – the resulting forecast of the line wear (%).

Results and Discussion

To evaluate the accuracy of the developed intelligent system for predicting the wear of 10 kV overhead power lines, a statistical database from the distribution networks of the Saryarka district of Astana (2024) was used. The dataset included the following parameters: conductor type; pole type (reinforced concrete, reinforced concrete + wood, wood); year of line commissioning; year of major overhaul; actual line wear calculated according to the current methodology of the distribution network operator (%).

Based on these data, the predictions of the model constructed using fuzzy logic principles with six input variables and one output variable-line wear (%) were evaluated.

For each 10 kV overhead line, the predicted wear percentage was calculated using the developed model. Table 1 presents examples of observations illustrating the structure and types of variables used in the model.

Table 1 – Examples of observations with line parameters and corresponding wear predictions

Line №	Conductor Type	Pole Type	Year of Commis-sioning	Year of major over-haul	Actual Wear According to Operational Assessment (%)	Predicted Wear by the Developed Model (%)
VL-10 kV RP 43 cell 3 – KTP 1720	SIP-3 1×70	Reinforced concrete	1995	2023	11.04	10.68
VL-10 kV TP 331 – TR 379	AC-50	Reinforced concrete	1996	–	52.22	52.61
2-circuit VL-10 kV f.111, 413 Koktem – EC 1	AC-120	Reinforced concrete	1997	–	50.13	49.73
VL-10 kV RP 43 – KTP 7	AC-50	Reinforced concrete	1995	–	54.31	54.91
VL-10 kV TP 303 – TR 314	AC-70	Reinforced concrete	1995	2011	20.89	20.11
VL-10 kV f.411 Shkolnaya – RP 31	AC-70	Reinforced concrete	1995	2015	12.53	11.59
VL-10 kV f.408 Shkolnaya	AC-70, 50	Reinforced concrete	1980	2022	42.60	43.83

The comparison showed that the developed model correctly reproduces the wear dynamics of overhead lines, generating predictions close to the values calculated using the current operational assessment methodology.

To quantitatively evaluate the prediction accuracy, the following indicators were used:

Mean Absolute Error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|Y_i^{\text{fact}} - Y_i^{\text{model}}\right|, \quad (2)$$

Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Y_i^{\text{fact}} - Y_i^{\text{model}}\right)^2}, \quad (3)$$

Coefficient of Determination (R^2) — shows what proportion of the variance of the actual wear values is explained by the model:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{\text{fact}} - Y_i^{\text{model}}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{\text{fact}} - \overline{Y}^{\text{fact}}\right)^2}, \quad (4)$$

The analysis of the results demonstrated that the developed system:

– adequately reproduces the wear dynamics of overhead lines, predicting values close to those calculated by regional distribution companies in Astana;

– better accounts for the influence of pole type and the presence of major overhauls compared with classical normative methods;

– allows the identification of lines with an increased risk of wear, for example old lines installed on wooden poles without major overhauls;

– provides high prediction accuracy even with incomplete or uncertain data.

The MAE was 9.67 %, the RMSE was 12.55 %, and the coefficient of determination was 0.639, which confirms the good adequacy of the proposed model.

For visual comparison of predicted and actual values, a graph comparing the actual and predicted wear levels is presented in Figure 2.

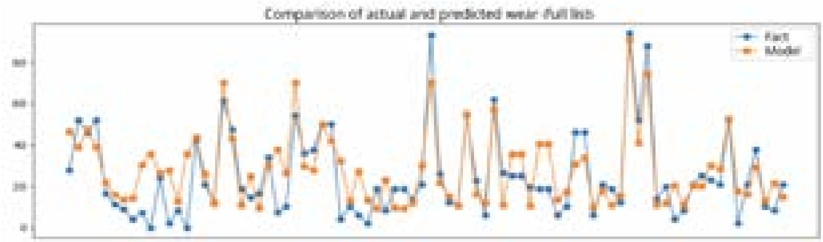

Figure 2 – Comparison of actual and predicted wear

The proposed methodology makes it possible to develop an intelligent system for predicting the wear of 10 kV overhead power lines, taking into account data uncertainty and expert knowledge. The system considers factors such as line age, pole type, and the presence of major overhauls, allowing numerical wear predictions to be obtained with high accuracy. The developed model also enables the optimization of maintenance scheduling and improves the reliability of distribution networks.

Conclusions

This study developed an intelligent system for predicting the wear of 10 kV overhead power lines based on fuzzy logic, taking into account key factors such as line age, pole type, and the presence of major overhauls. The obtained results demonstrated a high level of agreement between the model predictions and the wear assessments provided by regional distribution companies. The Mean Absolute Error was 9.67 %, while the Root Mean Square Error was 12.55 %. This level of accuracy confirms the practical applicability of the proposed approach.

The use of fuzzy logic makes it possible to formalize expert knowledge and account for data uncertainty, providing a more accurate assessment of line conditions compared with traditional methods. The developed system enables the identification of lines with an increased level of wear, supports the optimization of maintenance and reconstruction planning, reduces the risk of emergency outages, and improves the reliability of distribution networks.

A promising direction for further research is the expansion and refinement of the model to improve prediction accuracy and adapt it to different operating conditions. This will allow the system to become more universal and effective for application in various regions.

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БҰЛЫҢҒЫР ЛОГИКА НЕГІЗІНДЕ 10 КВ ЭЛЕКТР ЖЕЛІЛЕРІНІҢ ТОЗУЫН БОЛЖАУ ЖҮЙЕСІН ӘЗІРЛЕУ

Мақалада 10 кВ кернеулі әуе электр беру желілерінің техникалық жағдайын бағалау дәлдігін арттыру мәселесі қарастырылады. ТМД елдерінің тарату электр желілерінде мұндай желілердің едәуір бөлігі нормативтік қызмет ету мерзімінен асып пайдаланылып келеді және физикалық тозу деңгейінің жоғары болуымен сипатталады. Нормативтік пайдалану мерзіміне және визуалды тексеруге негізделген дәстүрлі диагностика әдістері желінің жасы, тірек түрі және күрделі жөндеу жүргізілген уақыт сияқты әртүрлі әрі ішінара анықталмаған факторлардың әсерін толық әрі сенімді түрде ескеруге мүмкіндік бермейді. Жұмыста бұлыңғыр логика әдістеріне негізделген 10 кВ әуе желілерінің тозуын болжауға арналған интеллектуалды жүйе ұсынылған. Әзірленген модель кіріс лингвистикалық айнымалыларды анықтауды, тиістілік функцияларын құруды, ережелер базасын қалыптастыруды және дефаззификация әдісі арқылы тозудың болжамдық мәнін алуды қамтиды. Жүйенің тиімділігін тексеру үшін өңірлік тарату электр желілерінің статистикалық деректері пайдаланылды. Модель болжамдарын нақты пайдалану бағаларымен салыстыру жақсы сәйкестікті көрсетті, бұл орташа абсолютті қате, орташа квадраттық қате және детерминация коэффициенті көрсеткіштерін есептеу арқылы расталды. Әзірленген жүйе диагностика дәлдігін арттыруға, жөндеу жұмыстарын жоспарлауды оңтайландыруға және тарату электр желілерінің сенімділігін арттыруға қолданылуы мүмкін.

Кілтті сөздер: әуе желілері, бұлыңғыр логика, желілердің тозуын болжау, интеллектуалды болжау жүйесі, электр тарату желілері.

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РАЗРАБОТКА СИСТЕМЫ ПРОГНОЗИРОВАНИЯ ИЗНОСА ЛИНИЙ 10 КВ НА ОСНОВЕ НЕЧЕТКОЙ ЛОГИКИ

В статье рассматривается задача повышения точности оценки технического состояния воздушных линий электропередачи напряжением 10 кВ, значительная часть которых в распределительных сетях стран СНГ эксплуатируется с превышением нормативных сроков службы и характеризуется высоким уровнем физического износа. Традиционные методы диагностики, основанные на нормативных сроках эксплуатации и визуальном осмотре, не позволяют достоверно учитывать влияние разнородных и частично неопределённых факторов, таких как возраст линии, тип опор и давность проведения капитальных ремонтов. В работе предложена интеллектуальная система прогнозирования износа ВЛ 10 кВ, основанная на методах нечеткой логики. Разработанная модель включает определение входных лингвистических переменных, построение функций принадлежности, формирование базы правил и получение прогнозного значения износа методом дефаззификации. Для проверки эффективности использованы статистические данные распределительных сетей одного из регионов. Сравнение прогнозов модели с фактическими эксплуатационными оценками показало хорошую согласованность, подтверждённую рассчитанными показателями: средняя абсолютная ошибка, средняя квадратическая ошибка и коэффициент детерминации. Разработанная система может быть использована для повышения точности диагностики, оптимизации графиков ремонтов и повышения надёжности распределительных сетей.

Ключевые слова: воздушные линии, нечеткая логика, прогнозирование износа линий, интеллектуальная система прогнозирования, распределительные электрические сети.

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