



Past kuchlanishli shahar elektr tarmoqlarida fazalararo nosimmetriyani optimal qayta fazalash orqali kamaytirish

Abduraxim D. Taslimov¹, Feruz M. Raximov^{2,a}, Asliddin O. Norqulov²

¹⁾ DSc, prof., Toshkent davlat texnika universiteti, Toshkent, 100095, O'zbekiston; ataslimov@mail.ru <https://orcid.org/0000-0003-2856-6287>

^{2,a)} PhD, dots., Navoiy davlat konchilik va texnologiyalar universiteti, Navoiy, 210100, O'zbekiston; feruz.raximov.2017@mail.ru <https://orcid.org/0009-0008-6832-0509>

²⁾ Katta o'qituvchi., Navoiy davlat konchilik va texnologiyalar universiteti, Navoiy, 210100, O'zbekiston; asliddin.norqulov.91@mail.ru <https://orcid.org/0000-0002-4521-8367>

Dolzarbli: Past kuchlanishli shahar elektr tarmoqlarida bir fazali iste'molchilarning fazalar bo'yicha notekis taqsimlanishi faza toklarining nosimmetriyasi, asosiy ishchi chastotadagi neytral tokning ortishi, tugun kuchlanishlarining farqlanishi va o'tkazgichlardagi aktiv quvvat isrofining ko'payishiga olib keladi. Fazalarni qayta taqsimlash bunday holatni yangi qurilma o'rnatmasdan yaxshilash imkonini beradi, biroq qayta ulashlar soni va tarmoq isrofini bir vaqtda hisobga olish zarur.

Maqsad: 0,4 kV uch fazali to'rt simli radial tarmoqda belgilangan faza aktiv quvvat nosimmetriyasi chegarasiga eng kam qayta ulash bilan erishish va shu minimal qatlamdagi variantlar orasidan aktiv quvvat isrofi eng kichik konfiguratsiyani aniqlash.

Usullar: 230/400 V kuchlanishli, 15 ta bir fazali ekvivalent yuklama guruhiga ega besh uchastkali radial tarmoq modeli tuzildi. Birinchi bosqichda to'liq kombinatorik qidiruv bilan minimal qayta ulashlar soni aniqlandi; ikkinchi bosqichda ruxsat etilgan variantlar uch fazali to'rt simli nolinear rejim hisobi orqali tekshirildi. Simmetrik tashkil etuvchilar, neytral toki, aktiv quvvat isrofi hamda 2, 5 va 10 % mezonlar, 30, 60 va 100 % yuklama darajalari va neytral qarshiligi bo'yicha sezgirlik tahlili qo'llandi.

Natijalar: 0, 1, 2 va 3 ta qayta ulash qatlamlarida eng kichik nosimmetriya mos ravishda 60,98; 28,05; 14,02 va 1,22 % bo'ldi. 5 % chegara uchun uchta qayta ulashli 57 ta konfiguratsiya topildi. L1: A→C, L7: A→B va L8: B→C varianti 5,3051 kW bilan minimal isrofini berdi; bunda faza quvvatlari 35,75; 34,45 va 36,40 kW, fundamental neytral tok 7,29 A, maksimal manfiy ketma-ketlik kuchlanish koeffitsiyenti 0,237 % bo'ldi. Dastlabki 7,5850 kW ga nisbatan aktiv quvvat isrofi 30,06 % kamaydi.

Kalit so'zlar: 0,4 kV elektr tarmog'i, faza nosimmetriyasi, qayta fazalash, uch fazali to'rt simli tarmoq, neytral tok, manfiy ketma-ketlik, aktiv quvvat isrofi, leksikografik optimallashtirish.

Снижение несимметрии фазных нагрузок в городских электрических сетях низкого напряжения путем оптимального перефазирования

Абдурахим Д. Таслимов¹, Феруз М. Рахимов^{2,а}, Аслиддин О. Норкулов²

¹⁾ DSc, проф., Ташкентский государственный технический университет, Ташкент, 100095, Узбекистан; ataslimov@mail.ru <https://orcid.org/0000-0003-2856-6287>

^{2,a)} PhD, доц., Навоийский государственный горно-технологический университет, Навои, 210100, Узбекистан; feruz.raximov.2017@mail.ru <https://orcid.org/0009-0008-6832-0509>

²⁾ Старший преподаватель., Навоийский государственный горно-технологический университет, Навои, 210100, Узбекистан; asliddin.norqulov.91@mail.ru <https://orcid.org/0000-0002-4521-8367>

Актуальность: В городских сетях низкого напряжения неравномерное распределение однофазных потребителей по фазам вызывает несимметрию токов, увеличение тока нейтральной основной частоты, различие узловых напряжений и рост активных потерь в проводниках. Перефазирование позволяет улучшить режим без установки дополнительного оборудования, однако требуется учитывать одновременно число переключений и сетевые потери.

Цель: достижение заданного предела несимметрии активной мощности фаз минимальным числом переключений и выбор среди решений минимального слоя конфигурации с наименьшими активными потерями в трехфазной четырехпроводной сети 0,4 кВ.

Методы: использована радиальная модель 230/400 В из пяти участков и 15 однофазных эквивалентных групп нагрузок. На первом этапе полным комбинаторным перебором определялось минимальное число перефазирований, на втором все допустимые решения минимального слоя проверялись нелинейным расчетом режима трехфазной четырехпроводной сети. Выполнен анализ чувствительности к пределу несимметрии, уровню нагрузки и сопротивлению нейтрали.

Результаты: для предела 5 % минимальное число переключений равно трем, причем найдено 57 допустимых конфигураций. Решение L1: A→C, L7: A→B, L8: B→C обеспечило минимальные потери 5,3051 кВт; ток нейтрали основной частоты составил 7,29 А, максимальный коэффициент напряжения

For citation: Taslimov A.D., Raximov F.M., Norqulov A.O. Reduction of Phase Unbalance in Low-Voltage Urban Distribution Networks through Optimal Rephasing. Scientific and technical journal of Problems of Energy and Sources Saving, 2026, no. 3(1), pp. 29-35.

<https://doi.org/10.5281/zenodo.23464401>

Received: 18.03.2026
Revised: 12.04.2026
Accepted: 24.05.2026
Published: 19.10.2026

Copyright: © Abduraxim D. Taslimov, Feruz M. Raximov, Asliddin O. Norqulov, 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/>).



обратной последовательности 0,237 %. По сравнению с исходными 7,5850 кВт активные потери уменьшились на 30,06 %.

Ключевые слова: сеть 0,4 кВ, несимметрия фаз, перефазирование, трехфазная четырехпроводная сеть, ток нейтрали, обратная последовательность, активные потери мощности, лексикографическая оптимизация.

Reduction of Phase Unbalance in Low-Voltage Urban Distribution Networks through Optimal Rephasing

Abduraxim D. Taslimov¹, Feruz M. Raximov^{2,a}, Asliddin O. Norqulov²

¹⁾ DSc, prof., Tashkent State Technical University, Tashkent, 100095, Uzbekistan; ataslimov@mail.ru <https://orcid.org/0000-0003-2856-6287>

^{2a)} PhD., Docent, Navoi State University of Mining and Technologies, Navoi, 210100, Uzbekistan; feruz.raximov.2017@mail.ru <https://orcid.org/0009-0008-6832-0509>

²⁾ Head teacher, Navoi State University of Mining and Technologies, Navoi, 210100, Uzbekistan; asliddin.norqulov.91@mail.ru <https://orcid.org/0000-0002-4521-8367>

Relevance: Uneven allocation of single-phase consumers in low-voltage urban networks causes phase-current unbalance, increased fundamental-frequency neutral current, unequal bus voltages and additional conductor losses. Rephasing can improve the operating state without new compensating equipment, but both the number of switching operations and feeder losses should be considered.

Aim: to reach a prescribed phase active-power imbalance limit with the minimum number of rephasings and then select, within that minimum-switch layer, the configuration with the lowest active-power loss in a 0.4 kV three-phase four-wire feeder.

Methods: a 230/400 V five-section radial feeder with 15 equivalent single-phase load groups was studied. The minimum number of rephasings was determined by complete combinatorial enumeration. All admissible configurations in the minimum layer were then evaluated by nonlinear three-phase four-wire power-flow calculation. Sensitivity to the imbalance limit, loading level and neutral resistance was also examined.

Results: for the 5% imbalance target the minimum number of rephasings is three, with 57 admissible configurations. The L1: A→C, L7: A→B, L8: B→C configuration gives the minimum active-power loss of 5.3051 kW, a fundamental neutral current of 7.29 A and a maximum negative-sequence voltage factor of 0.237%. Relative to the initial 7.5850 kW, active-power loss is reduced by 30.06%.

Keywords: 0.4 kV distribution network, phase unbalance, rephasing, three-phase four-wire feeder, neutral current, negative sequence, active-power loss, lexicographic optimization.

1. Kirish (Introduction)

Past kuchlanishli shahar elektr tarmoqlarida ko'p sonli bir fazali maishiy va kommunal iste'molchilar uch fazali 0,4 kV tizimdan ta'minlanadi. Abonentlar soni fazalar bo'yicha teng bo'lsa ham ularning quvvati, quvvat koeffitsiyenti va yuklama grafigi turlicha bo'lgani uchun faza toklarining amplitudalari farqlanadi. Natijada nol va manfiy ketma-ketlik tashkil etuvchilari paydo bo'ladi, neytral o'tkazgich yuklanadi, tugun kuchlanishlari farqlanadi va texnik isroflar ortadi [1–4].

Fazalarni qayta taqsimlash nosimmetriyani yangi kompensatsion qurilma o'rnatmasdan kamaytirish usullaridan biridir. Biroq qayta ulashlar sonini kamaytirish, neytral tokni pasaytirish va isrofini minimallashtirish alohida yangi mezonlar emas. Pérez Abril [6] ko'p mezonli faza balansini, Grigoraş va hammualliflar [8] aqlli hisoblagich ma'lumotlari asosidagi sutkalik balanslashni, Jimenez va hammualliflar [11] berilgan nosimmetriya maqsadida qayta ulanadigan iste'molchilar sonini kamaytirishni, Lin va hammualliflar [13] esa iqtisodiy xarajatlar bilan bog'langan butun-sonli modelni ko'rib chiqqan. Fidalgo va hammualliflar [7] katta past kuchlanishli tarmoqda ko'p bosqichli qidiruv orqali energiya isrofi va hisoblash murakkabligini kamaytirishga e'tibor qaratgan.

Mazkur ishning asosiy hissasi ma'lum optimallashtirish mezonlarini yangilik sifatida talqin qilishda emas, balki ularni uch fazali to'rt simli past kuchlanishli tarmoqda qat'iy leksikografik tartibda qo'llashdadir. Taklif etilgan yondashuvda masala ikki ketma-ket bosqichda yechiladi. Birinchi bosqichda berilgan faza aktiv quvvat nosimmetriyasi chegarasi bajarilgan holda iste'molchilarni fazalararo qayta ulashlar sonining global minimal qiymati aniqlanadi. Ikkinchi bosqichda esa faqat shu minimal qayta ulashlar qatlamiga kiruvchi barcha ruxsat etilgan konfiguratsiyalar uch fazali to'rt simli tarmoqning noliner elektr rejimi bo'yicha hisoblanadi. Har bir variant uchun faza va neytral toklar, tugun kuchlanishlari hamda aktiv quvvat isroflari aniqlanib, ular orasidan umumiy aktiv quvvat isrofi eng kichik bo'lgan konfiguratsiya tanlanadi. Shu tariqa, qayta ulashlar sonini minimallashtirish birlamchi, aktiv quvvat isrofini kamaytirish esa ikkilamchi mezon sifatida qat'iy ketma-ketlikda qo'llanadi. Bunday yondashuv bir nechta mezonni bitta og'irliklangan



maqsad funksiyasiga birlashtirish zaruratini bartaraf etadi va yechimni talqin qilishni soddalashtiradi.

1-jadval. Yaqin tadqiqotlardan metodik farqlar

Table 1. Methodological differences from related studies

Manba	Asosiy yondashuv	Rejim/isrof	Ushbu ish bilan farqi
Pérez Abril [6]	Ko'p mezonli Pareto qidiruvi	Isrof, neytral tok	Qat'iy leksikografik tartib yo'q
Jimenez va b. [11]	Minimal qayta ulash	Balans ko'rsatkichlari	Minimal qatlam to'liq uch fazali hisob bilan saralanmagan
Lin va b. [13]	Butun-sonli model	Isrof, neytral tok, xarajat	Mezonlar bitta umumiy funksiyada
Fidalgo va b. [7]	Ko'p bosqichli qidiruv	Energiya isrofi	Katta tarmoqqa yo'naltirilgan
Ushbu ish	To'liq kombinatorik qidiruv	Minimal qatlamda minimal isrof	57 variantning barchasi tekshirilgan

Tadqiqotning maqsadi 0,4 kV shahar tarmog'ida belgilangan faza aktiv quvvat nosimmetriyasi chegarasiga minimal sonli qayta ulash bilan erishish va minimal qayta ulashlar to'plami ichidan aktiv quvvat isrofi eng kichik konfiguratsiyani aniqlashdan iborat.

2. Materiallar va usullar (Methods and materials)

A, B va C fazalarning aktiv quvvatlari orqali o'rtacha faza quvvati va ushbu ishda algoritmik filtr sifatida qo'llangan nisbiy nosimmetriya indeksi quyidagicha aniqlandi:

$$P_{av} = \frac{P_A + P_B + P_C}{3}; \quad K_P = \frac{\max\{|P_A - P_{av}|, |P_B - P_{av}|, |P_C - P_{av}|\}}{P_{av}} \cdot 100\% \quad (1)$$

bu yerda: K_P - standart elektr energiyasi sifati ko'rsatkichi emas, balki qayta ulashlarni saralash uchun mualliflik hisobiy indeksidir. Asosiy hisobda $K_{p,lim}=5\%$ algoritmik maqsad sifatida qabul qilindi; 2 va 10 % holatlar alohida sezgirlik tahlilida tekshirildi.

Kuchlanish va tok nosimmetriyasi simmetrik tashkil etuvchilar orqali baholandi:

$$\underline{U}_1 = \frac{1}{3}(\underline{U}_A + a\underline{U}_B + a^2\underline{U}_C); \quad \underline{U}_2 = \frac{1}{3}(\underline{U}_A + a^2\underline{U}_B + a\underline{U}_C); \quad K_{2U} = \frac{|\underline{U}_2|}{|\underline{U}_1|} \quad (2)$$

$$\underline{I}_1 = \frac{1}{3}(\underline{I}_A + a\underline{I}_B + a^2\underline{I}_C); \quad \underline{I}_2 = \frac{1}{3}(\underline{I}_A + a^2\underline{I}_B + a\underline{I}_C); \quad K_{2I} = \frac{|\underline{I}_2|}{|\underline{I}_1|} \cdot 100\% \quad (3)$$

Uch fazali to'rt simli tarmoqning fundamental chastotadagi neytral toki va j-uchastkadagi faza hamda neytral o'tkazgichlarning aktiv quvvat isrofi:

$$\underline{I}_N = -(\underline{I}_A + \underline{I}_B + \underline{I}_C); \quad \Delta P_j = R_{\varphi,j} (|\underline{I}_{A,j}|^2 + |\underline{I}_{B,j}|^2 + |\underline{I}_{C,j}|^2) + R_{N,j} |\underline{I}_{N,j}|^2 \quad (4)$$

$$\Delta P_\Sigma = \sum_{j=1}^m \Delta P_j \quad (5)$$

Neytral tokning ushbu ifodasi garmonikalarni, xususan neytralda yig'iluvchi uch karrali garmonikalarni hisobga olmaydi; shuning uchun maqoladagi I_n qiymatlari fundamental chastotaga tegishlidir.

Hisoblash tajribasi 230/400 V kuchlanishli besh uchastkali radial tarmoqda bajarildi. Barcha yuklamalar doimiy kompleks quvvat modeli va $\cos\varphi=0,95$ bilan ifodalandi. Bazaviy holatda faza va neytral o'tkazgichlarning solishtirma impedansi $z_\varphi=z_N=0,253+j0,080 \Omega/\text{km}$ deb olindi.

2-jadval. Hisobiy fider va bir fazali yuklama guruhlar

Table 2. Calculation feeder and single-phase load groups

Tugun	Uchastka, m	A faza, kW	B faza, kW	C faza, kW
1	112	L1-11,70; L2-7,80	L3-5,20	—
2	98	L4-10,40	L5-6,50	L6-3,90
3	126	L7-9,75	L8-5,85	L9-4,55
4	112	L10-9,10	L11-7,15	L12-5,20
5	140	L13-8,45	L14-5,85	L15-5,20
Jami	588	57,20	30,55	18,85

Umumiy aktiv yuklama 106,60 kW, o'rtacha faza quvvati 35,533 kW bo'lib, boshlang'ich $K_P=60,98\%$ ni tashkil etdi. Har bir i-yuklamaning p fazaga ulanishi $x_{i,p}$ binar o'zgaruvchi bilan ifoda-



landi; har bir yuklama faqat bitta fazaga ulanadi. Qayta ulashlar soni dastlabki fazaga nisbatan aniqlanadi:

$$x_{i,p} \in \{0,1\}, \quad p \in \{A, B, C\}; \quad x_{i,A} + x_{i,B} + x_{i,C} = 1; \quad N_{sw} = \sum_{i=1}^n (1 - x_{i,p_i^0}) \quad (6)$$

Leksikografik optimallashtirishda birinchi bosqich qayta ulashlar sonini, ikkinchi bosqich esa faqat minimal qatlam ichida aktiv quvvat isrofini minimallashtiradi:

$$N_{sw}^{min} = \min N_{sw} \quad \text{shart ostida} \quad K_p \leq K_p^{lim}; \quad x^* = \arg \min_{x \in \Omega(N_{sw}^{min}, K_p^{lim})} \Delta P_{\Sigma}(x) \quad (7)$$

Nomzod konfiguratsiya umumiy algoritmda faza kuchlanishlari, faza va neytral o'tkazgich toklarining ruxsat etilgan qiymatlari hamda manfiy ketma-ketlik kuchlanish ko'effitsiyenti bo'yicha ekspluatatsion cheklovlardan o'tishi lozim. Ushbu sintetik modelda o'tkazgichning uzoq muddatli ruxsat etilgan toki berilmagani sabab termik limit sonli mezon sifatida faollashtirilmadi; kuchlanish uchun 0,9–1,1 nisbiy birlik muhandislik diapazoni nazorat qilindi.

Aynan k ta yuklama qayta fazalansa, har biri uchun dastlabki fazadan tashqari ikkita variant mavjud; shuning uchun to'liq qidiruvdagi konfiguratsiyalar soni:

$$N_k = \binom{n}{k} 2^k; \quad N_{\leq k^*} = \sum_{r=0}^{k^*} \binom{n}{r} 2^r \quad (8)$$

$n=15$ uchun 0–3 qayta ulash qatlamlarida jami 4091 ta algebraik konfiguratsiya tekshirildi. Katta fiderlarda kombinatorik o'sish sabab aralash butun-sonli dasturlash, tarmoqlangan qidiruv yoki metaevristik usullardan foydalanish maqsadga muvofiq [12,13].

Elektr rejimi ketma-ket orqaga-oldinga hisoblash usulida aniqlandi. Manba kuchlanishlari $U_A=230 \angle 0^\circ$, $U_B=230 \angle -120^\circ$ va $U_C=230 \angle 120^\circ$ V deb olindi; har bir iteratsiyada uchastka faza va neytral toklaridan tugun potentsiallari qayta hisoblandi. Yaqinlashish mezonini va maksimal iteratsiyalar soni:

$$\max |U^{(s+1)} - U^{(s)}| \leq 10^{-6} \text{ V} \quad (9)$$

ya'ni $\epsilon=10^{-6}$ V va 100 iteratsiya. Hisoblashlar Python 3.13.5 muhitida ikki karra aniqlikdagi kompleks arifmetika bilan bajarildi; boshlang'ich rejim 11, optimal rejim 8 iteratsiyada yaqinlashdi.

3. Natijalar va muhokama (Results and discussion)

0, 1, 2 va 3 ta qayta ulash qatlamlari to'liq sanab chiqildi. 5 % mezon uchun bir va ikki qayta ulash yetarli emasligi, minimal zarur qayta ulashlar soni uchta ekanligi aniqlandi.

3-jadval. Qayta ulash qatlamlari bo'yicha algebraik natijalar

Table 3. Algebraic results by switching layers

Qayta ulashlar soni	Konfiguratsiyalar soni	Eng kichik K_p , %
0	1	60,98
1	30	28,05
2	420	14,02
3	3640	1,22

Uchta qayta ulash qatlamida $K_p \leq 5$ % shartini 57 ta konfiguratsiya qanoatlantirdi. Ularning barchasi uch fazali to'rt simli nolinear rejim hisobidan o'tkazildi. Muhim jihat shundaki, eng kichik K_p va eng kichik fider isrofi bir xil konfiguratsiyada kuzatilmadi.

4-jadval. Ikki asosiy optimumning farqi

Table 4. Difference between the two main optima

Mezon	Qayta ulashlar	K_p , %	ΔP_{Σ} , kW	$I_n / K_{2U, \max}$
Eng yaxshi algebraik balans	L1 A→C; L7 A→C; L9 C→B	1,22	5,3242	2,27 A / 0,316 %
Eng kichik aktiv isrof	L1 A→C; L7 A→B; L8 B→C	3,05	5,3051	7,29 A / 0,237 %

Demak, 1,22 % uchta qayta ulashdagi eng yaxshi algebraik balans, 3,05 % esa 5 % lik ruxsat etilgan qatlam ichidagi minimal aktiv quvvat isrofiga mos optimumdir. Bu ikki natija bir-biriga zid emas, balki leksikografik modelning turli bosqichlariga tegishlidir.

Tanlangan L1 A→C, L7 A→B va L8 B→C konfiguratsiyasida faza aktiv quvvatlari quyidagicha bo'ldi:

$$P_A = 35,75 \text{ kW}, \quad P_B = 34,45 \text{ kW}, \quad P_C = 36,40 \text{ kW}; \quad K_p = 3,05\% \quad (10)$$

**5-jadval.** Dastlabki va tanlangan statik rejimlar**Table 5.** Initial and selected steady-state operating modes

Ko'rsatkich	Dastlabki	Optimal	O'zgarish
$P_A / P_B / P_C$, kW	57,20 / 30,55 / 18,85	35,75 / 34,45 / 36,40	–
K_p , %	60,98	3,05	–95,00 %
$I_A / I_B / I_C$, A	291,76 / 144,44 / 86,41	172,13 / 166,26 / 173,67	–
Fundamental I_n , A	175,51	7,29	–95,84 %
$K_{\Delta I}$, %	36,61	1,22	–96,66 %
$K_{\Delta U, \max}$, %	2,022	0,237	–88,26 %
$U_{\min}$, V	195,97	213,46	+8,93 %
ΔP_{Σ} , kW	7,5850	5,3051	–30,06 %

Aktiv quvvat isrofining nisbiy kamayishi:

$$\delta_{\Delta P} = \frac{7,5850 - 5,3051}{7,5850} \cdot 100\% = 30,06\% \quad (10)$$

bu yerda: 30,06 % qiymat energiya tejallishi emas, aynan 100 % hisobiy yuklamadagi statik aktiv quvvat isrofining kamayishidir.

5 % mezonning normativ emas, algoritmik parametr ekanini tekshirish, yuklama darajasi va neytral qarshiligi ta'sirini baholash uchun sezgirlik tahlili bajarildi. Natijalar quyidagi ixcham jadvalda umumlashtirilgan.

6-jadval. Asosiy sezgirlik natijalari**Table 6.** Main sensitivity analysis results

Sezgirlik turi	Variant	ΔP_0 , kW	ΔP_{opt} , kW	Kamayish, %	$K_{\Delta U, opt}$, %
K_p chegarasi	2 %	7,5850	5,3242	29,81	0,316
	5 %	7,5850	5,3051	30,06	0,237
	10 %	7,5850	5,3051	30,06	0,237
Yuklama darajasi	30 %	0,5896	0,4414	25,14	0,057
	60 %	2,4953	1,8238	26,91	0,125
	100 %	7,5850	5,3051	30,06	0,237
R_n/R_{ϕ}	1,0	7,5850	5,3051	30,06	0,237
	1,5	8,5179	5,3398	37,31	0,250
	2,0	9,6307	5,3745	44,19	0,263

2, 5 va 10 % chegaralarning barchasida minimal qayta ulashlar soni uchta bo'lib qoldi. 5 va 10 % hollarda bir xil minimal isrofli konfiguratsiya tanlandi; 2 % qat'iy chegarada esa algebraik balans bo'yicha eng yaxshi variant zarur bo'ldi. 30, 60 va 100 % mutanosib yuklama hamda $R_n/R_{\phi}=1-2$ oralig'ida 5 % mezon uchun L1 A→C, L7 A→B, L8 B→C konfiguratsiyasi saqlandi.

Olingan natijalarni «faza balanslashning yangi maqsadi» deb talqin qilish to'g'ri emas: qayta ulashlar soni, neytral tok va isroflarni optimallashtirish avvalgi ishlarda ko'rilgan [5,6,11–13,15]. Ushbu tadqiqotning himoyalangan tomoni – berilgan K_p chegarasi ostida qayta ulashlar sonini qat'iy birlamchi mezon sifatida global minimallashtirish va aynan shu minimal qatlamdagi barcha ruxsat etilgan variantlarni nolinear uch fazali to'rt simli elektr rejimi bo'yicha to'liq saralashdir. Shu sababli tanlangan 5,3051 kW natija heuristik topilma emas, mazkur test tarmog'i uchun tekshirilgan global minimum hisoblanadi.

1,22 va 3,05 % natijalari orasidagi farq ham shu tartib bilan izohlanadi. Birlamchi bosqich qayta ulashlar sonini uchta darajada mahkamlaydi; ikkilamchi bosqich esa $K_p \leq 5$ % shartini bajargan 57 ta variant orasida aktiv quvvat isrofini minimallashtiradi. Demak, faza quvvatlarini eng teng taqsimlash bilan o'tkazgichlardagi eng kichik quvvat isrofi bir xil konfiguratsiyaga mos kelishi shart emas.

EN 50160: 2022 bo'yicha kuchlanish nosimmetriyasi bir haftadagi 10 minutlik o'rtacha qiymatlarning 95 % statistik mezoni asosida baholanadi [1]. Shu sababli maqoladagi 2,022 va 0,237 % qiymatlar bitta statik ish nuqtasining hisobiy ko'rsatkichlari bo'lib, standartga vaqt bo'yicha muvofiqlik xulosasi sifatida talqin qilinmaydi. To'liq energiya tahlili ham 24 soatlik yoki haftalik haqiqiy yuklama qatorlarini talab qiladi.



Modelning cheklovlari quyidagicha: bazaviy holatda faza va neytral impedanslari teng qabul qilingan; barcha yuklamalar bir xil quvvat koeffitsiyentli chiziqli ekvivalentlar; garmonikalar hisobga olinmagan; 30/60/100 % tahlili mustaqil abonentlarning sutkalik grafisini almashtirmaydi. Neytral qarshiligi bo'yicha sezgirlik asosiy optimum saqlanishini ko'rsatdi, biroq real obyekt uchun haqiqiy o'tkazgich kesimi, harorati, ruxsat etilgan toki va garmonik spektr kiritilishi zarur.

To'liq kombinatorik qidiruv $n=15$ uchun global etalon beradi, ammo yuklamalar soni ortganda hisoblash hajmi tez o'sadi. Shuning uchun katta shahar fiderlarida xuddi shu leksikografik mezonni saqlagan holda aralash butun-sonli dasturlash, tarmoqlangan qidiruv, zarrachalar to'dasi yoki genetik algoritim, shuningdek ko'p bosqichli dekompozitsiya usullaridan foydalanish maqsadga muvofiq [12,13,14].

4. Xulosa (Conclusion)

0,4 kV uch fazali to'rt simli shahar tarmog'ida fazalarni qayta taqsimlash qat'iy ikki bosqichli leksikografik tartibda tekshirildi. To'liq kombinatorik qidiruv $K_p \leq 5$ % sharti uchun bir va ikki qayta ulash yetarli emasligini, minimal qayta ulashlar soni uchta ekanini va ushbu qatlamda 57 ta ruxsat etilgan konfiguratsiya mavjudligini ko'rsatdi.

57 konfiguratsiyaning barchasi elektr rejimi hisobidan o'tkazilganda L1 $A \rightarrow C$, L7 $A \rightarrow B$ va L8 $B \rightarrow C$ varianti 5,3051 kW bilan minimal statik aktiv quvvat isrofini berdi. Bunda faza quvvatlari 35,75; 34,45 va 36,40 kW, fundamental neytral tok 7,29 A va maksimal manfiy ketma-ketlik kuchlanish koeffitsiyenti 0,237 % bo'ldi; boshlang'ich 7,5850 kW ga nisbatan isrof 30,06 % kamaydi.

Uch qayta ulash bilan $K_p=1,22$ % ga erishish mumkin, biroq bu variantning isrofi 5,3242 kW. Demak, eng kichik faza quvvat nosimmetriyasi va eng kichik fider isrofi bir xil optimum emas. Sezgirlik tahlillari tanlangan test tarmog'ida yechimning parametrik barqarorligini tasdiqladi, ammo real vaqt qatorli dala ma'lumotlari bilan tekshirish keyingi tadqiqot vazifasi bo'lib qoladi.

ADABIYOTLAR

1. CENELEC. EN 50160:2022. Voltage Characteristics of Electricity Supplied by Public Distribution Networks. Brussels, 2022.
2. IEC. IEC 61000-4-30:2025, Ed. 4.0. Electromagnetic Compatibility (EMC) – Part 4-30: Testing and Measurement Techniques – Power Quality Measurement Methods. Corrected version 2026-07. Geneva, 2025/2026.
3. Kersting W.H. Distribution System Modeling and Analysis. 4th ed. Boca Raton: CRC Press, 2018.
4. Teng J.-H. A direct approach for distribution system load flow solutions. IEEE Transactions on Power Delivery. 2003;18(3):882–887. doi:10.1109/TPWRD.2003.813818.
5. Rakhimov, F. Improving Energy Efficiency in Urban Distribution Electric Networks through a Multi-Criteria Optimization Method // Journal of Advances in Engineering Technology. – 2025. – No. 4. – P. 33–40.
6. Pérez Abril I. Multi-objective optimization of the balancing of phases in primary distribution circuits. International Journal of Electrical Power & Energy Systems. 2016; 82:420–428. doi:10.1016/j.ijepes.2016.03.047.
7. Fidalgo J.N., Moreira C., Cavalheiro R. Impact of Load Unbalance on Low Voltage Network Losses. 2019 IEEE Milan PowerTech. 2019. doi:10.1109/PTC.2019.8810710.
8. Grigoraş G., Neagu B.-C., Gavrilăş M., Triştiu I., Bulac C. Optimal Phase Load Balancing in Low Voltage Distribution Networks Using a Smart Meter Data-Based Algorithm. Mathematics. 2020;8(4):549. doi:10.3390/math8040549.
9. Cortés-Cañedo B., Avellaneda-Gómez L.S., Montoya O.D., Alvarado-Barrios L., Chamorro H.R. Application of the Vortex Search Algorithm to the Phase-Balancing Problem in Distribution Systems. Energies. 2021;14(5):1282. doi:10.3390/en14051282.
10. Montoya O.D., Alarcon-Villamil J.A., Hernández J.C. Operating Cost Reduction in Distribution Networks Based on the Optimal Phase-Swapping including the Costs of the Working Groups and Energy Losses. Energies. 2021;14(15):4535. doi:10.3390/en14154535.
11. Jimenez V.A., Will A.L.E., Lizondo D.F. Phase reassignment for load balance in low-voltage distribution networks. International Journal of Electrical Power & Energy Systems. 2022;137:107691. doi:10.1016/j.ijepes.2021.107691.
12. Homaei O., Mirzaei M.J., Najafi A., Leonowicz Z., Jasinski M. A practical probabilistic approach for load balancing in data-scarce LV distribution systems using discrete PSO and 2m+1 PEM. International Journal of Electrical Power & Energy Systems. 2022;135:107530. doi:10.1016/j.ijepes.2021.107530.



13. Lin C.-H., Ku T.-T., Li C.-S., Chen C.-S. Optimal Phase Balancing in Electricity Distribution Feeders Using Mixed-Integer Linear Programming. *Sustainability*. 2023;15(5):4473. doi:10.3390/su15054473.
14. Rakhimov, F., Taslimov, A., Majidov, A., Norqulov, A. Optimization of Losses by Switching to Higher Voltage in Distribution Networks // *E3S Web of Conferences*. – 2024. – Vol. 525. – 03009.

REFERENCES

1. CENELEC. EN 50160:2022. Voltage Characteristics of Electricity Supplied by Public Distribution Networks. Brussels, 2022.
2. IEC. IEC 61000-4-30:2025, Ed. 4.0. Electromagnetic Compatibility (EMC) – Part 4-30: Testing and Measurement Techniques – Power Quality Measurement Methods. Corrected version 2026-07. Geneva, 2025/2026.
3. Kersting W.H. Distribution System Modeling and Analysis. 4th ed. Boca Raton: CRC Press, 2018.
4. Teng J.-H. A direct approach for distribution system load flow solutions. *IEEE Transactions on Power Delivery*. 2003;18(3):882–887. doi:10.1109/TPWRD.2003.813818.
5. Rakhimov, F. Improving Energy Efficiency in Urban Distribution Electric Networks through a Multi-Criteria Optimization Method // *Journal of Advances in Engineering Technology*. – 2025. – No. 4. – P. 33–40.
6. Pérez Abril I. Multi-objective optimization of the balancing of phases in primary distribution circuits. *International Journal of Electrical Power & Energy Systems*. 2016; 82:420–428. doi:10.1016/j.ijepes.2016.03.047.
7. Fidalgo J.N., Moreira C., Cavalheiro R. Impact of Load Unbalance on Low Voltage Network Losses. 2019 IEEE Milan PowerTech. 2019. doi:10.1109/PTC.2019.8810710.
8. Grigoraș G., Neagu B.-C., Gavrilas M., Triștiu I., Bulac C. Optimal Phase Load Balancing in Low Voltage Distribution Networks Using a Smart Meter Data-Based Algorithm. *Mathematics*. 2020;8(4):549. doi:10.3390/math8040549.
9. Cortés-Caicedo B., Avellaneda-Gómez L.S., Montoya O.D., Alvarado-Barrios L., Chamorro H.R. Application of the Vortex Search Algorithm to the Phase-Balancing Problem in Distribution Systems. *Energies*. 2021;14(5):1282. doi:10.3390/en14051282.
10. Montoya O.D., Alarcon-Villamil J.A., Hernández J.C. Operating Cost Reduction in Distribution Networks Based on the Optimal Phase-Swapping including the Costs of the Working Groups and Energy Losses. *Energies*. 2021;14(15):4535. doi:10.3390/en14154535.
11. Jimenez V.A., Will A.L.E., Lizondo D.F. Phase reassignment for load balance in low-voltage distribution networks. *International Journal of Electrical Power & Energy Systems*. 2022;137:107691. doi:10.1016/j.ijepes.2021.107691.
12. Homaei O., Mirzaei M.J., Najafi A., Leonowicz Z., Jasinski M. A practical probabilistic approach for load balancing in data-scarce LV distribution systems using discrete PSO and 2m+1 PEM. *International Journal of Electrical Power & Energy Systems*. 2022;135:107530. doi:10.1016/j.ijepes.2021.107530.
13. Lin C.-H., Ku T.-T., Li C.-S., Chen C.-S. Optimal Phase Balancing in Electricity Distribution Feeders Using Mixed-Integer Linear Programming. *Sustainability*. 2023;15(5):4473. doi:10.3390/su15054473.
14. Rakhimov, F., Taslimov, A., Majidov, A., Norqulov, A. Optimization of Losses by Switching to Higher Voltage in Distribution Networks // *E3S Web of Conferences*. – 2024. – Vol. 525. – 03009.