The 22nd International Conference on
Technical and Physical Problems of Engineering
ICTPE-2026
31 October 2026
International Organization of IOTPE

REGRESSION-BASED ASSESSMENT OF GROUND FAULT RESISTANCE EFFECTS ON ARC OVERVOLTAGE BEHAVIOR

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INTRODUCTION

In medium-voltage isolated-neutral networks (6-10 kV) single-phase ground faults are among the most frequently encountered undesirable operating conditions. The transient processes and arc phenomena arising during such faults lead to the formation of overvoltage's in the network, which in turn may result in insulation damage, equipment failure, and reduced reliability of power supply. At the same time, however, conducting on-load insulation testing in isolated-neutral networks is highly important for ensuring a reliable electricity supply to consumers. For this purpose, artificial earth faults may be intentionally created in such networks in order to perform insulation testing under load. In this context, the investigation of the mechanisms responsible for the occurrence of arc overvoltage's, the factors governing them, and the development of methods for their control constitute one of the urgent problems of modern electric power engineering.

Thus, the performed analysis demonstrates that, within the existing body of literature, the factors affecting arc overvoltages have predominantly been investigated independently, while their combined and interdependent effects remain insufficiently explored. However, the development of an integrated mathematical framework capable of adequately describing the cumulative influence of ground fault resistance, fault inception angle, and network phase-to-earth capacitance on the arc overvoltage factor remains a significant scientific and practical challenge. This circumstance, in turn, provides a clear justification for the formulation of the research objective and highlights the scientific novelty of the present study.

PROBLEM STATEMENT

Several studies have investigated the relationship between the arc overvoltage factor and ground fault resistance through the application of regression analysis. Although these studies derived regression equations describing this relationship, several important methodological aspects were not sufficiently addressed. In particular, the statistical significance of the regression and correlation coefficients was not evaluated to verify model adequacy, confidence intervals for the estimated parameters were not established, the level of agreement between theoretical predictions and experimental observations was not quantitatively assessed, and the predictive capability of the developed models with respect to arc overvoltage was not examined. Consequently, these limitations indicate that the problem remains insufficiently explored and continues to be of considerable scientific and practical interest.

Accordingly, the investigated problem remains an important research topic owing to its scientific relevance and practical implications. A rigorous analysis of the relationship between the arc overvoltage factor and ground fault resistance, combined with statistical validation of the regression model and quantitative evaluation of prediction uncertainty through confidence intervals, can significantly advance both the theoretical understanding and practical application of arc overvoltage analysis. Moreover, the integration of theoretical modeling with experimental observations establishes a more reliable and scientifically justified basis for predicting the arc overvoltage factor, thereby increasing the robustness, accuracy, and practical value of the proposed methodology.

DEVELOPMENT OF THE REGRESSION MODEL

Dependence of the Arc Overvoltage Factor on Ground Fault Resistance $k = f(R_0)$

R_0 , Ohm	5	10	15	20	25	30
k	3.3	2.96	2.77	2.62	2.49	2.38

$$k = \frac{a}{R_0} + b, \qquad \frac{1}{R_0} = x - \qquad k = ax + b,$$

Table of the Dependence of the Arc Overvoltage Factor on Conductivity $k = f(x)$

x, Sm	0.2	0.1	0.067	0.05	0.04	0.033
k	3.3	2.96	2.77	2.62	2.49	2.38

The parameters of the regression equation were estimated using the least-squares method, which determines the coefficient values by minimizing the sum of the squared residuals between the experimental observations and the corresponding values predicted by the fitted model.

$$S(a,b) = \sum_{i=1}^{n} \left(ax_i + b - k_i \right)^2 \rightarrow \min,$$

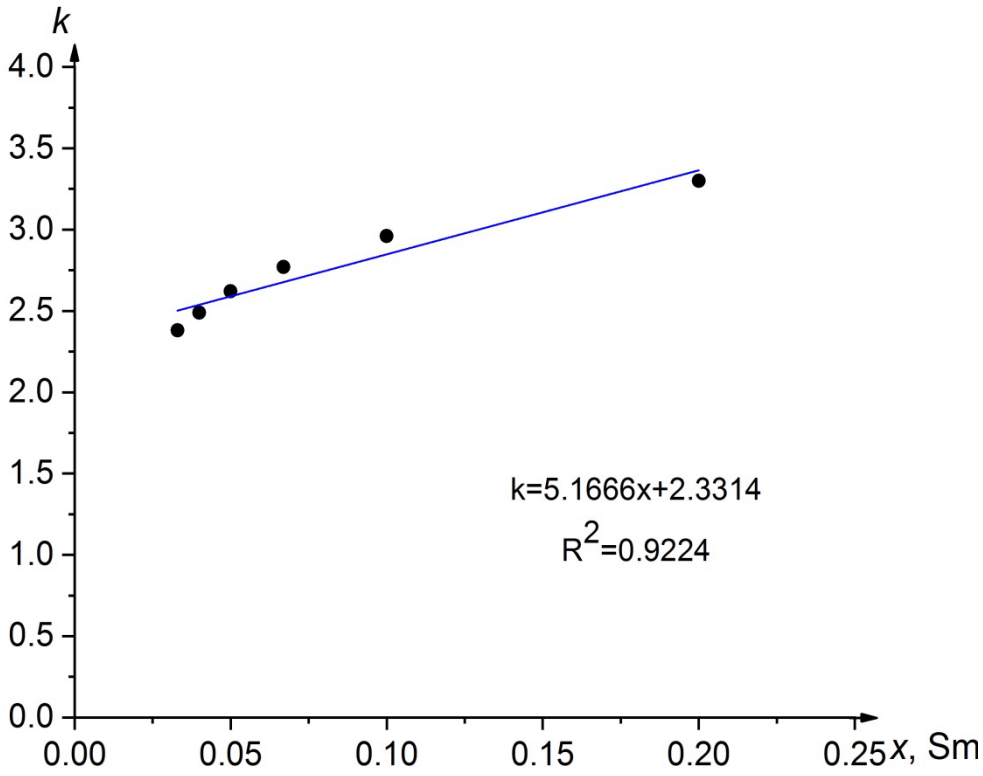
Calculation Table of the Parameters Describing the Correlation Relationship

		x_i^2	k_i	k_i^2	$x_i k_i$	$k(x_i)$	$(x_i - \bar{x})^2$	$(k_i - k(x_i))^2$	$\left\|\frac{k_i - k(x_i)}{k_i}\right\|$
1	0.200	3.30	0.040	10.89	0.66	3.365	0.01400	0.00419	0.01961
2	0.100	2.96	0.010	8.76	0.30	2.848	0.00034	0.01253	0.03782
3	0.067	2.77	0.004	7.67	0.18	2.676	0.00023	0.00887	0.03399
4	0.050	2.62	0.003	6.86	0.13	2.590	0.00100	0.00092	0.01156
5	0.040	2.49	0.002	6.20	0.10	2.538	0.00174	0.00231	0.01930
6	0.033	2.38	0.001	5.66	0.08	2.504	0.00234	0.01528	0.05194
∑	0.4900	16.5200	0.0597	46.0534	1.4506	16.520	0.01964	0.04409	0.17422

Substituting the estimated regression coefficients into equation yields the following explicit expression for the relationship between the arc overvoltage factor and the conductance of the ground fault path in isolated-neutral networks subjected to single-phase transient ground faults:

$$k = 5.1666x + 2.3314,$$

Dependence of the arc overvoltage factor on ground fault path conductance obtained from the regression model



VERIFICATION OF MODEL ADEQUACY

$$s = \sqrt{\frac{\sum_{i=1}^{n}\left(k_i - (ax_i + b)\right)^2}{n - m - 1}} = 0.10499; \quad \mu_a = \frac{s}{\sigma_x\sqrt{n}} = 0.7492; \quad \mu_b = \frac{s}{\sigma_x}\cdot\frac{\sqrt{\sum_{i=1}^{n} x_i^2}}{n} = 0.0747; \quad \mu_r = \sqrt{\frac{1 - r^2}{n - m - 1}} = 0.1393.$$

The calculated value of F - Fisher's criterion is determined from the given data as follows:

$$F = \frac{r^2}{1 - r^2}\cdot\frac{n - m - 1}{m} = 47.55.$$

$$F\left(\alpha, m, n - m - 1\right) = F\left(0.05; 1; 4\right) = 7.71.$$

$$F = 47.55 > F\left(\alpha, m, n - m - 1\right) = 7.71$$

EVALUATION OF THE CONSISTENCY BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

To assess the consistency between the regression model and the experimental observations, two widely used performance metrics, namely the mean absolute percentage error (MAPE) and the root mean square error (RMSE), were employed. These statistical indicators provide a quantitative measure of the predictive accuracy of the developed model. In the present study, the regression model was considered to exhibit satisfactory agreement with the experimental data when the MAPE value remained within the range of 5–7% and the RMSE did not exceed 10% of the arithmetic mean of the experimental values of the dependent (response) variable [17]. Compliance with these criteria indicates that the proposed model adequately reproduces the experimental observations and provides sufficiently accurate predictions.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{k_i - k(x_i)}{k_i}\right| \cdot 100\% = 2.9\% < \left(5-7\right)\%; \quad RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(k_i - k(x_i)\right)^2}{n}} = 0.08573 < \frac{\bar{k}}{100} \cdot 10\% = 0.27533.$$

The statistical comparison between the theoretical predictions and the experimental data confirms the adequacy and predictive capability of the proposed regression model. The satisfactory agreement achieved demonstrates that the model is sufficiently accurate for practical application in arc overvoltage prediction and may be confidently utilized for on-load insulation testing in isolated-neutral networks.

PREDICTION OF ARC OVERVOLTAGE

Within the framework of regression analysis, point forecasting is performed by estimating the expected value of the dependent (response) variable from the developed regression model. Accordingly, the point prediction of the arc overvoltage factor is obtained by substituting the forecast value of the ground fault path conductance in (6). This procedure yields the estimated value of the arc overvoltage factor associated with the specified conductance and serves as the basis for subsequent predictive analysis.

Interval forecasting consists in constructing a prediction interval within which the true value of the dependent variable (response variable) lies for a given significance level. The prediction interval for the arc overvoltage factor is expressed by the following inequality

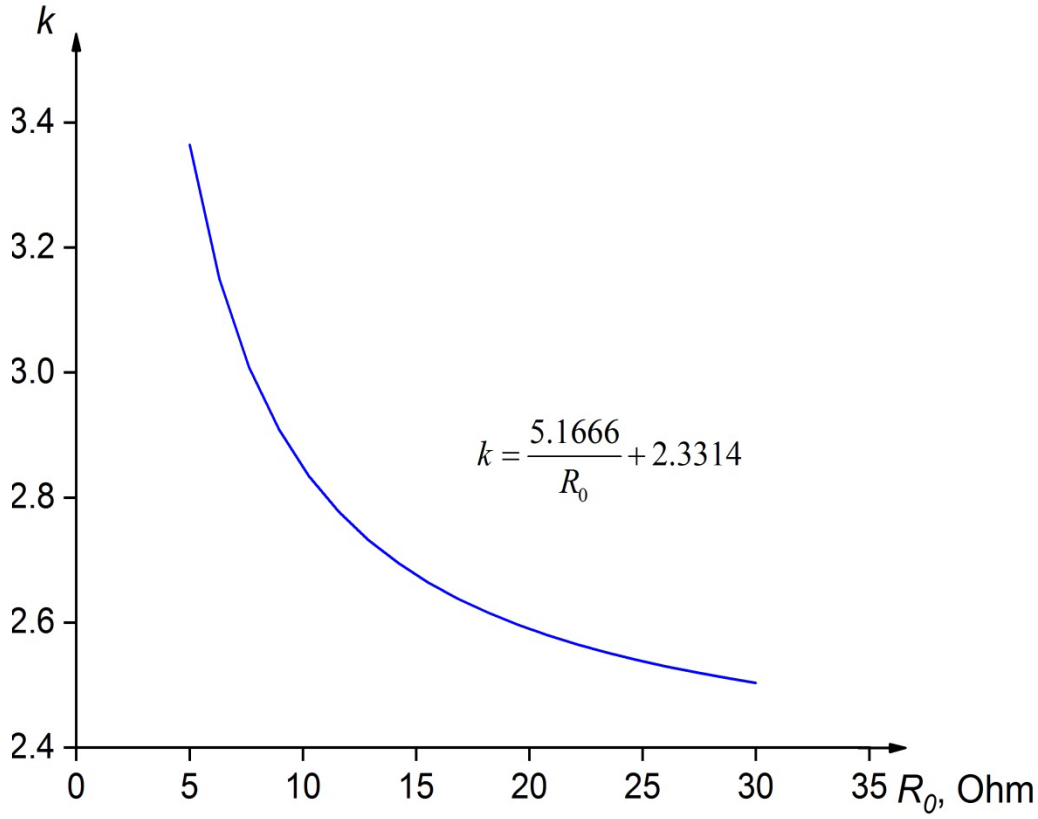
Results of the Prediction of the Arc Overvoltage Factor Based on the Developed Regression Model

x_p	k_p	μ_k	$\left(k_p - \mu_k t\left(\alpha, n-m-1\right); k_p + \mu_k t\left(\alpha, n-m-1\right)\right)$
0.200	3.365	0.144	(2.965; 3.764)
0.100	2.848	0.114	(2,531; 3,165)
0.067	2.676	0.114	(2.359; 2.992)
0.050	2.590	0.116	(2.268; 2.911)
0.040	2.538	0.118	(2.211; 2.865)
0.033	2.504	0.119	(2.173; 2.834)

MODELING RESULTS

Thus, the relationship given by equation between the arc overvoltage factor arising in isolated-neutral networks under single-phase non-stationary ground faults and the ground fault resistance can be written explicitly as follows:

$$k = \frac{5.1666}{R_0} + 2.3314,$$



CONCLUSION

1. The developed regression model confirms that, for isolated-neutral networks operating under single-phase non-stationary earth fault conditions described by Petersen's theory, the arc overvoltage factor varies hyperbolically with the ground fault resistance. The analysis shows that, as the ground fault resistance increases, the arc overvoltage factor decreases. This result is consistent with the physical nature of arc processes, since an increase in ground fault resistance lengthens the time required for the residual charges accumulated in the phase-to-earth capacitances of the network during arc extinction, which are responsible for the occurrence of arc overvoltage, to leak to ground through the ground fault circuit. As a result, a greater portion of the residual charge is discharged to ground, and the arc overvoltage factor decreases. The hyperbolic model therefore provides a reliable mathematical tool for assessing the influence of arc phenomena and optimizing network parameters.

2. The developed regression model can be effectively applied to on-load insulation testing in isolated-neutral networks. By taking into account ground fault resistance as one of the main parameters, the model makes it possible to predict the arc overvoltage factor. This approach simplifies the planning of test procedures, improves the accuracy of insulation level assessment, and makes it possible to determine in advance the hazard level of arc phenomena under actual network operating conditions. The statistical reliability of the regression model and its high correlation characteristics confirm its practical applicability and accuracy.

3. The obtained results are of considerable importance for the safe operation and protection of electrical networks. Prediction of arc overvoltage on the basis of hyperbolic correlation enables engineers to optimize insulation levels, minimize the consequences of fault conditions, and ensure the proper selection of protection systems. The use of the regression model may serve as an effective tool for assessing the hazard level of faults occurring in 6–10 kV distribution networks, standardizing test procedures, and improving the reliability of power supply. By integrating both theoretical modeling and experimental results, this approach provides a basis for stable and reliable control of arc overvoltage's during on-load insulation testing of network insulation.