



Past kuchlanishli elektr tarmoqlari uskunalarining texnik holati va ekspluatatsion ishonchliligiga ta'sir etuvchi omillar tahlili

Ikromjon U. Raxmonov^{1, a)}, Sardor D. Isakulov¹

^{a)} DSc, prof., Toshkent davlat texnika universiteti, Toshkent, 100095, O'zbekiston; ilider1987@yandex.com <https://orcid.org/0000-0003-2076-5919>

¹ Toshkent davlat texnika universiteti, Toshkent, 100095, O'zbekiston; sardorisakulov@icloud.com <https://orcid.org/0009-0004-9562-2140>

Dolzarbli: 0,4 kV taqsimlash tarmoqlarida uskunalarning eskirishi, yuklamaning notekisligi, garmonik buzilishlar, kuchlanish nosimmetriyasi, qizish va kontakt birikmalarining yomonlashuvi bir vaqtning o'zida ta'sir qilib, avariya xavfini oshiradi. Alohida parametr bo'yicha nazorat uskunaning haqiqiy texnik holatini to'liq ifodalaymaydi. Shu sababli rejim, issiqlik, ekspluatatsion va tashqi omillarni yagona ko'rsatkichga birlashtiruvchi ko'p omilli baholash metodikasini ishlab chiqish dolzarbdir.

Maqsad: past kuchlanishli elektr tarmoqlari uskunalarining texnik holati va ekspluatatsion ishonchliligiga ta'sir etuvchi omillarni tizimlashtirish, ularning miqdoriy ta'sirini baholash hamda texnik holat indeksi bilan nosozlik intensivligi o'rtasidagi bog'lanishni aniqlash.

Usullari: omilli tahlil, parametrlarni normallashtirish, vaznli integral baholash, Arrenius tipidagi harorat koef-fitsiyenti, eksponensial ishonchlik modeli, korrelyatsion-regression tahlil va 24 ta shartli obyekt uchun hisoblash eksperimenti.

Natijalar: 8 ta asosiy omilni birlashtiruvchi integral texnik holat indeksi taklif etildi. Hisoblash tajribasida yuklanish va haroratning integral riskka eng katta ulush berishi, texnik holat indeksi kamayishi bilan nosozlik intensivligi eksponensial ortishi ko'rsatildi. Metodika transformator, kabel, kommutatsiya apparati va kontakt birikmalarini yagona mezonda taqqoslash imkonini beradi.

Kalit so'zlar: past kuchlanishli tarmoq, texnik holat, ekspluatatsion ishonchlik, yuklanish, garmonikalar, kuchlanish nosimmetriyasi, harorat, nosozlik intensivligi, texnik holat indeksi.

Анализ факторов, влияющих на техническое состояние и эксплуатационную надежность оборудования низковольтных электрических сетей

Икромжон У. Рахмонов^{1, а)}, Сардор Д. Исакулов¹

^{a)} DSc, проф., Ташкентский государственный технический университет, Ташкент, 100095, Узбекистан; ilider1987@yandex.com <https://orcid.org/0000-0003-2076-5919>

¹ Ташкентский государственный технический университет, Ташкент, 100095, Узбекистан; sardorisakulov@icloud.com <https://orcid.org/0009-0004-9562-2140>

Актуальность: В сетях 0,4 кВ старение оборудования, неравномерность нагрузки, гармонические искажения, несимметрия напряжений, нагрев и деградация контактных соединений действуют совместно. Для достоверной диагностики требуется комплексная количественная оценка.

Цель: систематизировать влияющие факторы и установить количественную связь между интегральным индексом технического состояния и эксплуатационной надежностью оборудования.

Методы: нормирование параметров, взвешенная интегральная оценка, температурная модель старения, экспоненциальная модель надежности, корреляционно-регрессионный анализ и вычислительный эксперимент.

Результаты: предложена восьмифакторная модель оценки технического состояния; показана возможность перехода от измеряемых режимных параметров к интенсивности отказов и вероятности безотказной работы.

Ключевые слова: низковольтная сеть, техническое состояние, надежность, гармоника, температура, индекс состояния, интенсивность отказов.

For citation: Rakhmonov I.U., Isakulov S.D. Analysis of Factors Affecting the Technical Condition and Operational Reliability of Low-Voltage Electrical Network Equipment. Scientific and technical journal of Problems of Energy and Sources Saving, 2026, no. 3 (1), pp. 73-79.

<https://doi.org/10.5281/zenodo.2346463>

Received: 25.03.2026
Revised: 18.04.2026
Accepted: 28.05.2026
Published: 19.10.2026

Copyright: © Ikromjon U. Rakhmonov, Sardor D. Isakulov, 2026. Submitted to Problems of Energy and Sources Saving for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).



Analysis of Factors Affecting the Technical Condition and Operational Reliability of Low-Voltage Electrical Network Equipment

Ikromjon U. Rakhmonov^{1, a)}, Sardor D. Isakulov¹

^{1a)} DSc, prof., Tashkent State Technical University, Tashkent, 100095, Uzbekistan; ilider1987@yandex.com
<https://orcid.org/0000-0003-2076-5919>

¹ Tashkent State Technical University, Tashkent, 100095, Uzbekistan; sardorisakulov@icloud.com <https://orcid.org/0009-0004-9562-2140>

Relevance: Low-voltage distribution equipment is simultaneously exposed to loading, power-quality, thermal, ageing and environmental stresses. Single-parameter monitoring is therefore insufficient for condition-based maintenance.

Aim: to systematize the dominant factors and establish a quantitative relationship between an integrated technical-condition index and operational reliability.

Methods: parameter normalization, weighted health indexing, thermal ageing representation, exponential reliability modelling, correlation-regression analysis and a computational experiment.

Results: an eight-factor condition assessment model is proposed, enabling transition from measurable operating parameters to failure intensity and probability of failure-free operation.

Keywords: low-voltage network, technical condition, operational reliability, harmonics, temperature, health index, failure rate.

1. Kirish (Introduction)

Past kuchlanishli taqsimlash tarmoqlari iste'molchiga elektr energiyasini yetkazib berishning oxirgi va eng ko'p elementli bo'g'inidir. 0,4 kV tarmoqlarda transformatorlar, kabel va havo liniyalari, avtomatik o'chirgichlar, kontakt birikmalari hamda taqsimlash qurilmalari turli yuklanish va tashqi muhit sharoitida ishlaydi. Uskuna holatining yomonlashuvi odatda bitta sabab bilan emas, balki elektr, issiqlik, mexanik, ekspluatatsion va tashqi omillarning yig'ma ta'siri bilan shakllanadi.

Zamonaviy holat bo'yicha texnik xizmat ko'rsatish (condition-based maintenance) yondashuvida real vaqt rejimidagi va tarixiy ma'lumotlar, uskuna pasport ko'rsatkichlari hamda tashqi muhit sharoitlari birgalikda ko'rib chiqiladi. Elektr energiyasi sifati ko'rsatkichlarini o'lchashda kuchlanish kataligi, nosimmetriya, garmonikalar, tok va boshqa parametrlarni takrorlanuvchan usulda qayd etish muhimdir. Shu nuqtai nazardan ko'p omilli baholash uskunalar orasida ustuvor texnik xizmat obyektlarini ajratish imkonini beradi.

Ishning ilmiy vazifasi - o'lchanadigan rejim parametrlarini texnik holatning integral ko'rsatkichiga aylantirish va bu ko'rsatkichni ekspluatatsion ishonchlilik bilan bog'lashdir. Bunda maqoladagi sonli natijalar real ekspluatatsion statistika sifatida emas, taklif etilgan metodikaning ishlashini tekshirish uchun tuzilgan hisoblash eksperimenti sifatida qaraladi.

2. Metodlar va materiallar (Methods and materials)

2.1. Ta'sir etuvchi omillarni tizimlashtirish

1-jadval. Texnik holatga ta'sir etuvchi asosiy omillar

1-jadval. Texnik holatga ta'sir etuvchi asosiy omillar

Guruh	Ko'rsatkich	Asosiy ta'sir mexanizmi
Elektr	Yuklanish K _L	qo'shimcha I ² R yo'qotishlari, qizish
Elektr	THD _I	qo'shimcha yo'qotishlar va izolyatsiya issiqlik zo'riqishi
Elektr	K _{2U}	fazalar bo'yicha notekis qizish
Issiqlik	T	izolyatsiya va kontaktlarning tezlashgan eskirishi
Ekspluatatsion	t _{op}	material va izolyatsiya resursining kamayishi
Ekspluatatsion	R _c / kontakt holati	lokal qizish, kuchlanish tushuvi
Tashqi	Namlik H	izolyatsiya xossalaring yomonlashuvi, korroziya
Mexanik/kommutatsion	N _{sw}	kontaktlarning yeyilishi va mexanik resurs sarfi

Har bir o'lchanadigan X_i ko'rsatkich xavf yo'nalishida 0...1 oralig'iga normallashtiriladi:

$$X_i = \text{clip}[(X_i - X_{i,\min}) / (X_{i,\max} - X_{i,\min}), 0, 1] \quad (1)$$

Bu yerda x_{i=0} – me'yoriy yoki past riskli holat, x_{i=1} – tanlangan chegaradagi yuqori riskli holat.

Yuklanish koeffitsiyenti:

$$K_L = I_{\text{rms}} / I_{\text{nom}} \quad (2)$$



Tokning umumiy garmonik buzilish koeffitsiyenti:

$$THD_I = 100 \cdot \sqrt{\sum_{h=2}^{\infty} I_{h^2}} / I_1 \quad (3)$$

Kuchlanishning teskari ketma-ketlik bo'yicha nosimmetriya koeffitsiyenti:

$$K_{2U} = 100 \cdot U_2 / U_1 \quad (4)$$

Kontakt birikmasining qo'shimcha issiqlik ajratishi Joule-Lenz qonuniga ko'ra:

$$P_c = I^2 \cdot R_c \quad (5)$$

2.2. Integral texnik holat indeksi

Taklif etilgan modelda xavfning integral ko'rsatkichi D va texnik holat indeksi I_{TC} quyidagicha aniqlanadi:

$$D = \sum_{i=1}^m w_i x_i, \quad \sum w_i = 1 \quad (6)$$

$$I_{TC} = 100 \cdot (1 - D) \quad (7)$$

Hisoblash tajribasida vaznlar: yuklanish – 0,20; THD_I – 0,12; K_{2U} – 0,10; harorat – 0,18; ekspluatatsiya 750shi – 0,14; kontakt holati – 0,12; namlik – 0,06; kommutatsiyalar soni – 0,08 qilib qabul qilindi. Bu vaznlar metodikani namoyish qilish uchun ekspert-analitik boshlang'ich qiymatlar bo'lib, real korxonada AHP, entropiya usuli yoki avariya statistikasi bo'yicha qayta identifikatsiya qilinishi kerak.

2-jadval. I_{TC} bo'yicha tavsiya etilgan texnik holat shkalasi

Table 2. Recommended Technical Condition Scale Based on I_{TC}

I_{TC}	Holat	Tavsiya
85–100	Yaxshi	Rejali kuzatuv
70–84	Qabul qilinadigan	Davriy diagnostika
55–69	Qoniqarli	Qisqartirilgan diagnostika oralig'i
40–54	Qoniqarsiz	Ta'mirlashni rejalashtirish
<40	Kritik	Zudlik bilan chuqur diagnostika/almashtirish

2.3. Texnik holatni ishonchlilik ko'rsatkichlari bilan bog'lash

Bazaviy nosozlik intensivligi λ_0 ekspluatatsion zo'riqlashlar bilan tuzatiladi:

$$\Lambda = \lambda_0 \cdot \exp(\beta_D D + \beta_T x_T + \beta_C x_C) \quad (8)$$

bu yerda β_D , β_T va β_C - mos ravishda integral degradatsiya, harorat va kontakt holatining sezgirlik koeffitsiyentlari. Hisoblash tajribasida $\lambda_0=0,012$ 1/yil, $\beta_D=2,15$, $\beta_T=0,35$ va $\beta_C=0,20$ qabul qilindi.

Nosozlik intensivligi vaqt bo'yicha o'zgarish deb qaraladigan qisqa prognoz oralig'ida:

$$R(t) = \exp(-\lambda t) \quad (9)$$

$$F(t) = 1 - R(t) \quad (10)$$

$$MTTF = 1/\lambda \quad (11)$$

Haroratning eskirishga ta'sirini fizik izohlash uchun Arrenius tipidagi tezlashtirish koeffitsiyenti ishlatilishi mumkin:

$$K_T = \exp[(E_a/k_B) \cdot (1/T_{ref} - 1/T_{abs})] \quad (12)$$

Bu tenglama bevosita ushbu hisoblash tajribasining λ modeliga kiritilmagan, biroq real izolyatsiya tizimi uchun β_T ni fizik identifikatsiya qilishda qo'llanishi mumkin.

3-jadval. Taklif etilgan ko'p omilli baholash metodikasining ketma-ketligi

Fig.3. Sequence of the Proposed Multifactor Assessment Methodology

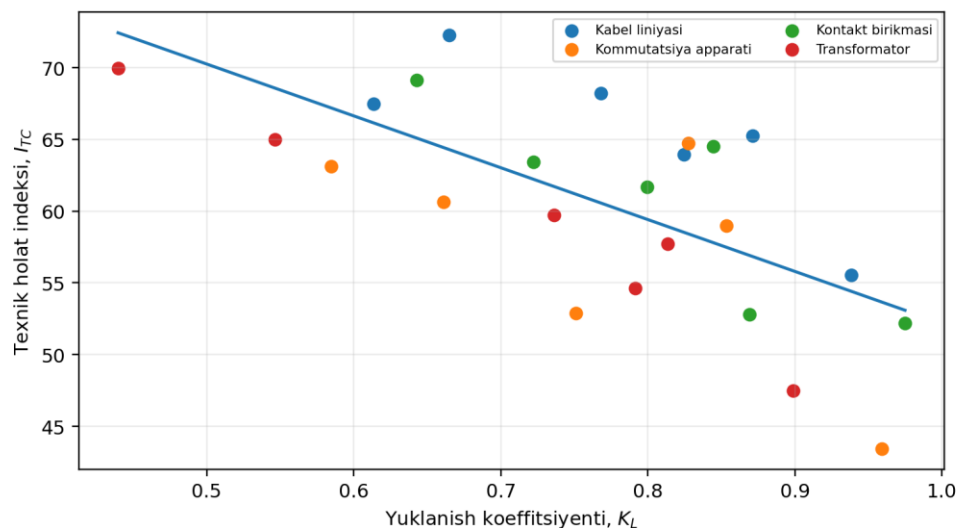
1-bosqich	2-bosqich	3-bosqich	4-bosqich	5-bosqich
U, I, THD, K_{2U} , T va tarixiy ma'lumotlarni yig'ish	Filtrlash va normallashtirish	D va I_{TC} ni hisoblash	λ , R(t), MTTF ni baholash	Texnik xizmat ustuvorligini belgilash

3. Natijalar va muhokama (Results and discussion)

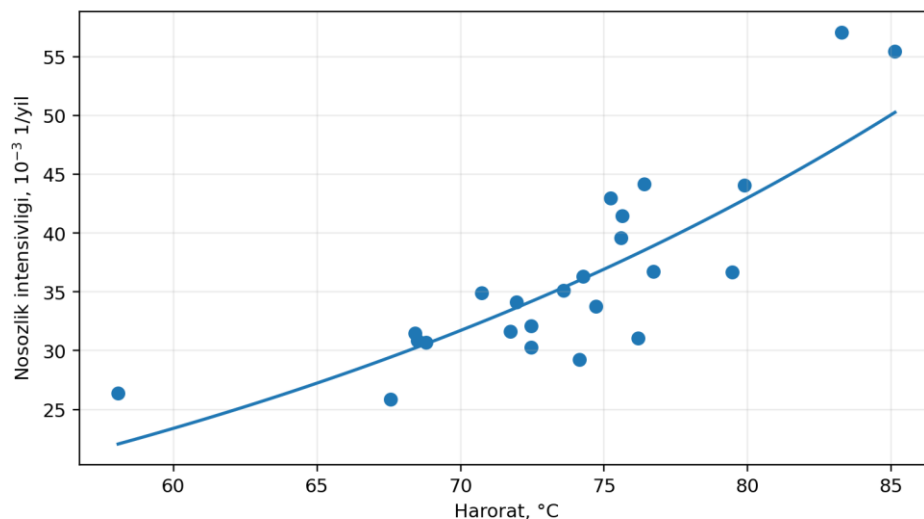
3.1. Hisoblash tajribasining tashkil etilishi. Metodikaning sezgirligi va ichki mantiqiyligini tekshirish uchun 24 ta shartli obyekt: 6 ta transformator, 6 ta kabel liniyasi, 6 ta kommutatsiya apparati va 6 ta kontakt birikmasidan iborat model to'plam tuzildi. Parametrlar past, o'rta va yuqori zo'riqlash holatlarini qamrab oladigan diapazonlarda generatsiya qilindi. Shuning uchun quyidagi natijalar metodik namoyish hisoblanadi va muayyan real tarmoqning avariya statistikasi sifatida talqin qilinishi kerak.

4-jadval. Uskuna turlari bo'yicha hisoblash tajribasining umumlashtirilgan natijalari**Table 4.** Summarized Results of the Computational Experiment by Equipment Type

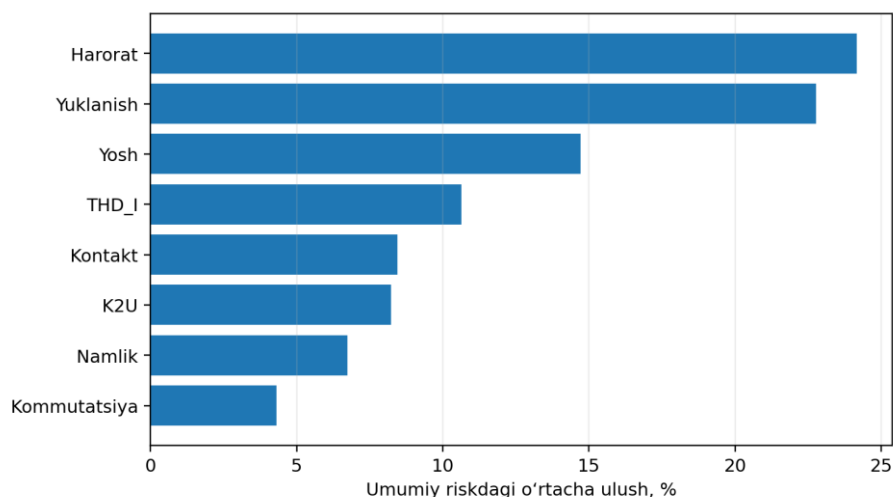
Uskuna turi	n	K _L	THD I, %	T, °C	I _{TC}	λ, 1/yil	R(5)
Kabel liniyasi	6	0.78	7.8	72.9	65.5	0.0319	0.853
Kommutatsiya apparati	6	0.77	9.4	74.2	57.3	0.0391	0.823
Kontakt birikmasi	6	0.81	5.9	74.1	60.6	0.0364	0.834
Transformator	6	0.71	9.7	74.0	59.1	0.0379	0.828

**1-rasm.** Yuklanish ko'effitsiyenti va texnik holat indeksi o'rtasidagi bog'lanish**Fig.1.** Relationship Between the Load Coefficient and the Technical Condition Index

Hisoblash tajribasida K_L va I_{TC} orasidagi Pearson korrelyatsiya ko'effitsiyenti $r=-0.671$ ni tashkil etdi. Manfiy bog'lanish yuklanish ortishi nafaqat to'g'ridan-to'g'ri risk komponentini, balki harorat va kontakt qizishi bilan bog'liq ikkilamchi ta'sirlarni ham kuchaytirishini ko'rsatadi.

**2-rasm.** Harorat va hisoblangan nosozlik intensivligi o'rtasidagi bog'lanish**Fig.2.** Relationship Between Temperature and Calculated Failure Intensity

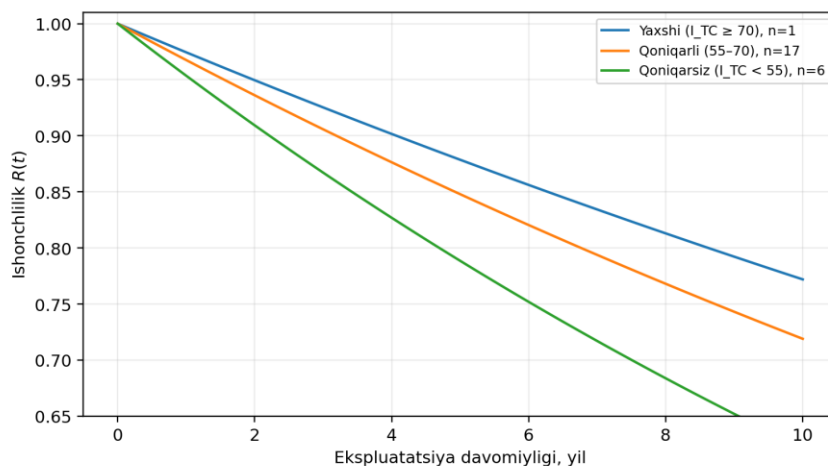
Harorat va λ orasida $r=0.815$ darajadagi bog'lanish olindi. Eksponensial model tufayli yuqori harorat zonasida nosozlik intensivligining o'sishi tezlashadi. Bu natija issiqlik holatini faqat himoya chegarasidan oshish hodisasi sifatida emas, balki uzluksiz degradatsiya indikatori sifatida hisobga olish zarurligini ko'rsatadi.



3-rasm. Integral riskdagi omillarning o'rtacha ulushi

Fig.3. Average Share of Factors in the Integral Risk

Qabul qilingan vaznlar va model diapazonlarida eng katta o'rtacha ulushlar Harorat (24.2 %), Yuklanish (22.8 %), Yosh (14.7 %) omillariga to'g'ri keldi. Bu qiymatlar universal normativ emas: real obyekt uchun ulushlar o'lchovlar va nosozliklar tarixi asosida qayta aniqlanishi kerak.



4-rasm. Texnik holat guruhlari uchun $R(t)$ ishonchlilik funksiyalari

Fig.4. Reliability Functions $R(t)$ for Technical Condition Groups

I_{TC} pasaygan sari λ ortadi va $R(t)$ egri chizig'i tezroq kamayadi. Shunday qilib, integral texnik holat indeksi diagnostik parametrlarni ekspluatatsion qaror bilan bog'lovchi oraliq ko'rsatkich vazifasini bajaradi.

5-jadval. Eng yuqori riskli 8 ta model obyekt

Table 5. Eight Model Objects with the Highest Risk

ID	Turi	K L	THD I, %	T, °C	I TC	λ	R(5)
O13	Kommutatsiya apparati	0.96	12.8	83.3	43.4	0.0571	0.752
O02	Transformator	0.90	10.6	85.1	47.5	0.0555	0.758
O23	Kontakt birikmasi	0.97	3.3	76.4	52.2	0.0442	0.802
O22	Kontakt birikmasi	0.87	7.9	75.2	52.8	0.0430	0.807
O17	Kommutatsiya apparati	0.75	12.7	79.9	52.9	0.0440	0.802
O04	Transformator	0.79	10.0	75.6	54.6	0.0415	0.813
O08	Kabel liniyasi	0.94	6.6	75.6	55.5	0.0396	0.820
O01	Transformator	0.81	10.9	76.7	57.7	0.0367	0.832

6-jadval. Alohida omilning yuqori darajaga chiqishi bo'yicha sezgirlik tahlili

Table 6. Sensitivity Analysis of the Increase of an Individual Factor to a High Level

Ssenariy	D	I _{TC}	λ , 1/yil	R(5)
Bazaviy	0.396	60.4	0.0358	0.836
Yuklanish yuqori	0.497	50.3	0.0446	0.800
THD I yuqori	0.472	52.8	0.0423	0.809
Nosimmetriya yuqori	0.465	53.5	0.0416	0.812
Harorat yuqori	0.479	52.1	0.0504	0.777
Kontakt yomon	0.482	51.8	0.0499	0.779

Sezgirlik tahlili omillarni bir xil birlikka keltirishning afzalligini ko'rsatadi: turli fizik tabiatga ega parametrlar bir xil risk shkalasida taqqoslanadi. Shu bilan birga, modelni amaliy joriy etishda vaznlarni faqat ekspert fikri bilan cheklash mumkin emas. Kamida 2-3 yillik nosozliklar tarixi mavjud bo'lsa, w_i va β koeffitsiyentlarini logistika regressiyasi, Cox modeli yoki maksimal ehtimollik usuli bilan identifikatsiya qilish maqsadga muvofiq.

3.2. Metrologik va amaliy jihatlar

Elektr energiyasi sifati parametrlarini qayd etishda o'lchov usuli va sinfi natijaning takrorlanuvchanligiga bevosita ta'sir qiladi. Shu sababli kuchlanish kattaligi, nosimmetriya, garmonikalar va tok parametrlarini amaldagi IEC 61000-4-30:2025 talablariga mos usulda olish tavsiya etiladi. Harorat uchun termografiya yoki kontakt datchiklari, kontakt qarshiligi uchun mikroohmmetr yoki bilvosita ΔT diagnostikasi qo'llanishi mumkin.

Taklif etilgan yondashuvning asosiy amaliy afzalligi shundaki, texnik xizmat faqat kalendar muddati bo'yicha emas, balki I_{TC} va $R(t)$ asosida ustuvorlashtiriladi. Masalan, yoshi katta, ammo past yuklangan va normal haroratli obyekt yoshroq, biroq doimiy ortiqcha yuklanadigan va qizib ishlaydigan obyektga nisbatan pastroq riskka ega bo'lishi mumkin.

4. Xulosa (Conclusion)

1. Past kuchlanishli tarmoq uskunalarning texnik holatiga ta'sir etuvchi omillar elektr, issiqlik, ekspluatatsion, tashqi va kommutatsion guruhlariga ajratildi; baholash uchun 8 ta asosiy ko'rsatkich tanlandi.

2. Turli fizik o'lchamdagi parametrlarni 0...1 diapazonga normallashtirish va vaznli yig'indi asosida D integral risk hamda $I_{TC}=100(1-D)$ texnik holat indeksini aniqlash metodikasi taklif etildi.

3. Texnik holatni ekspluatatsion ishonchlik bilan bog'lash uchun holatga bog'liq $\lambda=\lambda_0 \cdot \exp(\beta_{DD} + \beta_{Tx} T + \beta_{Cx} C)$ modeli va $R(t)=\exp(-\lambda t)$ funksiyasi qo'llanildi.

4. 24 ta shartli obyekt bo'yicha hisoblash tajribasida yuklanish koeffitsiyenti bilan I_{TC} orasida $r=-0.671$, harorat bilan λ orasida $r=0.815$ bog'lanish olindi; bu modelning kutilgan fizik tendensiylarni qayta ishlab berishini ko'rsatdi.

5. Taklif etilgan metodika transformator, kabel, kommutatsiya apparati va kontakt birikmalarini yagona mezonida saralash hamda holat bo'yicha texnik xizmat ustuvorligini shakllantirish uchun asos bo'la oladi. Keyingi bosqichda vazn va regressiya koeffitsiyentlarini real 0,4 kV tarmoq o'lchovlari hamda nosozliklar statistikasi asosida identifikatsiya qilish zarur.

ЛИТЕРАТУРА

- IEC 61000-4-30:2025. Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods. Geneva: IEC, 2025.
- Wang Q., Li Y., Wang X., et al. Rapid assessment of distribution network equipment status based on fuzzy decision making. *Frontiers in Energy Research*, 2024, 12, 1418833. DOI: 10.3389/fenrg.2024.1418833.
- Hu et al. Research on live detection technology of distribution network cable insulation deterioration state based on harmonic components. *IET Generation, Transmission & Distribution*, 2024. DOI: 10.1049/gtd2.13238.
- Improving the reliability of power distribution substations equipment for life extension by considering Condition Based Maintenance. *Procedia Computer Science*, 2024, vol. 232, pp. 2289–2301. DOI: 10.1016/j.procs.2024.02.048.
- Tenbohlen S., Martin D., et al. Analysis of AC Transformer Reliability. *CIGRE Technical Brochure 939*. Paris: CIGRE, 2024.
- Identification of Distribution Transformer Reliability Using the Weibull Approach at the Customer Service Unit Taman, Surabaya. 2024 International Conference on Electrical Engineering and Informatics. DOI: 10.1109/ICELTICs62730.2024.10776479.

7. Condition Monitoring and Health Index Determination of Operating 20 kV Distribution Transformers using Analytical Hierarchy Process Method. 2024 6th International Conference on Power Engineering and Renewable Energy. DOI: 10.1109/ICPERE63447.2024.10845538.
8. A real time study on condition monitoring of distribution transformer using thermal imager. *Infrared Physics & Technology*, 2018.
9. IEEE Std 1459-2010. IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions. New York: IEEE, 2010.
10. IEEE Std 1159-2019. IEEE Recommended Practice for Monitoring Electric Power Quality. Piscataway, NJ: IEEE, 2019.
11. IEC 60076-7:2018. Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers. Geneva: IEC, 2018.
12. IEC 60599:2022. Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis. Geneva: IEC, 2022.
13. IEC 60812:2018. Failure modes and effects analysis (FMEA and FMECA). Geneva: IEC, 2018.
14. IEC 60300-3-11:2009. Dependability management – Application guide – Reliability centred maintenance. Geneva: IEC, 2009.
15. IEC 61709:2017. Electric components – Reliability – Reference conditions for failure rates and stress models for conversion. Geneva: IEC, 2017.

REFERENCES

1. IEC 61000-4-30:2025. Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods. Geneva: IEC, 2025.
2. Wang Q., Li Y., Wang X., et al. Rapid assessment of distribution network equipment status based on fuzzy decision making. *Frontiers in Energy Research*, 2024, 12, 1418833. DOI: 10.3389/fenrg.2024.1418833.
3. Hu et al. Research on live detection technology of distribution network cable insulation deterioration state based on harmonic components. *IET Generation, Transmission & Distribution*, 2024. DOI: 10.1049/gtd2.13238.
4. Improving the reliability of power distribution substations equipment for life extension by considering Condition Based Maintenance. *Procedia Computer Science*, 2024, vol. 232, pp. 2289–2301. DOI: 10.1016/j.procs.2024.02.048.
5. Tenbohlen S., Martin D., et al. Analysis of AC Transformer Reliability. CIGRE Technical Brochure 939. Paris: CIGRE, 2024.
6. Identification of Distribution Transformer Reliability Using the Weibull Approach at the Customer Service Unit Taman, Surabaya. 2024 International Conference on Electrical Engineering and Informatics. DOI: 10.1109/ICELTICs62730.2024.10776479.
7. Condition Monitoring and Health Index Determination of Operating 20 kV Distribution Transformers using Analytical Hierarchy Process Method. 2024 6th International Conference on Power Engineering and Renewable Energy. DOI: 10.1109/ICPERE63447.2024.10845538.
8. A real time study on condition monitoring of distribution transformer using thermal imager. *Infrared Physics & Technology*, 2018.
9. IEEE Std 1459-2010. IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions. New York: IEEE, 2010.
10. IEEE Std 1159-2019. IEEE Recommended Practice for Monitoring Electric Power Quality. Piscataway, NJ: IEEE, 2019.
11. IEC 60076-7:2018. Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers. Geneva: IEC, 2018.
12. IEC 60599:2022. Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis. Geneva: IEC, 2022.
13. IEC 60812:2018. Failure modes and effects analysis (FMEA and FMECA). Geneva: IEC, 2018.
14. IEC 60300-3-11:2009. Dependability management – Application guide – Reliability centred maintenance. Geneva: IEC, 2009.
15. IEC 61709:2017. Electric components – Reliability – Reference conditions for failure rates and stress models for conversion. Geneva: IEC, 2017.