O‘ZBEKISTON RESPUBLIKASI OLIY VA O‘RTA MAXSUS
TA’LIM VAZIRLIGI

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TEXNIKA UNIVERSITETI

«ELEKTR STANSIYALAR REJIMLARI VA O‘TISH JARAYONLARINING MAXSUS MASALALARI»

fani bo‘yicha amaliy mashg‘ulotlar uchun

USLUBIY QO‘LLANMA

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«Elektr stansiyalar rejimlari va o‘tish jarayonlarining maxsus masalalari» fani bo‘yicha amaliy mashg‘ulotlar uchun uslubiy qo‘llanmada qisqacha nazariy ma’lumotlar va hisobiy topshiriqning mazmuni yoritilgan. Nazariy va amaliy materiallar elektr stansiyalari va elektr energetika tizimlarining turg‘un rejimlarida matematik uslublarning turli xillarini qo‘llash bilan chiziqlilik va nochiziqlilikni tashkil etishdagi kompleks savollarni qamrab oladi.

Uslubiy qo‘llanma 5A310203 – «Elektr stansiyalari» mutaxassisligi bo‘yicha magistratura talabalari uchun tuzilgan.

Abu Rayhon Beruniy nomidagi Toshkent davlat texnika universiteti ilmiy-uslubiy kengashi qaroriga muvofiq chop etildi

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1. HISOBIY TOPSHIRIQ MUNDARIJASI

Berilgan elektr bog'lanishli sxema uchun (1.1- rasm):

1. Berilgan tarmoq qarshiliklari (1.1-jadval) bo'yicha tugun o'tkazuvchanliklari matritsasini va barcha tugunlarning balanslovchi tugun bilan bog'lanishining o'tkazuvchanlik vektorini tuzish.

2. Berilgan tugunlardagi toklar va balanslovchi tugun kuchlanishi (1.2-jadval) bo'yicha sistemani Gauss (algebraik va jadval ko'rinishida) va triangulyatsiya uslubida yechish yo'li bilan tugunlardagi kuchlanishlarni aniqlash.

3. Gauss (jadval ko'rinishida), faktorizatsiya, topologiya va kommutatsiya uslubida tugun qarshiliklar matritsasini aniqlash va tugunlardagi kuchlanishlarni teskari matritsa uslubida topish.

4. Insidensiya (tugunlar va shahobchalar bog'lanish) matritsasini tuzish va u bo'yicha tarmoqlardagi toklarni aniqlash.

5. Tugunlardagi quvvatlar va tarmoqdagi umumiy quvvat isroflarini aniqlash.

6. Tugunlardagi berilgan quvvat va balanslovchi tugun kuchlanishi bo'yicha quyidagi uslublarda tugunlardagi kuchlanishlarni aniqlash:

– oddiy iteratsiya;
– Gauss-Zeydel;
– Nyuton-Rafson.

Izoh. Hisoblashlarni osonlashtirish maqsadida tarmoqning aktiv qarshiliklarga ega bo'lgan gipotetik sxemasi ko'rib chiqiladi.

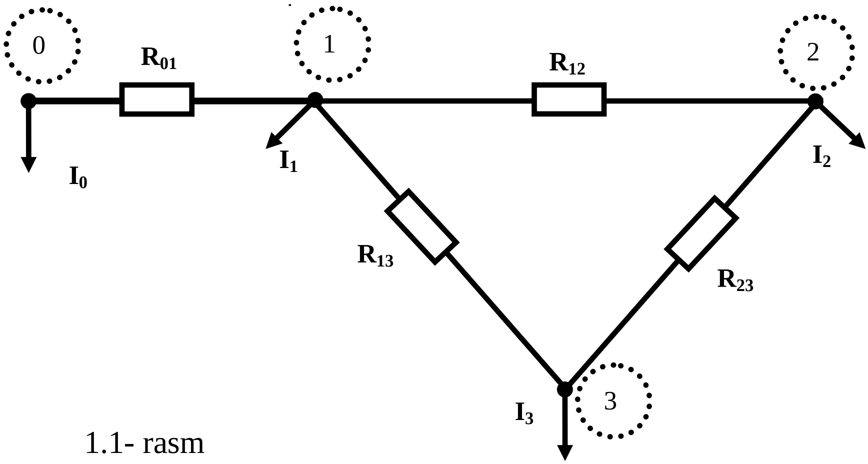
Variant nomeri o'qituvchi tomonidan ikkita son ko'rinishida beriladi. Birinchi son bo'yicha 1.1 – jadvaldan shahobchalar qarshiligi, ikkinchi son bo'yicha 1.2 – jadvaldan balanslovchi tugun kuchlanishi va tugunlardagi toklar olinadi.

1.1-jadval. Tarmoqlar qarshiliklari (Om)

Variantlar	**R_{01}**	**R_{12}**	**R_{13}**	**R_{23}**
0	1	3	6	4
1	1	4	5	3
2	2	1	4	8
3	5	8	2	5
4	3	4	1	2
5	3	5	1	4
6	2	2	6	5
7	4	1	7	6
8	4	6	8	1
9	5	6	7	2

1.2-jadval. Balanslovchi tugun kuchlanishi U_0 (kV) va tugunlardagi toklar I_i (kA)

Variantlar	**U_0**	**I_1**	**I_2**	**I_3**
0	110	2	6	-4
1	110	3	-2	4
2	115	5	-6	3
3	115	4	-4	6
4	121	8	3	-5
5	121	7	5	-3
6	220	10	-11	9
7	220	12	-10	8
8	230	15	7	-13
9	230	14	9	-16



1.1- rasm

2. QISQACHA NAZARIY MA'LUMOTLAR

Foydalaniladigan tushuncha va tamoyillar:

$\dot{\Pi}$ - parametrning kompleks qiymati (kuchlanish, tok, to'la quvvat, qarshilik va h.k.).

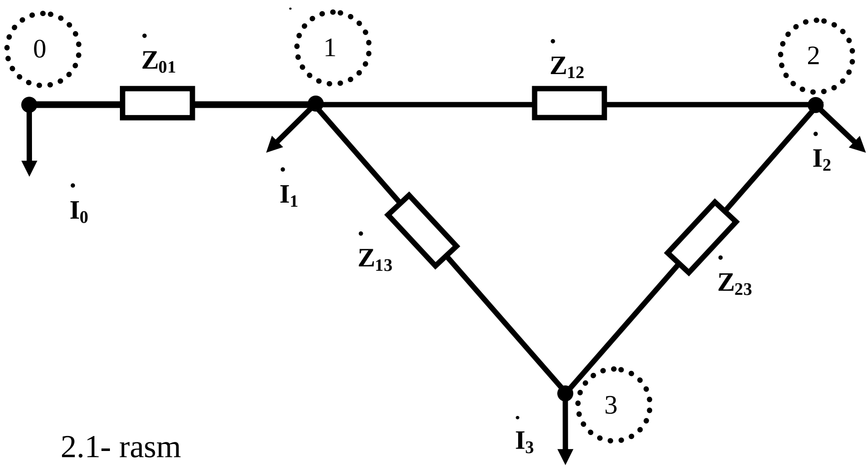
$\hat{\Pi}$ - parametrning kompleks-qo'shma qiymati (kuchlanish, tok, to'la quvvat, qarshilik va h.k.). Agar $\dot{\Pi} = a + jb$ bo'lsa, u holda $\hat{\Pi} = a - jb$ bo'ladi.

$|\Pi|^T$ - transponirlangan matritsa. Bu shuni bildiradiki, $|\Pi|^T$ matritsa qatorlari $|\Pi|$ matritsa ustunlaridir, mos ravishda $|\Pi|^T$ matritsa ustunlari $|\Pi|$ matritsa qatorlaridir.

2.1. TUGUN KUCHLANISH TENGLAMALARINING TUZILISHI

Elektr energetika tizimlarining (EET) turg‘un rejimlarini hisob-lash elektr tarmoqlari tugunlarining kuchlanishlarini aniqlashga olib boradi, qolgan barcha rejim parametrlarini (quvvatlar, isroflar, katta toklar) kuchlanish kattaligiga bog‘liq bo‘lmagan kabi aniqlash mumkin. Shuning uchun EET turg‘un rejimlarini hisoblashning ko‘proq maqsadga muvofiq bo‘lgan modeli tugun kuchlanish tenglamalari (TKT) hisoblanadi.

EETning elektr tarmog‘i uchun TKT tuzilishini ko‘rib chiqamiz, almashtirish sxemasi 2.1-rasmda taqdim etilgan.



2.1- rasm

Kirxgofning birinchi qonuniga muvofiq har bir tugundagi tok tenglamalarini quyidagi ko‘rinishda yozish mumkin:

$$\left.\begin{aligned} &\dot{y}_{01}\cdot(\dot{U}_0-\dot{U}_1)+\dot{I}_0=0\\ &\dot{y}_{10}\cdot(\dot{U}_1-\dot{U}_0)+\dot{y}_{12}\cdot(\dot{U}_1-\dot{U}_2)+\dot{y}_{13}\cdot(\dot{U}_1-\dot{U}_3)+\dot{I}_1=0\\ &\dot{y}_{21}\cdot(\dot{U}_2-\dot{U}_1)+\dot{y}_{23}\cdot(\dot{U}_2-\dot{U}_3)-\dot{I}_2=0\\ &\dot{y}_{31}\cdot(\dot{U}_3-\dot{U}_1)+\dot{y}_{32}\cdot(\dot{U}_3-\dot{U}_2)+\dot{I}_3=0 \end{aligned}\right\}, \qquad (2.1)$$

bu yerda $\dot{y}_{ij}$ - i-j bog‘lanishli o‘tkazuvchanlik, i va j tugunlar orasida;

$\dot{U}_i$, $\dot{I}_i$ - mos ravishda i-tugundagi kuchlanish va tok.

(2.1) tenglamalar sistemasini o‘zgartirib, quyidagini olamiz:

$$\left.\begin{array}{r} \dot{y}_{00}\cdot\dot{U}_0 - y_{01}\cdot\dot{U}_1 + 0\cdot\dot{U}_2 + 0\cdot\dot{U}_3 + \dot{I}_0 = 0 \\ -\dot{y}_{10}\cdot\dot{U}_0 + \dot{y}_{11}\cdot\dot{U}_1 - \dot{y}_{12}\cdot\dot{U}_2 - \dot{y}_{13}\cdot\dot{U}_3 + \dot{I}_1 = 0 \\ 0\cdot\dot{U}_0 - \dot{y}_{21}\cdot\dot{U}_1 + \dot{y}_{22}\cdot\dot{U}_2 - \dot{y}_{23}\cdot\dot{U}_3 + \dot{I}_2 = 0 \\ 0\cdot\dot{U}_0 - \dot{y}_{31}\cdot\dot{U}_1 - \dot{y}_{32}\cdot\dot{U}_2 + \dot{y}_{33}\cdot\dot{U}_3 + \dot{I}_3 = 0 \end{array}\right\}, \quad (2.2)$$

bu yerda

$$\dot{y}_{00} = y_{01}, \qquad \dot{y}_{11} = \dot{y}_{10} + \dot{y}_{12} + \dot{y}_{13},$$
$$\dot{y}_{22} = \dot{y}_{21} + \dot{y}_{23}, \qquad \dot{y}_{33} = \dot{y}_{31} + \dot{y}_{32}.$$

(2.2) tenglamalar sistemasini matritsa ko‘rinishida yozish mumkin:

$$\begin{vmatrix} \dot{y}_{00} & -\dot{y}_{01} & 0 & 0 \\ -\dot{y}_{10} & \dot{y}_{11} & -\dot{y}_{12} & -\dot{y}_{13} \\ 0 & -\dot{y}_{21} & \dot{y}_{22} & -\dot{y}_{23} \\ 0 & -\dot{y}_{31} & -\dot{y}_{32} & \dot{y}_{33} \end{vmatrix} \cdot \begin{vmatrix} \dot{U}_0 \\ \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_3 \end{vmatrix} + \begin{vmatrix} \dot{I}_0 \\ \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}, \qquad (2.3)$$

yoki

$$\dot{Y}_n \cdot \dot{U}_n + \dot{I}_n = 0. \qquad (2.4)$$

Aniqlangan $\dot{Y}_n$ (2.4) matritsa nolga teng, demak uning har bir qator (yoki ustun) elementlari yig‘indisi nolga teng. Shuning uchun (2.3) tenglamalar sistemasidan bittasi qolganlarining natijasi hisoblanadi, toklar balansi tenglamasi quyidagidan boshlanadi

$$\dot{I}_0 + \dot{I}_1 + \dot{I}_2 + \dot{I}_3 = 0.$$

(2.3) sistema tenglamalaridan bittasi (balanslovchi 0 tugun) ni qisqartirib, quyidagini olamiz:

$$\begin{vmatrix} \dot{y}_{11} - \dot{y}_{12} - \dot{y}_{13} \\ -\dot{y}_{21} \quad \dot{y}_{22} - \dot{y}_{23} \\ -\dot{y}_{31} - \dot{y}_{32} \quad \dot{y}_{33} \end{vmatrix} \cdot \begin{vmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_3 \end{vmatrix} = \begin{vmatrix} \dot{y}_{10} \\ 0 \\ 0 \end{vmatrix} \cdot \dot{U}_0 - \begin{vmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{vmatrix}, \qquad (2.5)$$

yoki

$$\dot{Y} \cdot \dot{U} = \left|\dot{Y}_{k0}\right| \cdot \dot{U}_0 - \dot{I}\,. \qquad (2.6)$$

Bu yerda $\left|\dot{Y}_{k0}\right|$ - tugunlarning balanslovchi nol tugun bilan bog‘langan tarmoq o‘tkazuvchanliklarining ustun matritsasi.

(2.6) ni xuddi chiziqli sistema kabi teskari matritsa $\dot{Y}^{-1} = \dot{Z}$ yordamida yechib, quyidagini olamiz:

$$\dot{U} = \dot{Z} \cdot (\left|\dot{Y}_{k0}\right| \cdot \dot{U}_0 - \dot{I}) = \left|\dot{A}_k\right| \cdot \dot{U}_0 - \dot{Z} \cdot \dot{I} \qquad (2.7)$$

2.1-rasm uchun tenglamalar sistemasi (2.7) quyidagi ko‘rinishga ega bo‘ladi:

$$\begin{vmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_3 \end{vmatrix} = \begin{vmatrix} \dot{A}_{10} \\ \dot{A}_{20} \\ \dot{A}_{30} \end{vmatrix} \cdot \dot{U}_0 - \begin{vmatrix} \dot{z}_{11} & \dot{z}_{12} & \dot{z}_{13} \\ \dot{z}_{21} & \dot{z}_{22} & \dot{z}_{23} \\ \dot{z}_{31} & \dot{z}_{32} & \dot{z}_{33} \end{vmatrix} \cdot \begin{vmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \end{vmatrix}. \qquad (2.8)$$

Sxemada transformatorlar bo‘lmagan, ya’ni parametrlar bir pog‘ona kuchlanishga keltirilgan holda quyidagini isbot qilish mumkin:

$$\dot{A}_{k0} = \dot{Z} \cdot \dot{Y}_{k0} = 1 \qquad (2.9)$$

Hisoblashlar uchun berilgan ma’lumotlar hisobiy sxema tugunlari orasidagi bog‘lanish qarshiliklari hamda tugunlarning yoki tok kattaliklari ($\dot{I}$ matritsa), yoki quvvat kattaliklari ($\dot{S}$ matritsa) hisoblanadi.

Tugunlardagi dastlabki ma’lumotlar quvvat $\dot{S}_k = \dot{U}_k \hat{I}$ ko‘rinishida berilgan hollarda toklar matritsasi (2.6) va (2.7) tenglamalarda quyidagicha aniqlanadi:

$$\left|\dot{I}_k\right| = \left\|\hat{S}_k / \hat{U}_k\right\| \qquad (2.10)$$

va tugun tenglamalari qidirilayotgan kuchlanishga nisbatan nochiziqli tenglamalarga o‘zgaradi.

Agar tugun toklar berilgan bo‘lsa, tugun kuchlanish tenglamalari (2.6) yoki (2.7) chiziqli hisoblanadi. Bunday holatlarda tugunlardagi kuchlanishlarni aniqlash uchun chiziqli tenglamalar sistemasini yechishning matematik uslublari (Gauss, triangulyatsiya, teskari matritsa uslubi) dan foydalanish mumkin. Nochiziqli TKT ni faqat iteratsion uslublar (oddiy iteratsiya, Gauss-Zeydel, Nyuton-Rafson va boshqa uslublar) dan foydalanish bilan yechish mumkin.

2.2. CHIZIQLI TUGUN KUCHLANISH TENGLAMALARINI YECHISH USLUBLARI

2.2.1. GAUSS USLUBI

Gauss uslubining qo‘llanilishini quyidagi chiziqli tenglamalar sistemasida ko‘rib chiqamiz:

$$\begin{aligned} a_{11} \cdot X_1 + a_{12} \cdot X_2 + a_{13} \cdot X_3 &= a_{14} \\ a_{21} \cdot X_1 + a_{22} \cdot X_2 + a_{23} \cdot X_3 &= a_{24} \\ a_{31} \cdot X_1 + a_{32} \cdot X_2 + a_{33} \cdot X_3 &= a_{34} \end{aligned} \qquad (2.11)$$

Yetaklovchi element $a_{11} \neq 0$ tanlaymiz va (2.11) sistema birinchi tenglamasi barcha koeffitsiyentlarini unga bo‘lamiz. Natijalarda quyidagilarni olamiz:

$$X_1 + b_{12} \cdot X_2 + b_{13} \cdot X_3 = b_{14}, \qquad (2.12)$$

bu yerda

$$b_{1j} = a_{1j}/a_{11} \quad (j = \overline{2,4}).$$

Keyin (2.11) sistemadan noma’lum X_1 (2.12) tenglamani a_{21} va a_{31} koeffitsiyentlariga ketma-ket ko‘paytirish va (2.11) sistema ikkinichi va uchinchi tenglamalaridan mos ravishda ayirish yo‘li bilan yo‘qotiladi. U holda quyidagi ko‘rinishdagi tenglamalar sistemasini olamiz:

$$\left.\begin{aligned} a_{22}^{(1)} \cdot X_2 + a_{23}^{(1)} \cdot X_3 = a_{24}^{(1)} \\ a_{32}^{(1)} \cdot X_2 + a_{33}^{(1)} \cdot X_3 = a_{34}^{(1)} \end{aligned}\right\}, \qquad (2.13)$$

bu yerda

$$a_{22}^{(1)} = a_{22} - a_{21} \cdot b_{12}, \quad a_{32}^{(1)} = a_{32} - a_{31} \cdot b_{12},$$
$$a_{23}^{(1)} = a_{23} - a_{21} \cdot b_{13}, \quad a_{33}^{(1)} = a_{33} - a_{31} \cdot b_{13},$$
$$a_{24}^{(1)} = a_{24} - a_{21} \cdot b_{14}, \quad a_{34}^{(1)} = a_{34} - a_{31} \cdot b_{14}.$$

(2.13) sistema koeffitsiyentini hisoblash uchun umumiy formula quyidagicha ko‘rinishni oladi:

$$a_{ij}^{(1)} = a_{ij} - a_{i1} \cdot b_{1j}, \text{ bu yerda } (i = \overline{2,3}), (j = \overline{2,4}).$$

Endi yetaklovchi element $a_{22}^{(1)} \neq 0$ tanlaymiz va (2.13) sistema birinchi tenglamasining barcha koeffitsiyentlarini unga bo‘lamiz. Natijada quyidagini olamiz:

$$X_2 + b_{23}^{(1)} \cdot X_3 = b_{24}^{(1)}, \qquad (2.14)$$

bu yerda

$$b_{2j}^{(1)} = a_{2j}^{(1)}/a_{22}^{(1)} \quad (j = \overline{3,4}).$$

Keyin (2.13) sistemadan noma'lum X_2 (2.14) tenglamani $a_{32}^{(1)}$ ga ko'paytirish va natijani (2.13) sistema ikkinchi tenglamasidan ayirish yo'li bilan yo'qotiladi. U holda quyidagini olamiz:

$$a_{33}^{(2)} \cdot X_3 = a_{34}^{(2)}, \qquad (2.15)$$

bu yerda

$$a_{33}^{(2)} = a_{33}^{(1)} - a_{32}^{(1)} \cdot b_{23}^{(1)},$$
$$a_{34}^{(2)} = a_{34}^{(1)} - a_{32}^{(1)} \cdot b_{24}^{(1)}.$$

(2.15) sistema koeffitsiyentini hisoblash uchun umumiy formula quyidagicha ko'rinishni oladi:

$$a_{3j}^{(2)} = a_{32}^{(1)} - a_{32}^{(1)} \cdot b_{2j}^{(1)}, \text{ где } (j = \overline{3,4}).$$

Yetaklovchi element $a_{33}^{(2)} \neq 0$ tanlaymiz va (2.15) tenglamaning barcha koeffitsiyentlarini unga bo'lamiz. Natijada quyidagini olamiz:

$$X_3 = b_{34}^{(2)}, \qquad (2.16)$$

bu yerda

$$b_{34}^{(2)} = a_{34}^{(2)} / a_{33}^{(2)}.$$

Bunday vaziyatlarda, Gauss uslubining to'g'ri yurishi qo'llaniladi, ya'ni berilgan (2.11) tenglamalar sistemasidan noma'lumlar ketma-ket yo'qotiladi va oxirida bir noma'lumli bitta tenglama (2.15) ga keladi.

X_3 (2.16) tenglamadan aniqlanadi, X_2 (2.14) tenglamadan topiladi:

$$X_2 = b_{24}^{(1)} - b_{23}^{(1)} \cdot X_3 .$$

Va nihoyat, X_3 va X_2 ni bilgan holda, (2.12) tenglamadan X_1 aniqlanadi:

$$X_1 = b_{14} - b_{13} \cdot X_3 - b_{12} \cdot X_2.$$

Bunday vaziyatlarda Gauss uslubining teskari yurishi qo‘llaniladi, ya’ni (2.16), (2.14), (2.12) tenglamalardan barcha noma’lumlarning qiymatlari ketma-ket topiladi. (2.11) tenglamalar sistemasi yechildi.

Gauss uslubi faqat barcha yetaklovchi elementlar nolga teng bo‘lmagan holatlarda qo‘llaniladi.

2.2.2. GAUSS USLUBINING JADVAL KO‘RINISHI

Gauss uslubi bo‘yicha hisoblashlar jadval shakldа (2.1- jadval) qulayroqdir, ya’ni formulalar yozilmaydi.

2.1- jadval

1	**2**	**3**	**4**	**Σ**	**Sxema qismlari**
a_{11} a_{21} a_{31} 1	a_{12} a_{22} a_{32} b_{12}	a_{13} a_{23} a_{33} b_{13}	a_{14} a_{24} a_{34} b_{14}	a_{15} a_{25} a_{35} b_{15}	A
	$a_{22}^{(1)}$ $a_{32}^{(1)}$ 1	$a_{23}^{(1)}$ $a_{33}^{(1)}$ $b_{23}^{(1)}$	$a_{24}^{(1)}$ $a_{34}^{(1)}$ $b_{24}^{(1)}$	$a_{25}^{(1)}$ $a_{35}^{(1)}$ $b_{25}^{(1)}$	A_1
		$a_{33}^{(2)}$ 1	$a_{34}^{(2)}$ $b_{34}^{(2)}$ (X_3)	$a_{35}^{(2)}$ $b_{35}^{(2)}$ $(\bar{X}_3)$	A_2
  1	 1 	1 	X_3 X_2 X_1	$\bar{X}_3$ $\bar{X}_2$ $\bar{X}_1$	B

2.2.3. TRIANGULYATSIYA USLUBI

Bu uslubda tenglamalar sistemasi koeffitsiyentlaridan tuzilgan kvadrat matritsadan ikkita uchburchakli ko‘paytma matritsaga ajratilib foydalaniladi.

Berilgan tenglamalar sistemasi

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} \cdot \begin{vmatrix} X_1 \\ X_2 \\ X_3 \end{vmatrix} = \begin{vmatrix} b_1 \\ b_2 \\ b_3 \end{vmatrix} . \qquad (2.17)$$

Noma'lumlarni yuqoridagi uchburchakli matritsa bilan sistemaga keltirib ketma-ket yo'qotiladi

$$\left.\begin{aligned} X_1 + \alpha_{12} \cdot X_2 + \alpha_{13} \cdot X_3 &= V_1 \\ X_2 + \alpha_{23} \cdot X_3 &= V_2 \\ X_3 &= V_3 \end{aligned}\right\} \qquad (2.18)$$

Agar qayta tuzilgan o'zgarmaslar V_1, V_2, V_3 aniqlangan bo'lsa, u holda (2.18) ga o'tib X_3 dan X_1 gacha bo'lgan barcha noma'lumlarning qiymatlarini osonlikcha aniqlash mumkin.

Qayta tuzilgan o'zgarmaslar bir qancha sistemalardan aniqlanadi:

$$\begin{vmatrix} \gamma_{11} & 0 & 0 \\ \gamma_{21} & \gamma_{22} & 0 \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{vmatrix} \cdot \begin{vmatrix} V_1 \\ V_2 \\ V_3 \end{vmatrix} = \begin{vmatrix} b_1 \\ b_2 \\ b_3 \end{vmatrix} \qquad (2.19)$$

Pastki uchburchakli matritsa bilan γ quyidagicha ko'rinish oladi:

$$\begin{vmatrix} \gamma_{11} & 0 & 0 \\ \gamma_{21} & \gamma_{22} & 0 \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{vmatrix} \cdot \begin{vmatrix} 1 & \alpha_{12} & \alpha_{13} \\ 0 & 1 & \alpha_{23} \\ 0 & 0 & 1 \end{vmatrix} \cdot \begin{vmatrix} X_1 \\ X_2 \\ X_3 \end{vmatrix} = \begin{vmatrix} b_1 \\ b_2 \\ b_3 \end{vmatrix} . \qquad (2.20)$$

Ya'ni

$$A \cdot X = \gamma \cdot \alpha \cdot X = \gamma \cdot V = B , \qquad (2.21)$$

γ·α = A tenglikdan γ va α matritsa elementlari qiymatlarini aniqlash uchun rekkurent bog‘lanish chiqarish mumkin:

$$\left.\begin{aligned} &\gamma_{k1} = a_{k1}\ (k = \overline{1,3}), \quad \alpha_{1t} = a_{1t} / a_{11}\ (t = \overline{2,3}), \\ &\gamma_{kt} = a_{kt} - \sum_{j=1}^{t-1} \gamma_{kj} \cdot \alpha_{jt} \quad (k,t = \overline{2,3}), \quad (k \geq t), \\ &\alpha_{kt} = (1/\gamma_{kk}) \cdot (a_{kt} - \sum_{j=1}^{k-1} \gamma_{kj} \cdot \alpha_{jt}) \quad (k,t = \overline{2,3}), \quad (k < t). \end{aligned}\right| \tag{2.22}$$

Koeffitsiyentlarning o‘zgartirilgan qiymatlarini va noma’lumlar quyidagi bog‘lanishdan aniqlanadi:

$$V_1 = b_1 / a_{11}, \quad V_k = (1/\gamma_{kk}) \cdot (b_k - \sum_{j=1}^{k-1} \gamma_{kj} \cdot V_j) \quad (k = \overline{2,3}), \tag{2.23}$$

$$X_n = V_n, \quad X_k = V_k - \sum_{j=k+1}^{n} \alpha_{kj} \cdot X_j \quad (k < 3). \tag{2.24}$$

2.2.4. TUGUN QARSHILIKLAR MATRITSASINI ANIQLASH USLUBLARI

$\dot{Z} = \dot{Y}^{-1}$ matritsani topish quyidagi uslublar asosida bajarilishi mumkin:

- Gauss,
- faktorizatsiya.

Tugun qarshiliklar matritsasi $\dot{Z}$ EETning elektr tarmoq sxemasi bo‘yicha bevosita topologiya va kommutatsiya uslubida ham aniqlanishi mumkin.

2.2.4.1. Teskari matritsaga asoslangan Gauss uslubi

Berilgan A matritsaga teskari bo‘lgan matritsani topish kerak bo‘lsin.

A^{-1} = C deb belgilaymiz. U holda A matritsa tartibi uchun matritsali ifoda A· A^{-1} = E (bu yerda E – birlik matritsa) 3 ga teng va quyidagi ko‘rinishga ega:

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} \cdot \begin{vmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \qquad (4.25)$$

Matritsalarni ko‘paytiramiz va quyidagilarni olamiz:

$$\left\{ \begin{aligned} a_{11} \cdot c_{11} + a_{12} \cdot c_{21} + a_{13} \cdot c_{31} &= 1 \\ a_{21} \cdot c_{11} + a_{22} \cdot c_{21} + a_{23} \cdot c_{31} &= 0 \\ a_{31} \cdot c_{11} + a_{32} \cdot c_{21} + a_{33} \cdot c_{31} &= 0 \end{aligned} \right\} \qquad (2.26)$$

$$\left\{ \begin{aligned} a_{11} \cdot c_{12} + a_{12} \cdot c_{22} + a_{13} \cdot c_{32} &= 0 \\ a_{21} \cdot c_{12} + a_{22} \cdot c_{22} + a_{23} \cdot c_{32} &= 1 \\ a_{31} \cdot c_{12} + a_{32} \cdot c_{22} + a_{33} \cdot c_{32} &= 0 \end{aligned} \right\} \qquad (2.27)$$

$$\left\{ \begin{aligned} a_{11} \cdot c_{13} + a_{12} \cdot c_{23} + a_{13} \cdot c_{33} &= 0 \\ a_{21} \cdot c_{13} + a_{22} \cdot c_{23} + a_{23} \cdot c_{33} &= 0 \\ a_{31} \cdot c_{13} + a_{32} \cdot c_{23} + a_{33} \cdot c_{33} &= 1 \end{aligned} \right\} \qquad (2.28)$$

Bunday holatda, (2.26)–(2.28) sistemalarda gruppalangan C matritsaning to‘qqizta noma’lum elementi bilan to‘qqizta to‘g‘ri chiziqli tenglamalarga ega bo‘linadi. Asosiysi bu sistema bitta A koeffitsiyent matritsasi bo‘lib hisoblanadi. Bu barcha uchta sistemani yechish va teskari matritsani Gauss uslubining jadval ko‘rinishini (2.2 - jadval) bir marta qo‘llash orqali aniqlash imkonini beradi.

2.2 - jadval

Etap №	**1**	**2**	**3**	**4**	**5**	**6**	**Σ**
I	a_{11}	a_{12}	a_{13}	1	0	0	d_1
	a_{21}	a_{22}	a_{23}	0	1	0	d_2
	a_{31}	a_{32}	a_{33}	0	0	1	d_3
	1	b_{12}	b_{13}	b_{14}	0	0	e_1
II		$a_{22}^{(1)}$	$a_{23}^{(1)}$	$a_{24}^{(1)}$	1	0	$d_2^{(1)}$
		$a_{32}^{(1)}$	$a_{33}^{(1)}$	$a_{34}^{(1)}$	0	1	$d_3^{(1)}$
		1	$b_{23}^{(1)}$	$b_{24}^{(1)}$	$b_{25}^{(1)}$	0	$e_2^{(1)}$
III			$a_{33}^{(2)}$	$a_{34}^{(2)}$	$a_{35}^{(2)}$	1	$d_3^{(2)}$
			1	$b_{34}^{(2)}$	$b_{35}^{(2)}$	$b_{36}^{(2)}$	$e_3^{(2)}$
			1	c_{31}	c_{32}	c_{33}	$\sum_{j=1}^{3} c_{3j} + 1$
		1		c_{21}	c_{22}	c_{23}	$\sum_{j=1}^{3} c_{2j} + 1$
	1			c_{11}	c_{12}	c_{13}	$\sum_{j=1}^{3} c_{1j} + 1$

Olingan matritsa $C = A^{-1}$ ning to‘g‘riligini tekshirish uchun $A \cdot C = E$ bog‘lanish qo‘llaniladi.

2.2.4.2. Faktorizatsiya uslubi

Demak, tugun qarshiliklar matritsasi $\dot{Z}$ to‘liq to‘ldirilganligi uchun $\dot{Z}$ matritsani noaniq ko‘rinishda tasvirlash maqsadga muvofiq (hisob-kitob hajmi kamayadi).

$C = A^{-1}$ matritsani aniqlashni ko‘rib chiqamiz, bu yerda A – tenglamalar sistemasi koeffitsiyentlaridan tuzilgan matritsa:

$$\begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix} \cdot \begin{vmatrix} X_1 \\ X_2 \\ X_3 \end{vmatrix} = \begin{vmatrix} b_1 \\ b_2 \\ b_3 \end{vmatrix}$$

C matritsani n ta ko'paytma matritsa ko'rinishida aniqlaymiz:

$C = T_n \cdot T_{n-1} \cdots T_2 \cdot T_1$, (2.29)
bu yerdan $n = 3$.

A matritsani chap tomondan o'zgartirish matritsasiga ko'paytiramiz:

$$T_1 = \begin{vmatrix} 1/a_{11} & 0 & 0 \\ -a_{21}/a_{11} & 1 & 0 \\ -a_{31}/a_{11} & 0 & 1 \end{vmatrix},$$

Matritsa quyidagini beradi:

$$A^{(1)} = T_1 \cdot A = \begin{vmatrix} 1 & a_{12}^{(1)} & a_{13}^{(1)} \\ 0 & a_{22}^{(1)} & a_{23}^{(1)} \\ 0 & a_{32}^{(1)} & a_{33}^{(1)} \end{vmatrix}.$$

$A^{(1)}$ matritsa elementlari Gauss uslubi bo'yicha hisoblanganda diagonal elementlar asosiy element sifatida qabul qilinadi:

$a_{1k}^{(1)} = a_{1k} / a_{11}$,
$a_{ik}^{(1)} = a_{ik} - a_{i1}^{(1)} \cdot a_{1k} / a_{11}$ $(i, k = \overline{2,3})$.

Dastlabki tenglamalar sistemasini olamiz:

$$A^{(1)} \cdot X = T_1 \cdot A \cdot X = T_1 \cdot B .$$

$A^{(1)}$ matritsani chap tomondan ikkinchi o‘zgartirilgan matritsa T_2 ga ko‘paytirib, $A^{(1)}$ matritsadan ikkinchi ustun elementlarini yo‘qotamiz, faqat diagonal birliklardan tashqari. Buning natijasida

$$T_2 = \begin{vmatrix} 1 & -a_{12}^{(1)} / a_{22}^{(1)} & 0 \\ 0 & 1 / a_{22}^{(1)} & 0 \\ 0 & -a_{32}^{(1)} / a_{22}^{(1)} & 1 \end{vmatrix}$$

va

$$A^{(2)} = T_2 \cdot A^{(1)} = T_2 \cdot T_1 \cdot A = \begin{vmatrix} 1 & 0 & a_{13}^{(2)} \\ 0 & 1 & a_{23}^{(2)} \\ 0 & 0 & a_{33}^{(2)} \end{vmatrix}.$$

U holda dastlabki tenglamalar sistemasi quyidagi ko‘rinishni oladi :

$$A^{(2)} \cdot X = T_2 \cdot A^{(1)} \cdot X = T_2 \cdot T_1 \cdot A \cdot X = T_2 \cdot T_1 \cdot B.$$

Bunday jarayon sistema tartibi n uchun davom ettirilib, quyidagi ko‘rinishda bo‘ladi:

$$A^{(n)} \cdot X = T_n \cdot T_{n-1} \cdots T_2 \cdot T_1 \cdot A \cdot X = T_n \cdot T_{n-1} \cdots T_2 \cdot T_1 \cdot B.$$

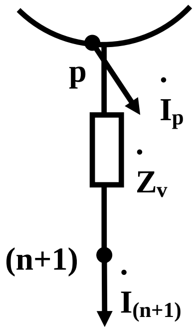
Demak $A^{(n)}$ birlik matritsaga kelib qoladi:

$$X = T_n \cdot T_{n-1} \cdots T_2 \cdot T_1 \cdot B = A^{-1} \cdot B = C \cdot B. \qquad (2.30)$$

Demak (2.29) bog‘lanish to‘g‘ridir.

Tugun o‘tkazuvchanlik matritsasi $\dot{Y}$ siyrak to‘ldirilganligi sababli hamda har bir o‘zgartirish matritsasi T_j (i = $\overline{1, n}$) birlamchi matritsadan faqatgina i-ustun bilan farq qilganligi sababli faqat shu ustun aniqlanishi yetarlidir. Shunday qilib, to‘liq to‘ldirilgan matritsa o‘rniga EHMda faqat nolga teng elementlarsiz matritsa saqlanadi.

2.2.4.3. Topologiya va kommutatsiya uslubi



2.2-rasm

Bu uslub tugun qarshiliklar matritsasi $\dot{Z}$ ni bosqichma-bosqich olish uchun xizmat qiladi va topologik (strukturaviy) sxema qo‘llanilishiga asoslangan. Agar hisobiy sistema tarmoqlari n tartibli $\dot{Z}^c$ matritsa bilan shahobchalarning bog‘lanishi p–(n+1), qarshilik $\dot{Z}_v$ ga teng bo‘lsa, yangi (n+1) tugun uchun 2.2-rasm o‘rinlidir va p tugundagi tok quyidagiga teng bo‘ladi:

$$\dot{I}_p + \dot{I}'_p = \dot{I}_p + \dot{I}'_{n+1}.$$

O‘zaro bog‘langan tugunlardagi kuchlanish

$$\dot{U}_{n+1} = \dot{U}_p - \dot{Z}_v \dot{I}_{n+1}.$$

Bu holatda yangi matritsa $\dot{Z}^н$ quyidagi ko‘rinishni oladi:

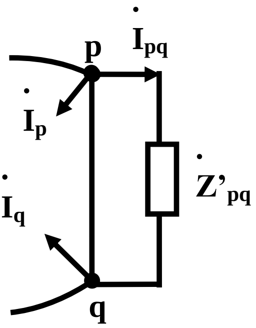
$$\dot{Z}^н = \left| \begin{array}{c:c} \dot{Z}^c & \dot{Z}_{k,n+1} \\ \hdashline \dot{Z}_{n+1,k} & \dot{Z}_{n+1,n+1} \end{array} \right|, \tag{2.31}$$

bu yerda

$$\left.\begin{aligned} \dot{Z}_{k,n+1} &= \dot{Z}_{kp} \\ \dot{Z}_{n+1,k} &= \dot{Z}_{pk} \end{aligned}\right\} (k = \overline{1,n})$$

– (n+1)ga muvofiq $\dot{Z}^c$ matritsa ustun va qator elementlari;

$$\dot{Z}_{n+1,n+1} = \dot{Z}_{pp} + \dot{Z}_v.$$



2.3-rasm

$\dot{Z}_{pq}$ shahobcha bog‘lanishida, yopiq kontur (2.3-rasm), n-tartibli matritsa $\dot{Z}$ o‘zgarmaydi, faqat uning elementlari qandaydir kattalik $\Delta\dot{Z}$ ga tuzatiladi, qiymatni keyingi holatlarda yaqqol ko‘rinishda olish mumkin. Yangi tuzilgan p-q shahobcha uchun (2.3-rasm) $\dot{Z}'_{pq}$ qarshilikni quyidagicha yozish mumkin:

$$\dot{U}_p - \dot{U}_q = \dot{Z}'_{pq} \cdot \dot{I}_{pq} . \qquad (2.32)$$

Bu shahobcha p va q tugunlar uchun $\dot{I}_{pq}$ va $(-\dot{I}_{pq})$ ga muvofiq yuzaga keluvchi toklarni chorlaydi. Bunday vaziyatlarda har qanday k-tugundagi kuchlanish quyidagiga teng bo‘ladi:

$$\dot{U}_k = \dot{a}_{k0} \cdot \dot{U}_0 + \sum_{t=1}^{n} \dot{Z}_{kt} \cdot \dot{I}_t - \dot{Z}_{kp} \cdot \dot{I}_{pq} + \dot{Z}_{kq} \cdot \dot{I}_{pq}, \qquad (2.33)$$

bu yerda $\dot{a}_{k0} = \sum_{t=1}^{n} \dot{Z}_{kt} \cdot \dot{y}_{t0}$.

Hisobiy sxemada barcha tugunlar soni o‘zgarmaydi, (2.33) tenglamani undan $\dot{I}_{pq}$ tok yo‘qotilgandan keyin tuzatilgan parametrlar bilan ko‘rsatish zarur:

$$\dot{U}_k = a_{k0} \cdot \dot{U}_0 + \sum_{t=1}^{n} \dot{Z}_{kt} \cdot \dot{I}_t . \qquad (2.34)$$

Shuni hisobga olish kerakki:

$$a_{k0} = \sum_{t=1}^{n} Z_{kt} \cdot \dot{y}_{t0} \; . \qquad (2.35)$$

Qayta tuzatilgan qiymat Z_{kt} yetarlichadir. Shuning uchun (2.33)da $\dot{U}_0 = 0$ bo‘lishi mumkun, p va q tugunlar uchun quyidagini yozish mumkin:

$$\dot{U}_p = \sum_{t=1}^{n} \dot{Z}_{pt} \cdot \dot{I}_t - (\dot{Z}_{pp} - \dot{Z}_{pq}) \cdot \dot{I}_{pq},$$
$$\dot{U}_q = \sum_{t=1}^{n} \dot{Z}_{qt} \cdot \dot{I}_t - (\dot{Z}_{qp} - \dot{Z}_{qq}) \cdot \dot{I}_{pq}. \qquad (2.36)$$

(2.36) ni (2.32)ga qo‘yib quyidagini olamiz:

$$\dot{I}_{pq} = \frac{\sum_{t=1}^{n} (\dot{Z}_{pt} - \dot{Z}_{qt}) \cdot \dot{I}_t}{\Delta pq}, \qquad (2.37)$$

bu yerda $\Delta pq = \dot{Z}'_{pq} + \dot{Z}_{pp} + \dot{Z}_{qq} - \dot{Z}_{pq} - \dot{Z}_{qp}$. (2.38)

(2.33)ga qaytib (2.38) ni hisobga olsak quyidagicha ko‘rinishga ega bo‘ladi:

$$\dot{U}_k = \dot{a}_{k0} \cdot \dot{U}_0 + \sum_{t=1}^{n} (\dot{Z}_{kt} - \Delta \dot{Z}_{kt}) \cdot \dot{I}_t = a_{k0} \cdot \dot{U}_0 + \sum_{t=1}^{n} Z_{kt} \cdot \dot{I}_t, \qquad (2.39)$$

bu yerda

$$\Delta \dot{Z}_{kt} = \frac{(\dot{Z}_{kp} - \dot{Z}_{kq}) \cdot (\dot{Z}_{pt} - \dot{Z}_{qt})}{\Delta pq} \quad (k, t = \overline{1, n}). \qquad (2.40)$$

$\dot{Z}$ matritsa aniqlangandan keyin tugunlardagi kuchlanishlarni ko'rib chiqilgan uslublardan osonlikcha topiladi. TKT (2.8) aylantirilgan tuzilishidan teskari matritsa uslubi.

2.3. INSIDENSIYA MATRITSASI VA EET ELEKTR TARMOQ SHAHOBCHALARIDAGI TOKLARNI ANIQLASH

Elektr tarmoqlar strukturasi insidensiya (tugunlar va shahobchalar bog'lanishi) matritsada $C = |c_{ij}|$ yozilsa, to'g'ri burchakli matritsa hisoblanib, qatorlar soni tugunlar soni n ga, ustunlar soni esa shahobchalar soni m ga teng bo'ladi.

C matritsa elementlari quyidagi qoidalar bo'yicha topiladi:

$$C_{ij} = \begin{cases} +1, \text{ agar j shahobchai tugundan yo'nalgan bo'lsa;} \\ -1, \text{ agar j shahobchai tugunga yo'nalgan bo'lsa;} \\ 0, \text{ agar j shahobchai tugunbilan bog'lanmaganbo'lsa.} \end{cases}$$

C insidensiya matritsasini tuzish oldidan shahobchalar yo'nalishini berish zarur.

Insidensiya matritsasini qo'llash bilan j shahobchadagi kuchlanishlar tushuvi quyidagicha aniqlanadi:

$$\Delta \dot{U}_j^{в} = \sum_{i=0}^{n} c_{ji} \cdot \dot{U}_i \quad (j = \overline{1, m}),$$

Yoki matritsa ko'rinishida

$$\Delta \dot{U}^{в} = C^T \cdot \dot{U}. \tag{2.41}$$

Boshqa tomondan,

$$\Delta \dot{U}^{в} = \dot{Z}^{в} \cdot \dot{J}^{в}, \tag{2.42}$$

bu yerda

$$\dot{Z}^{в} = \begin{vmatrix} \dot{Z}_{10}^{в} & 0 & 0 & 0 \\ 0 & \dot{Z}_{12}^{в} & 0 & 0 \\ 0 & 0 & \dot{Z}_{13}^{в} & 0 \\ 0 & 0 & 0 & \dot{Z}_{23}^{в} \end{vmatrix}$$

- 2.1-rasmdagi sxema uchun shahobchalar qarshiliklari matritsasi;

$\dot{J}^{в}$ - shahobcha toklari vektori.

(2.42) dan quyidagiga ega bo‘lamiz:

$$\dot{J}^{в} = (\dot{Z}^{в})^{-1} \cdot \Delta\dot{U}^{в},$$

yoki, (2.41) ni hisobga olib,

$$\dot{J}^{в} = C^{T} \cdot (\dot{Z}^{в})^{-1} \cdot \dot{U}, \tag{2.43}$$

bu yerda

$$(\dot{Z}^{в})^{-1} = \begin{vmatrix} \dot{y}_{10} & 0 & 0 & 0 \\ 0 & \dot{y}_{12} & 0 & 0 \\ 0 & 0 & \dot{y}_{13} & 0 \\ 0 & 0 & 0 & \dot{y}_{23} \end{vmatrix}$$

- shahobchalar o‘tkazuvchanligi matritsasi.

2.4. TUGUNLARDAGI QUVVATLAR VA ELEKTR TARMOQLARIDAGI UMUMIY QUVVAT ISROFLARINI ANIQLASH

Balanslangan EETning turg‘un rejimlarida quvvat balansini saqlash majburiydir:

$$\sum_{i=0}^{n} \dot{S}_i + \Delta\dot{S} = 0. \tag{2.44}$$

Tugunlardagi quvvat vektori quyidagiga teng:

$$\dot{S} = I^T \cdot \dot{U} . \qquad (2.45)$$

Yuqoridagilarni hisobga olib

$$\dot{U} = \left|\dot{A}_{k0}\right| \cdot \dot{U}_0 - \dot{Z} \cdot \dot{I} = n \cdot \dot{U}_0 - \dot{Z} \cdot \dot{I}.$$

Bu yerda n – birlik vektor ((2.8) murojaat qilinsin), yozish mumkinki:

$$\dot{S} = I^T \cdot (n \cdot \dot{U}_0 - \dot{Z} \cdot \dot{I}).$$

U holda quvvat isrofi $\Delta\dot{S}$ (2.44) dan quyidagicha aniqlanadi:

$$\Delta\dot{S} = -\dot{S} = I^T \cdot \dot{Z} \cdot \dot{I} - I^T \cdot n \cdot \dot{U}_0 . \qquad (2.46)$$

(2.46) da ikkinchi qism nolga teng, demak

$$I^T \cdot n \cdot \dot{U}_0 = I_0 \cdot 1 \cdot \dot{U}_0 + I_1 \cdot 1 \cdot \dot{U}_0 + \ldots + I_n \cdot 1 \cdot \dot{U}_0 = \left(\sum_{i=1}^{n} I_i \right) \cdot \dot{U}_0 = 0 \cdot \dot{U}_0 = 0.$$

Shuning uchun quvvat isrofi $\Delta\dot{S}$ quyidagiga teng:

$$\Delta\dot{S} = I^T \cdot \dot{Z} \cdot \dot{I}. \qquad (2.47)$$

2.5. NOCHIZIQLI TUGUN KUCHLANISH TENGLAMALARINI YECHISH USLUBLARI

2.5.1. ODDIY ITERATSIYA USLUBI (GAUSS USLUBI)

2.1-rasm sxemasi uchun TKT dastlabki shaklini quyidagicha algebraik ko‘rinishda yozish mumkin:

$$\left.\begin{cases} \dot{Y}_{11}\cdot\dot{U}_1-\dot{Y}_{12}\cdot\dot{U}_2-\dot{Y}_{13}\cdot\dot{U}_3=\dot{Y}_{10}\cdot\dot{U}_0-S_1/U_1 \\ -\dot{Y}_{21}\cdot\dot{U}_1+\dot{Y}_{22}\cdot\dot{U}_2-\dot{Y}_{23}\cdot\dot{U}_3=-S_2/U_2 \\ -\dot{Y}_{31}\cdot\dot{U}_1-\dot{Y}_{32}\cdot\dot{U}_2+\dot{Y}_{33}\cdot\dot{U}_3=-S_3/U_3 \end{cases}\right\} \quad (2.48)$$

(2.48) sistemaning birinchi tenglamasini $\dot{U}_1$ kuchlanishga, ikkinchisini $\dot{U}_2$ kuchlanishga, uchinchisini $\dot{U}_3$ kuchlanishga nisbatan yechib, quyidagi hisobiy formulalarni olamiz:

$$\left.\begin{aligned} U_1^{(n+1)} &= \frac{1}{Y_{11}}(Y_{10}U_0+Y_{12}\dot{U}_2^{(n)}+Y_{13}\dot{U}_3^{(n)}-\frac{S_1}{U_1^{(n)}}), \\ U_2^{(n+1)} &= \frac{1}{Y_{22}}(Y_{21}\dot{U}_1^{(n)}+Y_{23}\dot{U}_3^{(n)}-\frac{S_2}{U_2^{(n)}}), \\ U_3^{(n+1)} &= \frac{1}{Y_{33}}(Y_{31}\dot{U}_1^{(n)}+Y_{32}\dot{U}_2^{(n)}-\frac{S_3}{U_3^{(n)}}), \end{aligned}\right\} \quad (2.49)$$

Oddiy iteratsiya uslubi bo‘yicha tugun kuchlanishlarini aniqlash algoritmi quyidagi etaplardan tashkil topgan:

1. Kuchlanishlarning boshlang‘ich qiymatlari beriladi:
   $\dot{U}_i^{(k)}=\dot{U}_0$ (i = 1, 3), k = 0 bo‘lganda.

2. (2.49) o‘ng qismiga qiymatlar $\dot{U}_i^{(k)}$ (i = 1, 3) qo‘yiladi va kuchlanishning keyingi qiymatlari $\dot{U}_i^{(k+1)}$ (i = 1, 3) aniqlanadi.

3. k ning qiymatini birga oshiramiz va p.2 ga o‘tamiz.

Iteratsiya jarayoni yechimga yaqinlashishini aniqlash uchun ikkita kriteriy ishlatiladi: taxminiy va aniq.

Taxminiy kriteriydan foydalanilganda ikkita ketma-ket iteratsiyalardagi kuchlanish modullari qiymatlari farqi $|\Delta\dot{U}_i|$ $(i=\overline{1,n})$

bo‘yicha iteratsiyalarni yechimga yaqinlashganligi to‘g‘risida xulosa qilinadi:

$$\left|\Delta\dot{U}_i^{(k)}\right| = \left|\Delta\dot{U}_i^{(k)} - \Delta\dot{U}_i^{(k-1)}\right| \le \varepsilon \quad (i = \overline{1,n}) \qquad (2.50)$$

Bu yerda ε – ruxsat etilgan xatolik, yuqoridagi shart bajarilsa hisob-lashlar tugatiladi, aks holda davom ettiriladi.

Umuman olganda (2.50) shartlarning bajarilishi har doim yechimning olinishini kafolatlaydi.

Aniq kriteriy quyidagicha aniqlanadi. Tugun kuchlanish teng-lamalarining xatolik vektorlarini belgilaymiz:

$$\dot{W} = \dot{Y} \cdot \dot{U} - \left|\dot{Y}_{k0}\right| \cdot \dot{U}_0 + \dot{I} \ . \qquad (2.51)$$

2.1-rasm sxemasi uchun (2.51) tenglamalar matritsasi quyidagicha ko‘rinish oladi:

$$\begin{vmatrix} \dot{W}_1^{(k)} \\ \dot{W}_2^{(k)} \\ \dot{W}_3^{(k)} \end{vmatrix} = -\begin{vmatrix} \dot{y}_{11} & -\dot{y}_{12} & -\dot{y}_{13} \\ -\dot{y}_{21} & \dot{y}_{22} & -\dot{y}_{23} \\ -\dot{y}_{31} & -\dot{y}_{32} & \dot{y}_{33} \end{vmatrix} \cdot \begin{vmatrix} \dot{U}_1^{(k)} \\ \dot{U}_2^{(k)} \\ \dot{U}_3^{(k)} \end{vmatrix} - \begin{vmatrix} \dot{y}_{10} \\ 0 \\ 0 \end{vmatrix} \cdot \dot{U}_0 + \begin{vmatrix} S_1 / U_1^{(k)} \\ S_2 / U_2^{(k)} \\ S_3 / U_3^{(k)} \end{vmatrix}. \qquad (2.52)$$

Demak, TKTning yechimida barcha xatolik vektorlarining qiymatlari $\dot{W}_i (i = \overline{1,n})$ nolga teng bo‘ladi.

Agar quyidagi shart bajarilsa, TKT sistemasi amaliy yechilgan hisoblanadi:

$$|W_i^{(k)}| \le \delta \qquad (i = \overline{1,n}), \qquad (2.53)$$

bu yerda δ - hisoblashlarda berilgan xatolik.

(2.53) shart aniq kriteriyda hisoblashlar yakunlanganligini bil-diradi.

(2.49) bo‘yicha oddiy iteratsiya jarayoni ko‘pincha past tezlik-ka ega bo‘ladi, ayrim hollarda esa jarayon yechimdan uzoqlashadi.

2.5.2. TESKARI MATRITSAGA ASOSLANGAN TKT UCHUN ODDIY ITERATSIYA USLUBI

2.1-rasm hisobiy sxema uchun TKT quyidagicha ko‘rinishga ega:

$$\begin{vmatrix} \dot{U}_1 \\ \dot{U}_2 \\ \dot{U}_3 \end{vmatrix} = \begin{vmatrix} 1 \\ 1 \\ 1 \end{vmatrix} \cdot \dot{U}_0 - \begin{vmatrix} \dot{Z}_{11} & \dot{Z}_{12} & \dot{Z}_{13} \\ \dot{Z}_{21} & \dot{Z}_{22} & \dot{Z}_{23} \\ \dot{Z}_{31} & \dot{Z}_{32} & \dot{Z}_{33} \end{vmatrix} \cdot \begin{vmatrix} S_1 / U_1 \\ S_2 / U_2 \\ S_3 / U_3 \end{vmatrix} \qquad (2.54)$$

(2.53) da matritsalarni ko‘paytirish natijasida va (2.9) ni hisobga olib, oddiy iteratsiya uslubining hisobiy shaklini olamiz:

$$\left.\begin{aligned} U_1^{(k+1)} &= \dot{U}_0 - \dot{Z}_{11} \cdot \frac{S_1}{U_1^{(k)}} - \dot{Z}_{12} \cdot \frac{S_2}{U_2^{(k)}} - \dot{Z}_{13} \cdot \frac{S_3}{U_3^{(k)}}, \\ U_2^{(k+1)} &= \dot{U}_0 - \dot{Z}_{21} \cdot \frac{S_1}{U_1^{(k)}} - \dot{Z}_{22} \cdot \frac{S_2}{U_2^{(k)}} - \dot{Z}_{23} \cdot \frac{S_3}{U_3^{(k)}}, \\ U_3^{(k+1)} &= \dot{U}_0 - \dot{Z}_{31} \cdot \frac{S_1}{U_1^{(k)}} - \dot{Z}_{32} \cdot \frac{S_2}{U_2^{(k)}} - \dot{Z}_{33} \cdot \frac{S_3}{U_3^{(k)}}, \end{aligned}\right\} \qquad (2.55)$$

bu yerda k = 0, 1, 2, … - iteratsiya nomeri.

Oddiy iteratsiya uslubi bo‘yicha tugun kuchlanishlarini aniqlash algoritmi quyidagi etaplardan tashkil topgan:

1. Kuchlanishlarning boshlang‘ich qiymatlari beriladi:

   $\dot{U}_i^{(k)} = \dot{U}_0$ (i = 1, 3), k = 0 bo‘lganda.

2. (2.49) o‘ng qismiga qiymatlar $\dot{U}_i^{(k)}$ (i = 1, 3) qo‘yiladi va kuchlanishning keyingi qiymatlari $\dot{U}_i^{(k+1)}$ (i = 1, 3) aniqlanadi.

3. k ning qiymatini birga oshiramiz va p.2 ga o‘tamiz.

Iteratsiya jarayoni yechimga yaqinlashishini aniqlash uchun ikkita kriteriy ishlatiladi: taxminiy va aniq.

Taxminiy kriteriydan foydalanilganda ikkita ketma-ket iteratsiyalardagi kuchlanish modullari qiymatlari farqi $\left|\Delta\dot{U}_i\right| \quad (i=\overline{1,n})$ bo‘yicha iteratsiyalarni yechimga yaqinlashganligi to‘g‘risida xulosa qilinadi:

$$\left|\Delta\dot{U}_i^{(k)}\right| = \left|\Delta\dot{U}_i^{(k)} - \Delta\dot{U}_i^{(k-1)}\right| \le \varepsilon \quad (i=\overline{1,n}), \qquad (2.56)$$

bu yerda ε – ruxsat etilgan xatolik, yuqoridagi shart bajarilsa, hisoblashlar tugatiladi, aks holda davom ettiriladi.

Umuman olganda (2.56) shartlarning bajarilishi har doim yechimning olinishini kafolatlaydi.

Aniq kriteriy quyidagicha aniqlanadi. Tugun kuchlanish tenglamalarining xatolik vektorlarini belgilaymiz:

$$\dot{W} = \dot{Y}\cdot\dot{U} - \left|\dot{Y}_{k0}\right|\cdot\dot{U}_0 + \dot{I}\,. \qquad (2.57)$$

2.1-rasm sxemasi uchun (2.57) tenglamalar matritsasi quyidagicha ko‘rinish oladi:

$$\begin{vmatrix}\dot{W}_1^{(k)}\\ \dot{W}_2^{(k)}\\ \dot{W}_3^{(k)}\end{vmatrix} = -\begin{vmatrix}\dot{y}_{11} & -\dot{y}_{12} & -\dot{y}_{13}\\ -\dot{y}_{21} & \dot{y}_{22} & -\dot{y}_{23}\\ -\dot{y}_{31} & -\dot{y}_{32} & \dot{y}_{33}\end{vmatrix}\cdot\begin{vmatrix}\dot{U}_1^{(k)}\\ \dot{U}_2^{(k)}\\ \dot{U}_3^{(k)}\end{vmatrix} - \begin{vmatrix}\dot{y}_{10}\\ 0\\ 0\end{vmatrix}\cdot\dot{U}_0 + \begin{vmatrix}S_1/U_1^{(k)}\\ S_2/U_2^{(k)}\\ S_3/U_3^{(k)}\end{vmatrix}. \qquad (2.58)$$

Demak, TKTning yechimida barcha xatolik vektorlarining qiymatlari $\dot{W}_i (i=\overline{1,n})$ nolga teng bo‘ladi.

Agar quyidagi shart bajarilsa, TKT sistemasi amaliy yechilgan hisoblanadi:

$$|W_i^{(k)}| \le \delta \qquad (i=\overline{1,n}) \;, \qquad (2.59)$$

bu yerda δ - hisoblashlarda ruxsat etilgan xatolik.

(2.59) shart aniq kriteriyda hisoblashlar yakunlanganligini bildiradi.

Oddiy iteratsiya uslubining qulayligi algoritmning soddaligidadir. Bu uslubning kamchiligi yechimdan uzoqlashishlar bo‘lishi mumkin.

2.5.3. GAUSS-ZEYDEL USLUBI

2.1-rasm sxemasi uchun TKT dastlabki shaklini quyidagicha algebraik ko‘rinishda yozish mumkin:

$$\left\{\begin{aligned} &\dot{Y}_{11}\cdot\dot{U}_1-\dot{Y}_{12}\cdot\dot{U}_2-\dot{Y}_{13}\cdot\dot{U}_3=\dot{Y}_{10}\cdot\dot{U}_0-S_1/U_1\\ &-\dot{Y}_{21}\cdot\dot{U}_1+\dot{Y}_{22}\cdot\dot{U}_2-\dot{Y}_{23}\cdot\dot{U}_3=-S_2/U_2\\ &-\dot{Y}_{31}\cdot\dot{U}_1-\dot{Y}_{32}\cdot\dot{U}_2+\dot{Y}_{33}\cdot\dot{U}_3=-S_3/U_3 \end{aligned}\right\} \qquad (2.60)$$

(2.60) sistemaning birinchi tenglamasini $\dot{U}_1$ kuchlanishga, ikkinchisini $\dot{U}_2$ kuchlanishga, uchinchisini $\dot{U}_3$ kuchlanishga nisbatan yechib, Gauss-Zeydel uslubining hisobiy shakllarini olamiz:

$$\left.\begin{aligned} \dot{U}_1^{(k+1)}&=\frac{\dot{Y}_{10}\cdot\dot{U}_0+\dot{Y}_{12}\cdot\dot{U}_2^{(k)}+\dot{Y}_{13}\cdot\dot{U}_3^{(k)}-S_1/(U_1^{(k)})}{\dot{Y}_{11}}\\ \dot{U}_2^{(k+1)}&=\frac{\dot{Y}_{21}\cdot\dot{U}_1^{(k+1)}+\dot{Y}_{23}\cdot\dot{U}_3^{(k)}-S_2/(U_2^{(k)})}{\dot{Y}_{22}}\\ \dot{U}_3^{(k+1)}&=\frac{\dot{Y}_{31}\cdot\dot{U}_1^{(k+1)}+\dot{Y}_{32}\cdot\dot{U}_2^{(k+1)}-S_3/(U_3^{(k)})}{\dot{Y}_{33}} \end{aligned}\right\} \qquad (2.61)$$

1. Kuchlanishlarning boshlang‘ich qiymatlari beriladi:
$\dot{U}_i^{(k)} = \dot{U}_0$ (i = 1, 3), k = 0 bo‘lganda.

2. (2.61) o‘ng qismiga qiymatlar $\dot{U}_i^{(k)}$ (i = 1, 3) qo‘yiladi va kuchlanishning keyingi qiymatlari $\dot{U}_i^{(k+1)}$ (i = 1, 3) aniqlanadi, har bir *i* - tugunda topilgan kuchlanish qiymatlari (*i*+1) dan N gacha tugunlar kuchlanishlari hisobida foydalaniladi.

3. k ning qiymatini birga oshiramiz va p.2 ga o‘tamiz.

Iteratsiya jarayoni yechimga yaqinlashishini aniqlash uchun ikkita kriteriy ishlatiladi: taxminiy va aniq.

Taxminiy kriteriydan foydalanilganda ikkita ketma-ket iteratsiyalardagi kuchlanish modullari qiymatlari farqi $\left|\Delta \dot{U}_i\right|$ $(i = \overline{1, n})$ bo‘yicha iteratsiyalarni yechimga yaqinlashganligi to‘g‘risida xulosa qilinadi:

$$\left|\Delta \dot{U}_i^{(k)}\right| = \left|\Delta \dot{U}_i^{(k)} - \Delta \dot{U}_i^{(k-1)}\right| \le \varepsilon \quad (i = \overline{1, n}), \qquad (2.62)$$

bu yerda ε – ruxsat etilgan xatolik, yuqoridagi shart bajarilsa hisoblashlar tugatiladi, aks holda davom ettiriladi.

Umuman olganda (2.62) shartlarning bajarilishi har doim yechimning olinishini kafolatlaydi.

Aniq kriteriy quyidagicha aniqlanadi. Tugun kuchlanish tenglamalarining xatolik vektorlarini belgilaymiz:

$$\dot{W} = \dot{Y} \cdot \dot{U} - \left|\dot{Y}_{k0}\right| \cdot \dot{U}_0 + \dot{I} \,. \qquad (2.63)$$

2.1-rasm sxemasi uchun (2.63) tenglamalar matritsasi quyidagicha ko‘rinish oladi:

$$\begin{vmatrix} \dot{W}_1^{(k)} \\ \dot{W}_2^{(k)} \\ \dot{W}_3^{(k)} \end{vmatrix} = -\begin{vmatrix} \dot{y}_{11} & -\dot{y}_{12} & -\dot{y}_{13} \\ -\dot{y}_{21} & \dot{y}_{22} & -\dot{y}_{23} \\ -\dot{y}_{31} & -\dot{y}_{32} & \dot{y}_{33} \end{vmatrix} \cdot \begin{vmatrix} \dot{U}_1^{(k)} \\ \dot{U}_2^{(k)} \\ \dot{U}_3^{(k)} \end{vmatrix} - \begin{vmatrix} \dot{y}_{10} \\ 0 \\ 0 \end{vmatrix} \cdot \dot{U}_0 + \begin{vmatrix} S_1 / U_1^{(k)} \\ S_2 / U_2^{(k)} \\ S_3 / U_3^{(k)} \end{vmatrix}. \tag{2.64}$$

Demak, TKTning yechimida barcha xatolik vektorlarining qiymatlari $\dot{W}_i \, (i = \overline{1,n})$ nolga teng bo‘ladi.

Agar quyidagi shart bajarilsa, TKT sistemasi amaliy yechilgan hisoblanadi:

$$|W_i^{(k)}| \leq \delta \qquad (i = \overline{1,n}), \tag{2.65}$$

bu yerda δ - hisoblashlarda berilgan xatolik.

(2.65) shart aniq kriteriyda hisoblashlar yakunlanganligini bildiradi.

Gauss – Zeydel uslubida ham yuqorida keltirilgan yaqinlashish kriteriylari ishlatiladi. Gauss-Zeydel uslubi oddiy iteratsiyaga nisbatan kamroq iteratsiya talab qiladi.

2.5.4. TUGUN O‘TKAZUVCHANLIK MATRITSASINING DIAGONAL ELEMENTLARI KUCHAYTIRILGANDA GAUSS-ZEYDEL USLUBINI QO‘LLASH

Yechimga yaqinlashishni tezlatish uchun amaliyotdagi algoritmlarda Y matritsa diagonal elementlarini yuklama tugunlarining o‘tkazuvchanliklari hisobiga kuchaytirish usuli qo‘llaniladi:

$$\left.\begin{aligned}
\dot{U}_1^{(k+1)} &= \frac{\dot{Y}_{10}\cdot\dot{U}_0+\dot{Y}_{12}\cdot\dot{U}_2^{(k)}+\dot{Y}_{13}\cdot\dot{U}_3^{(k)}}{\dot{Y}_{11}+S_1/\left(U_1^{(k)}\right)^2}\\
\dot{U}_2^{(k+1)} &= \frac{\dot{Y}_{21}\cdot\dot{U}_1^{(k+1)}+\dot{Y}_{23}\cdot\dot{U}_3^{(k)}-S_2/U_2^{(k)}}{\dot{Y}_{22}}\\
\dot{U}_3^{(k+1)} &= \frac{\dot{Y}_{31}\cdot\dot{U}_1^{(k+1)}+\dot{Y}_{32}\cdot\dot{U}_2^{(k+1)}}{\dot{Y}_{33}+S_3/\left(U_3^{(k)}\right)^2}
\end{aligned}\right\} \qquad (2.66)$$

1. Kuchlanishlarning boshlang‘ich qiymatlari beriladi:
   $\dot{U}_i^{(k)} = \dot{U}_0$ (i = 1, 3), k = 0 bo‘lganda.

2. (2.66) o‘ng qismiga qiymatlar $\dot{U}_i^{(k)}$ (i = 1, 3) qo‘yiladi va kuchlanishning keyingi qiymatlari $\dot{U}_i^{(k+1)}$ (i = 1, 3) aniqlanadi, har bir *i* - tugunda topilgan kuchlanish qiymatlari (*i*+1) dan N gacha tugunlar kuchlanishlari hisobida foydalaniladi.

3. k ning qiymatini birga oshiramiz va p.2 ga o‘tamiz.

Iteratsiya jarayoni yechimga yaqinlashishini aniqlash uchun ikkita kriteriy ishlatiladi: taxminiy va aniq.

Taxminiy kriteriydan foydalanilganda ikkita ketma-ket iteratsiyalardagi kuchlanish modullari qiymatlari farqi $|\Delta\dot{U}_i|$ $(i=\overline{1,n})$ bo‘yicha iteratsiyalarni yechimga yaqinlashganligi to‘g‘risida xulosa qilinadi:

$$\left|\Delta\dot{U}_i^{(k)}\right| = \left|\Delta\dot{U}_i^{(k)} - \Delta\dot{U}_i^{(k-1)}\right| \le \varepsilon \quad (i=\overline{1,n}), \quad (2.67)$$

bu yerda ε – ruxsat etilgan xatolik, yuqoridagi shart bajarilsa hisoblashlar tugatiladi, aks holda davom ettiriladi.

Umuman olganda (2.67) shartlarning bajarilishi har doim yechimning olinishini kafolatlaydi.

Aniq kriteriy quyidagicha aniqlanadi. Tugun kuchlanish tenglamalarining xatolik vektorlarini belgilaymiz:

$$\dot{W} = \dot{Y} \cdot \dot{U} - \left|\dot{Y}_{k0}\right| \cdot \dot{U}_0 + \dot{I} \,. \tag{2.68}$$

2.1-rasm sxemasi uchun (2.68) tenglamalar matritsasi quyidagicha ko'rinish oladi:

$$\begin{vmatrix} \dot{W}_1^{(k)} \\ \dot{W}_2^{(k)} \\ \dot{W}_3^{(k)} \end{vmatrix} = -\begin{vmatrix} \dot{y}_{11} & -\dot{y}_{12} & -\dot{y}_{13} \\ -\dot{y}_{21} & \dot{y}_{22} & -\dot{y}_{23} \\ -\dot{y}_{31} & -\dot{y}_{32} & \dot{y}_{33} \end{vmatrix} \cdot \begin{vmatrix} \dot{U}_1^{(k)} \\ \dot{U}_2^{(k)} \\ \dot{U}_3^{(k)} \end{vmatrix} - \begin{vmatrix} \dot{y}_{10} \\ 0 \\ 0 \end{vmatrix} \cdot \dot{U}_0 + \begin{vmatrix} S_1 / U_1^{(k)} \\ S_2 / U_2^{(k)} \\ S_3 / U_3^{(k)} \end{vmatrix}. \tag{2.69}$$

Demak, TKTning yechimida barcha xatolik vektorlarining qiymatlari $\dot{W}_i \, (i = \overline{1,n})$ nolga teng bo'ladi.

Agar quyidagi shart bajarilsa, TKT sistemasi amaliy yechilgan hisoblanadi:

$$|W_i^{(k)}| \leq \delta \qquad (i = \overline{1,n}) \,, \tag{2.70}$$

bu yerda δ - hisoblashlarda berilgan xatolik.

(2.70) shart aniq kriteriyda hisoblashlar yakunlanganligini bildiradi.

Tugun o'tkazuvchanlik matritsasining diagonal elementlari kuchaytirilganda Gauss – Zeydel uslubini qo'llashda ham yuqorida keltirilgan yaqinlashish kriteriylari ishlatiladi. Tugun o'tkazuvchanlik matritsasining diagonal elementlari kuchaytirilganda Gauss – Zeydel uslubini qo'llashda oddiy iteratsiyaga nisbatan kamroq iteratsiya talab qiladi.

2.5.5. NYUTON-RAFSON USLUBI

Nyuton-Rafson uslubi nochiziqli tenglamalar sistemasini yechishda yechimga nisbatan tezroq yaqinlashadigan uslublardan biri hisoblanadi. Bu uslub nochiziqli tenglamalar sistemasini ketma-ket chiziqli tenglamalar sistemasi bilan alishtirishga asoslanadi. Hisob-lashlar oldingilarga nisbatan yechimga yaqinroq bo‘lgan noma’lumlarning qiymatlarini beradi.

Nochiziqli tenglamalar sistemasini yechishda Nyuton-Rafson uslubini qo‘llashni ko‘rib chiqamiz:

$$\left\{\begin{array}{l} w_1(x_1 \cdots x_n) = 0 \\ w_2(x_1 \cdots x_n) = 0 \\ \dots\dots\dots\dots\dots\dots \\ w_n(x_1 \cdots x_n) = 0 \end{array}\right\} \qquad (2.71)$$

Dastlabki vektor qiymatlarini beramiz:

$$X = |x_1 \ldots x_n|^T = X^{(0)}.$$

Bu nuqtada funksiyalarni to‘g‘ri chiziqli funksiyalarga keltiramiz va (2.71) dagi funksiyalardan har birini nolga tenglaymiz:

$$\left\{\begin{array}{l} w_1\left(X^{(0)}\right) + \dfrac{\partial w_1}{\partial x_1}\left(x_1 \cdots x_1^{(0)}\right) + \ldots + \dfrac{\partial w_1}{\partial x_n}\left(x_n \cdots x_n^{(0)}\right) = 0 \\ w_2\left(X^{(0)}\right) + \dfrac{\partial w_2}{\partial x_1}\left(x_1 \cdots x_1^{(0)}\right) + \ldots + \dfrac{\partial w_2}{\partial x_n}\left(x_n \cdots x_n^{(0)}\right) = 0 \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ w_n\left(X^{(0)}\right) + \dfrac{\partial w_n}{\partial x_1}\left(x_1 \cdots x_1^{(0)}\right) + \ldots + \dfrac{\partial w_n}{\partial x_n}\left(x_n \cdots x_n^{(0)}\right) = 0 \end{array}\right\} \qquad (2.72)$$

(2.72) da barcha $\frac{\partial w_i}{\partial X_j}$ xususiy hosilalar $X = X^{(0)}$ nuqtada hisoblanadi. To‘g‘ri chiziqli nisbiy noma’lumlar orttirmasini olamiz:

$$\Delta X_i = X_i - X_i^0 \qquad (i = \overline{1, n}). \qquad (2.73)$$

Tenglamalar sistemasini – aniq (Gauss uslubi) yoki iteratsion (oddiy iteratsiya, Gauss-Zeydel uslubi) uslublarida yechish mumkin. Noma’lumlar ottirmasi aniqlangandan keyin (2.72) sistemadan yangi noma’lumlar orttirmasini aniqlaymiz:

$$x^{(1)} = x^{(0)} + \Delta x. \qquad (2.74)$$

Bu yerda $\Delta x = |\Delta x_1 \ldots \Delta x|^T$ - orttirma vektori. Shu nuqtada funksiyalarni to‘g‘ri chiziqli funksiyaga keltirish, to‘g‘ri chiziqli sistemani yechish va boshqa jarayonlar takrorlanadi. Bu takrorlanishlar (2.72)dagi barcha funksiyalar modul bo‘yicha hisoblashlarda berilgan aniqlik qiymatidan kichik bo‘lmagunicha davom ettiriladi.

$$W(X) = |w_1(x)\ldots w_n(x)|^T,$$

$$\left|\frac{\partial W}{\partial X}\right| = \left|\frac{\partial W_i}{\partial X_j}\right| \qquad (2.75)$$

$$\left|\frac{\partial W}{\partial X}\right|^{(k)} \cdot \Delta X^{(k)} = -W(X^{(k)}) = -W^{(k)}. \qquad (2.76)$$

$\left|\frac{\partial W}{\partial X}\right|$ matritsa – Yakobi matritsasi deyiladi va uni yakobianlar aniqlaydi. EETlarining turg`un rejimlarini hisoblashda X noma’lum kuchlanish $\dot{U}$ vektori; (2.71) sistema TKTning dastlabki ko‘rinishi.

$$\dot{W}(\dot{U}) = \dot{Y} \cdot \dot{U} - \left|\dot{Y}_{k0}\right| \cdot \dot{U}_0 + \dot{I} \;; \qquad (2.77)$$

Yakobi matritsasi – $\left|\frac{\partial \dot{W}}{\partial \dot{U}}\right|$.

2.1-rasm sxemasi uchun (2.77) algebraik ko‘rinishda quyidagicha yoziladi:

$$\dot{W}^{(k)} = \left\{ \begin{aligned} \dot{W}_1^{(k)} &= \dot{y}_{11} \cdot \dot{U}_1^{(k)} - \dot{y}_{12} \cdot \dot{U}_2^{(k)} - \dot{y}_{13} \cdot \dot{U}_3^{(k)} - \dot{y}_{10} \cdot \dot{U}_0 + S_1 / U_1^{(k)} \\ \dot{W}_2^{(k)} &= -\dot{y}_{21} \cdot \dot{U}_1^{(k)} + \dot{y}_{22} \cdot \dot{U}_2^{(k)} - \dot{y}_{23} \cdot \dot{U}_3^{(k)} + S_2 / U_2^{(k)} \\ \dot{W}_3^{(k)} &= -\dot{y}_{31} \cdot \dot{U}_1^{(k)} - \dot{y}_{32} \cdot \dot{U}_2^{(k)} + \dot{y}_{33} \cdot \dot{U}_3^{(k)} + S_3 / U_3^{(k)} \end{aligned} \right\} \qquad (2.78)$$

Yakobi matritsasi quyidagi ko‘rinishni oladi:

$$\begin{vmatrix} \frac{\partial \dot{W}_1}{\partial \dot{U}_1} & \frac{\partial \dot{W}_1}{\partial \dot{U}_2} & \frac{\partial \dot{W}_1}{\partial \dot{U}_3} \\ \frac{\partial \dot{W}_2}{\partial \dot{U}_1} & \frac{\partial \dot{W}_2}{\partial \dot{U}_2} & \frac{\partial \dot{W}_2}{\partial \dot{U}_3} \\ \frac{\partial \dot{W}_3}{\partial \dot{U}_1} & \frac{\partial \dot{W}_3}{\partial \dot{U}_2} & \frac{\partial \dot{W}_3}{\partial \dot{U}_3} \end{vmatrix} = \begin{vmatrix} (\dot{y}_{11} - \frac{S_1}{(U_1^{(k)})^2}) & -\dot{y}_{12} & -\dot{y}_{13} \\ -\dot{y}_{21} & (\dot{y}_{22} - \frac{S_2}{(U_2^{(k)})^2}) & -\dot{y}_{23} \\ -\dot{y}_{31} & -\dot{y}_{32} & (\dot{y}_{33} - \frac{S_3}{(U_3^{(k)})^2}) \end{vmatrix} \qquad (2.79)$$

(2.78) va (2.79) da k = 0,1,2,… - iteratsiya nomeri.

Demak, EET turg‘un rejimlarini Nyuton – Rafson uslubi bo‘yicha hisoblash algoritmi quyidagi etaplardan tashkil topgan.

1. k = 0 deb olamiz va kuchlanishning dastlabki qiymatlarini beramiz:

$$\dot{U}^{(0)} = \left| \dot{U}_1^{(0)} \quad \dot{U}_2^{(0)} \quad \dot{U}_3^{(0)} \right|^T = \dot{U}_0 \ .$$

2. $\dot{U}^{(k)}$ ning qiymatini (2.78) ga qo‘yamiz va quyidagi funksiyaning qiymatini hisoblaymiz $\dot{W}_i^{(k)} \quad (i = \overline{1,3})$.

3. Agar quyidagi shart bajarilsa

$|W_i^{(k)}| \le \delta$

hisoblashlar to‘xtatiladi. Aks holda p.4 ga o‘tiladi.

4. $\dot{U}^{(k)}$ ning qiymatini (2.74) ga qo‘yamiz va Yakobi matritsasi $\left| \dfrac{\partial \dot{W}}{\partial \dot{U}} \right|^{(k)}$ komponentlari kattaliklarini aniqlaymiz.

5. To‘g‘ri chiziqli tenglamalar sistemasini yechamiz

$$\left| \frac{\partial \dot{W}}{\partial \dot{U}} \right|^{(k)} \cdot \Delta \dot{U}^{(k)} = -\dot{W}^{(k)} \qquad (2.80)$$

va kuchlanish orttirmasi $\Delta \dot{U}^{(k)}$ vektorini aniqlaymiz.

6. Keyingi kuchlanish qiymatini topamiz

$$\dot{U}^{(k+1)} = \dot{U}^{(k)} + \Delta \dot{U}^{(k)} . \qquad (2.81)$$

7. k ning qiymatini birga oshiramiz va p.2 ga o‘tamiz.

Nyuton-Rafson uslubida boshqa uslublarga qaraganda natijalarga yaqinlashish nisbatan tezroq va ishonchliroq amalga oshiriladi. Uning kamchiligi – boshqa uslublar bilan solishtirilganda alohida iteratsiyalar hisobiga uslub hajmining kattaligi, ya’ni Nyuton-Rafson uslubining har bir iteratsiyasida Yakobi matritsasining hisoblanishidir. Bundan tashqari nochiziqli tenglamalar sistemasining yechilishidir (2.80).

3. TOPSHIRIQNI BAJARISH UCHUN NAMUNA

2.1-rasm sxemasi uchun dastlabki ma’lumotlar:
Shahobchalar qarshiligi: R_{01}= 1 Ом,
R_{12}= 3 Ом,
R_{13}= 6 Ом,
R_{23}= 4 Ом.
Balanslovchi tugun kuchlanishi: U_0= 110 kV.
Tugun toklari: I_1 = 3 kA, I_2 = -2 kA, I_3 = 4 kA.

3.1. TUGUN O‘TKAZUVCHANLIKLARI MATRITSASINI Y VA BARCHA TUGUNLARNING BALANSLOVCHI TUGUN BILAN BOG‘LANISH O‘TKAZUVCHANLIKLARI VEKTORNI $|Y_{KO}|$ ANIQLASH

Shahobchalar o‘tkazuvchanliklarini aniqlaymiz, ya’ni Y matritsada o‘zaro o‘tkazuvchanliklar (diagonal bo‘lmagan elementlar) aniqlanadi:

$$y_{01} = y_{10} = \frac{1}{R_{01}} = \frac{1}{1} = 1 \quad \text{Sim};$$

$$y_{12} = y_{21} = \frac{1}{R_{12}} = \frac{1}{3} = 0{,}33333 \quad \text{Sim};$$

$$y_{13} = y_{31} = \frac{1}{R_{13}} = \frac{1}{6} = 0{,}16666 \quad \text{Sim};$$

$$y_{23} = y_{32} = \frac{1}{R_{23}} = \frac{1}{4} = 0{,}25 \quad \text{Sim}.$$

Tugunlarning o‘tkazuvchanliklarini aniqlaymiz (Y matritsa diagonal elementlari):

$y_{11} = y_{10} + y_{12} + y_{13}$ =1+0,3333+0,16666=1,5 Sim;

$y_{22} = y_{21} + y_{23}$ = 0,333+0,25=0,5833 Sim;
$y_{33} = y_{31} + y_{32}$ = 0,16666+0,25=0,41666 Sim.

Demak 2- va 3- tugunlar balanslovchi 0 tugun bilan bog‘lanmagan, ya’ni

$$y_{20} = y_{30} = 0.$$

Shuning uchun, Y matritsa quyidagicha bo‘ladi:

$$Y = \begin{vmatrix} \dot{y}_{11} - \dot{y}_{12} - \dot{y}_{13} \\ -\dot{y}_{21} \quad \dot{y}_{22} - \dot{y}_{23} \\ -\dot{y}_{31} - \dot{y}_{32} \quad \dot{y}_{33} \end{vmatrix} = \begin{vmatrix} 1{,}5 & -0{,}3333 & -0{,}1666 \\ -0{,}3333 & 0{,}5833 & -0{,}25 \\ -0{,}16666 & -0{,}25 & 0{,}41666 \end{vmatrix} \quad [Сим].$$

$|Y_{ko}|$ vektor esa quyidagi ko‘rinishda bo‘ladi:

$$|Y_{k0}| = \begin{vmatrix} y_{10} \\ y_{20} \\ y_{30} \end{vmatrix} = \begin{vmatrix} 1 \\ 0 \\ 0 \end{vmatrix} \quad [\text{Sim}].$$

3.2. TO‘G‘RI CHIZIQLI TUGUN KUCHLANISH TENGLAMALARINI YECHISH

3.2.1. Tugunlardagi kuchlanishlarni Gauss va triangulyatsiya uslubida aniqlash

(2.6) da vektorning o‘ng qismi quyidagiga teng:

$$(|Y_{k0}| \cdot U_0 - I) = \begin{vmatrix} y_{10} \\ y_{20} \\ y_{30} \end{vmatrix} \cdot U_0 - \begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix} = \begin{vmatrix} 1 \\ 0 \\ 0 \end{vmatrix} \cdot 110 - \begin{vmatrix} 3 \\ -2 \\ 4 \end{vmatrix} = \begin{vmatrix} 107 \\ 2 \\ -4 \end{vmatrix} \; [кА].$$

Tugunlardagi kuchlanishlarni chiziqli TKT sistemasini yechish yo‘li orqali dastlabki ko‘rinishda aniqlaymiz va quyidagini olamiz:

$$\begin{aligned} 1{,}5U_1 - 0{,}3333U_2 - 0{,}1666U_3 &= 107, \\ -0{,}3333U_1 + 0{,}5833U_2 - 0{,}25U_3 &= 2, \\ -0{,}1666U_1 - 0{,}25U_2 + 0{,}41666U_3 &= -4. \end{aligned} \qquad (3.1)$$

(3.1) sistemani Gauss uslubining algebraic ko‘rinishida yechamiz.

Asosiy element $a_{11} = 1{,}5 \neq 0$ tanlaymiz va (3.1) sistema birinchi tenglamasining barcha koeffitsiyentlarini unga bo‘lamiz:

$$b_{12} = \frac{a_{12}}{a_{11}} = \frac{-0{,}3333}{1{,}5} = -0{,}22222;$$

$$b_{13} = \frac{a_{13}}{a_{11}} = \frac{-0{,}16667}{1{,}5} = -0{,}11111;$$

$$b_{14} = \frac{a_{14}}{a_{11}} = \frac{107}{1{,}5} = 71{,}3333.$$

Natijada quyidagi tenglamaga ega bo‘lamiz:

$$U_1 + (-0{,}2222)U_2 + (-0{,}11111)U_3 = 71{,}3333. \qquad (3.2)$$

(2.13) sistema koeffitsiyentlarining qiymatlarini aniqlaymiz (2.2.1 ga asosan):

$$a_{22}^{(1)} = a_{22} - a_{21}b_{12} = 0{,}58333 - (-0{,}33333)(-0{,}22222) = $$
$$= 0{,}509259;$$
$$a_{23}^{(1)} = a_{23} - a_{21}b_{13} = (-0{,}25) - (-0{,}33333)(-0{,}11111) =$$
$$= -0{,}28704;$$
$$a_{24}^{(1)} = a_{24} - a_{21}b_{14} = 2 - (-0{,}33333)\cdot 71{,}3333 = 25{,}77778;$$
$$a_{32}^{(1)} = a_{32} - a_{31}b_{12} = (-0{,}25) - (-0{,}16667)(-0{,}22222) =$$
$$= -0{,}28704;$$

$a_{33}^{(1)} = a_{33} - a_{31}b_{13} = 0{,}41667 - (-0{,}16667)(-0{,}11111) =$
$= 0{,}398148;$

$a_{34}^{(1)} = a_{34} - a_{31}b_{14} = (-4) - (-0{,}16667)\cdot 71{,}33333 = 7{,}88889.$

Natijada quyidagi tenglamalar sistemasini olamiz:

$$0{,}509259U_2 - 0{,}28704U_3 = 25{,}77778,$$
$$-0{,}28704U_2 + 0{,}398148U_3 = 7{,}88889. \qquad (3.3)$$

Asosiy element $a_{22}^{(1)} = 0{,}509259 \neq 0$ tanlaymiz va (3.3) sistema birinchi tenglamasining barcha koeffitsiyentlarini unga bo‘lamiz:

$$b_{23}^{(1)} = \frac{a_{23}^{(1)}}{a_{22}^{(1)}} = \frac{-0{,}28704}{0{,}509259} = -0{,}56364;$$
$$b_{24}^{(1)} = \frac{a_{24}^{(1)}}{a_{22}^{(1)}} = \frac{25{,}77778}{0{,}509259} = 50{,}61818.$$

Quyidagi tenglamaga ega bo‘lamiz:

$$U_2 + (-0{,}56364)U_3 = 50{,}61818. \qquad (3.4)$$

(2.15) sistema koeffitsiyentlarining qiymatlarini aniqlaymiz (2.2.1 ga qaralsin):

$a_{33}^{(2)} = a_{33}^{(1)} - a_{32}^{(1)}b_{23}^{(1)} = 0{,}398148 - (-0{,}28704)(-0{,}56364) =$
$= 0{,}236364;$

$a_{34}^{(2)} = a_{34}^{(1)} - a_{32}^{(1)}b_{24}^{(1)} = 7{,}88889 - (-0{,}28704)\cdot 50{,}61818 =$
$= 22{,}41818.$

Quyidagi tenglamani olamiz:

$$0{,}236364U_3 = 22{,}41818. \qquad (3.5)$$

Asosiy element $a_{33}^{(2)}$ = 0,236364≠0 tanlaymiz va (3.3) tenglamaning barcha koeffitsiyentlarini unga bo‘lamiz:

$$b_{34}^{(2)} = \frac{a_{34}^{(2)}}{a_{33}^{(2)}} = \frac{22{,}41818}{0{,}236364} = 94{,}84615.$$

Quyidagi tenglamaga ega bo‘lamiz:

$$U_3 = b_{34}^{(2)} = 94{,}84615 \text{ kV}. \qquad (3.6)$$

Shu bilan Gauss uslubining to‘g‘ri qadami tugaydi.

Teskari yurishini bajaramiz. (3.4) tenglamadan U_2 aniqlanadi:

$$U_2 = b_{24}^{(1)} - b_{23}^{(1)} \cdot U_3 = 50{,}61818 - (-0{,}56364) \cdot 94{,}84615 = $$
$$= 104{,}0769 \text{ kV}.$$

(3.2) tenglamadan U_1 topiladi:

$$U_1 = b_{14} - b_{13} \cdot U_3 - b_{12} \cdot U_2 =$$
$$= 71{,}33333 - (-0{,}11111) \cdot 94{,}84615 - (-0{,}22222) \cdot 104{,}0769 =$$
$$= 105 \text{ kV}.$$

Shuning uchun, tugun kuchlanishlari vektori quyidagiga teng:

$$U = \begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} 105 \\ 104{,}0769 \\ 94{,}84615 \end{vmatrix} \quad [\text{kV}].$$

(3.1) sistemaga topilgan kuchlanish qiymatlarini qo‘yib tekshirish bilan hisoblashlarni to‘xtatamiz:

1,5·105 – 0,3333·104,0769 – 0,16666·94,84615 =107 107,

–0,3333·105 + 0,5833·104,0769 – 0,25·94,84615 = 2 2,

–0,1666·105 – 0,25·104,0769 + 0,41666·94,84615 = –4 –4.

Topilgan qiymatlar sistemani qanoatlantirayapti, demak qiymatlar to‘g‘ri topilgan. (Olingan qiymatlarda kichik xatoliklar bo‘lishi mumkin, bu xatoliklar oraliq va oxirgi natijalarni hisoblayotganda yuzaga keladi).

(3.1) sistema Gauss uslubining jadval ko‘rinishida quyidagicha yechiladi:

Etap №	**1**	**2**	**3**	**4**	**Σ**	
I	1.5	-0.33333	-0.16667	107	108	**To‘g‘ri qadam**
	-0.33333	0.583333	-0.25	2	2	
	-0.16667	-0.25	0.416667	-4	-4	
	1	-0.22222	-0.11111	71.33333	72	
II		0.509259	-0.28704	25.77778	26	
		-0.28704	0.398148	7.888889	8	
		1	-0.56364	50.61818	51.05455	
III			0.236364	22.41818	22.65455	
			1	94.84615	95.84615	
			1	94.84615	95.84615	**Teskari qadam**
		1		104.0769	105.0769	
	1			105	106	

(3.1) sistemani triangulyatsiya uslubida yechamiz. γ va α matritsa elementlari qiymatlarini aniqlaymiz:

$$\alpha_{12}=\frac{a_{12}}{a_{11}}=\frac{-0,3333}{1,5}=-0,22222;$$

$$\alpha_{13}=\frac{a_{13}}{a_{11}}=\frac{-0,16666}{1,5}=-0,11111;$$

γ_{11} = a_{11} = 1,5;

γ_{21} = a_{12} = -0,3333;

γ_{31} = a_{13} = -0,1666;

$$\gamma_{22}=a_{22}-a_{12}\frac{a_{12}}{a_{11}}=0,5833-(-0,3333)\frac{-0,3333}{1,5}=0,50926;$$

$$\gamma_{32}=a_{23}-a_{13}\frac{a_{13}}{a_{11}}=-0,25-(-0,1666)\frac{-0,1666}{1,5}=-0,28704;$$

$$\alpha_{23}=\frac{1}{\gamma_{22}}(a_{23}-\gamma_{21}\cdot\alpha_{13})=\frac{1}{0,50926}(-0,25-(-0,3333)\frac{-0,1666}{1,5})=-0,56364;$$

$$\gamma_{33}=a_{33}-\gamma_{31}\cdot\alpha_{13}-\gamma_{32}\cdot\alpha_{23}=0,416667-(0,16666)(0,11111)-$$
$$-(-0,28704)(-0,56364)=0,23636$$

Shunday qilib, γ va α matritsa quyidagi ko‘rinishni oladi:

$$\gamma=\begin{vmatrix}\gamma_{11} & 0 & 0\\ \gamma_{21} & \gamma_{22} & 0\\ \gamma_{31} & \gamma_{32} & \gamma_{33}\end{vmatrix}=\begin{vmatrix}1,5 & 0 & 0\\ -0,3333 & 0,50926 & 0\\ -0,1666 & -0,28704 & 0,23636\end{vmatrix};$$

$$\alpha=\begin{vmatrix}1 & \alpha_{12} & \alpha_{13}\\ 0 & 1 & \alpha_{23}\\ 0 & 0 & 1\end{vmatrix}=\begin{vmatrix}1 & -0,2222 & -0,11111\\ 0 & 1 & -0,56364\\ 0 & 0 & 1\end{vmatrix}.$$

Tuzatilgan doimiylar qiymatlarini topamiz:

$$V_1 = \frac{b_1}{a_{11}} = \frac{107}{1{,}5} = 71{,}33333;$$

$$V_2 = \frac{1}{\gamma_{22}} \cdot (b_2 - \gamma_{21} \cdot V_1) = \frac{1}{0{,}50926}(2 - (-0{,}3333) \cdot 71{,}333) = 50{,}61811;$$

$$V_3 = \frac{1}{\gamma_{33}} \cdot (b_3 - \gamma_{31} \cdot V_1 - \gamma_{32} \cdot V_2) =$$

$$= \frac{1}{0{,}23636}((-4) - (-0{,}16666) \cdot 71{,}3333 - (-0{,}28704) \cdot 50{,}61811) = 94{,}84655$$

Tugun kuchlanishlarini topamiz:

$U_3 = V_3 = 94{,}84655$ kV;

$U_2 = V_2 - \alpha_{23} \cdot U_3 = 50{,}61811 - (-0{,}56364) \cdot 94{,}84655 = 104{,}0774$ kV;

$U_1 = V_1 - \alpha_{12} \cdot U_2 - \alpha_{13} \cdot U_3 = 71{,}3333 - (-0{,}2222) \cdot 104{,}0774 -$
$-(-0{,}111111) \cdot 94{,}84655 = 105{,}00015$ kV.

Demak, yuqoridagilardan:

$$U = \begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} 105{,}00015 \\ 104{,}0774 \\ 94{,}84655 \end{vmatrix} \quad [\text{kV}]$$

Demak, natijalar Gauss uslubi bo‘yicha olingan natijalarga mos kelmoqda.

3.2.2. Tugun qarshiliklar matritsasini Gauss (jadval ko‘rinishida), faktorizatsiya, topologiya va kommutatsiya uslublarida aniqlash

Z matritsani Gauss uslubi bo‘yicha teskari matritsa yo‘li bilan topamiz, jadval shakli quyidagicha ko‘rinish oladi.

Etap №	**1**	**2**	**3**	**4**	**5**	**6**	**Σ**
I	1.5	-0.33333	-0.16667	1	0	0	2
	-0.33333	0.583333	-0.25	0	1	0	1
	-0.16667	-0.25	0.416667	0	0	1	1
	1	-0.22222	-0.11111	0.666667	0	0	1.333333
II		0.509259	-0.28704	0.222222	1	0	1.444444
		-0.28704	0.398148	0.111111	0	1	1.222222
		1	-0.56364	0.436364	1.963636	0	2.836364
III			0.236364	0.236364	0.563636	1	2.036364
			1	1	2.384615	4.230769	8.615385
			1	1	2.384615	4.230769	8.615385
		1		1	3.307692	2.384615	7.692308
	1			1	1	1	4

Olingan matritsa Z quyidagi ko‘rinishga ega bo‘ladi:

$$Z=\begin{vmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{vmatrix}=\begin{vmatrix} 1 & 1 & 1 \\ 1 & 3,30769 & 2,38462 \\ 1 & 2,38462 & 4,230769 \end{vmatrix} \quad Om.$$

Quyidagi boglanish bilan olingan matritsa to‘g‘riligini tekshiramiz:

$$Z\cdot Y=\begin{vmatrix} 1 & 1 & 1 \\ 1 & 3,30769 & 2,38462 \\ 1 & 2,38462 & 4,230769 \end{vmatrix}\cdot\begin{vmatrix} 1,5 & -0,3333 & -0,1666 \\ -0,3333 & 0,5833 & -0,25 \\ -0,16666 & -0,25 & 0,41666 \end{vmatrix}=\begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix}=E$$

Endi Z matritsani faktorizatsiya uslubida aniqlaymiz. Birinchi o‘zgartirish matritsani topamiz (p.2.2.4.2 ga qaralsin):

$$T_1 = \begin{vmatrix} 1/a_{11} & 0 & 0 \\ -a_{21}/a_{11} & 1 & 0 \\ -a_{31}/a_{11} & 0 & 1 \end{vmatrix} = \begin{vmatrix} 1/1{,}5 & 0 & 0 \\ 0{,}3333/1{,}5 & 1 & 0 \\ 0{,}1667/1{,}5 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 0{,}6667 & 0 & 0 \\ 0{,}2222 & 1 & 0 \\ 0{,}1111 & 0 & 1 \end{vmatrix}.$$

$A^{(1)}=T_1 \cdot Y$ matritsa elementlari qiymatlarini aniqlaymiz:

$a_{12}^{(1)} = a_{12}/a_{11}$=-0,3333/1,5= -0,22222;
$a_{13}^{(1)} = a_{13}/a_{11}$=-0,16667/1,5= -0,11111;
$a_{22}^{(1)} = a_{22}-a_{21}\cdot a_{12}/a_{11}$=0,5833-(-0,3333)(-0,3333)/1,5=0,509259;
$a_{23}^{(1)} = a_{23}-a_{21}\cdot a_{13}/a_{11}$=-0,25-(-0,3333)(-0,16667)/1,5= -0,28704;
$a_{32}^{(1)} = a_{32}-a_{31}\cdot a_{12}/a_{11}$=-0,25-(-0,16667)(-0,3333)/1,5= -0,28704;
$a_{33}^{(1)} = a_{33}-a_{31}\cdot a_{13}/a_{11}$=0,416667-(-0,16667)(-0,16667)/1,5=
=0,398148.

Shuning uchun, $A^{(1)}$ matritsa quyidagiga teng

$$A^{(1)} = T_1 \cdot A = \begin{vmatrix} 1 & -0{,}22222 & -0{,}11111 \\ 0 & 0{,}50926 & -0{,}28704 \\ 0 & -0{,}28704 & 0{,}398148 \end{vmatrix}.$$

Endi ikkinchi o‘zgartirish matritsani topamiz :

$$T_2 = \begin{vmatrix} 1 & -a_{12}^{(1)}/a_{22}^{(1)} & 0 \\ 0 & 1/a_{22}^{(1)} & 0 \\ 0 & -a_{32}^{(1)}/a_{22}^{(1)} & 1 \end{vmatrix} = \begin{vmatrix} 1 & 0{,}2222/0{,}50926 & 0 \\ 0 & 1/0{,}50926 & 0 \\ 0 & 0{,}28704/0{,}50926 & 1 \end{vmatrix} = \begin{vmatrix} 1 & 0{,}436364 & 0 \\ 0 & 1{,}963636 & 0 \\ 0 & 0{,}56364 & 1 \end{vmatrix}.$$

$A^{(2)}=T_2 \cdot A^{(1)}$ matritsa elementlari qiymatlarini aniqlaymiz:

$a_{13}^{(2)} = a_{13}^{(1)} - a_{12}^{(1)} \cdot a_{23}^{(1)}/a_{22}^{(1)}$ = –0,1111 – (–0,2222)x (–0,28704)/0,50926 = –0,236364;

$a_{23}^{(2)} = a_{23}^{(1)}/a_{22}^{(1)} = –0,28704/0,50926 = –0,563636;$
$a_{33}^{(2)} = a_{33}^{(1)} - a_{32}^{(1)}·a_{23}^{(1)}/a_{22}^{(1)} = 0,398148 – (–0,28704)x$
$(–0,28704)/0,50926 = 0,236364.$

Demak:

$$A^{(2)} = T_2 \cdot A^{(1)} = T_2 \cdot T_1 \cdot A = \begin{vmatrix} 1 & 0 & a_{13}^{(2)} \\ 0 & 1 & a_{23}^{(2)} \\ 0 & 0 & a_{33}^{(2)} \end{vmatrix} = \begin{vmatrix} 1 & 0 & -0,236364 \\ 0 & 1 & -0,563636 \\ 0 & 0 & 0,236364 \end{vmatrix}$$

Uchinchi o‘zgartirish matritsa T_3 ni topamiz:

$$T_3 = \begin{vmatrix} 1 & 0 & -a_{13}^{(2)}/a_{33}^{(2)} \\ 0 & 1 & -a_{23}^{(2)}/a_{33}^{(2)} \\ 0 & 0 & 1/a_{33}^{(2)} \end{vmatrix} = \begin{vmatrix} 1 & 0 & -(-0,236364)/0,236364 \\ 0 & 1 & -(-0,563636)/0,236364 \\ 0 & 0 & 1/0,2236364 \end{vmatrix} = \begin{vmatrix} 1 & 0 & 1 \\ 0 & 1 & 2,384615 \\ 0 & 0 & 4,230769 \end{vmatrix}$$

Endi Z matritsani topamiz:

$$Z = T_3 \cdot T_2 \cdot T_1 = \begin{vmatrix} 1 & 0 & 1 \\ 0 & 1 & 2,384615 \\ 0 & 0 & 4,230769 \end{vmatrix} \cdot \begin{vmatrix} 1 & 0,436364 & 0 \\ 0 & 1,963636 & 0 \\ 0 & 0,563636 & 1 \end{vmatrix} \cdot \begin{vmatrix} 0,66667 & 0 & 0 \\ 0,22222 & 1 & 0 \\ 0,11111 & 0 & 1 \end{vmatrix} =$$

$$= \begin{vmatrix} 1 & 1 & 1 \\ 1 & 3,30769 & 2,38462 \\ 1 & 2,38462 & 4,23077 \end{vmatrix}$$

Natijalar Gauss uslubi bilan mos keladi.

Tugun qarshiliklar matritsasi Z ni topologiya va kommutatsiya uslubida aniqlaymiz:

$$Z^{\partial} = \begin{vmatrix} 1 & 1 & 1 \\ 1 & 4 & 1 \\ 1 & 1 & 7 \end{vmatrix} \quad [Om].$$

ΔZ matritsa elementlari qiymatlarini 2-3 shahobcha ulanganini hisobga olib (Z'_{23}=3 Om) topamiz:

$$\Delta pq \doteq Z'_{23} + Z^{\partial}_{22} + Z^{\partial}_{33} - Z^{\partial}_{23} - Z^{\partial}_{32} = 4 + 4 + 7 - 1 - 1 = 13 \text{ Om}.$$

$$\Delta Z_{11} = \frac{(Z^{\partial}_{12} - Z^{\partial}_{13}) \cdot (Z^{\partial}_{21} - Z^{\partial}_{32})}{\Delta pq} = \frac{(1-1)\cdot(1-1)}{13} = 0,$$

$$\Delta Z_{12} = \frac{(Z^{\partial}_{12} - Z^{\partial}_{13}) \cdot (Z^{\partial}_{22} - Z^{\partial}_{32})}{\Delta pq} = \frac{(1-1)\cdot(4-1)}{13} = 0,$$

$$\Delta Z_{13} = \frac{(Z^{\partial}_{12} - Z^{\partial}_{13}) \cdot (Z^{\partial}_{23} - Z^{\partial}_{33})}{\Delta pq} = \frac{(1-1)\cdot(1-7)}{13} = 0,$$

$$\Delta Z_{22} = \frac{(Z^{\partial}_{21} - Z^{\partial}_{22}) \cdot (Z^{\partial}_{23} - Z^{\partial}_{22})}{\Delta pq} = \frac{(1-4)\cdot(1-4)}{13} = 0{,}69231$$

$$\Delta Z_{21} = \frac{(Z^{\partial}_{22} - Z^{\partial}_{23}) \cdot (Z^{\partial}_{21} - Z^{\partial}_{31})}{\Delta pq} = \frac{(4-1)\cdot(1-1)}{13} = 0,$$

$$\Delta Z_{23} = \frac{(Z^{\partial}_{22} - Z^{\partial}_{23}) \cdot (Z^{\partial}_{23} - Z^{\partial}_{33})}{\Delta pq} = \frac{(4-1)\cdot(1-7)}{13} = -1{,}384615$$

$$\Delta Z_{31} = \frac{(Z^{\partial}_{32} - Z^{\partial}_{33}) \cdot (Z^{\partial}_{21} - Z^{\partial}_{31})}{\Delta pq} = \frac{(1-7)\cdot(1-1)}{13} = 0,$$

$$\Delta Z_{33} = \frac{(Z^{\partial}_{32} - Z^{\partial}_{33}) \cdot (Z^{\partial}_{23} - Z^{\partial}_{33})}{\Delta pq} = \frac{(1-7)\cdot(1-7)}{13} = 2{,}7692308$$

Demak, ΔZ quyidagicha ko‘rinish oladi:

$$\Delta Z = \begin{vmatrix} \Delta Z_{11} & \Delta Z_{12} & \Delta Z_{13} \\ \Delta Z_{21} & \Delta Z_{22} & \Delta Z_{23} \\ \Delta Z_{31} & \Delta Z_{32} & \Delta Z_{33} \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0{,}69231 & -1{,}384615 \\ 0 & -1{,}384615 & 2{,}7692308 \end{vmatrix} \text{ [Om]}$$

Z matritsa quyidagicha aniqlanadi:

$$Z = Z^{\partial} - \Delta Z = \begin{vmatrix} 1 & 1 & 1 \\ 1 & 4 & 1 \\ 1 & 1 & 7 \end{vmatrix} - \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0{,}69231 & -1{,}384615 \\ 0 & -1{,}384615 & 2{,}7692308 \end{vmatrix} =$$

$$= \begin{vmatrix} 1 & 1 & 1 \\ 1 & 3{,}30769 & 2{,}38462 \\ 1 & 2{,}38462 & 4{,}230769 \end{vmatrix} \text{ [Om]}.$$

Natijalar oldingilari bilan mos kelmoqda.

Topilgan tugun qarshiliklar matritsasi Z dan foydalanib, teskari matritsa uslubi yordamida TKT (2.8) ning teskari shaklidan kuchla-nishlarni aniqlaymiz:

$$\begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{vmatrix} \cdot \left(\begin{vmatrix} y_{10} \\ 0 \\ 0 \end{vmatrix} \cdot U_0 - \begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix} \right) =$$

$$= \begin{vmatrix} 1 & 1 & 1 \\ 1 & 3{,}30769 & 2{,}38462 \\ 1 & 2{,}38462 & 4{,}230769 \end{vmatrix} \cdot \begin{vmatrix} 107 \\ 2 \\ -4 \end{vmatrix} = \begin{vmatrix} 105 \\ 104{,}0769231 \\ 94{,}84615385 \end{vmatrix} \text{ [kV]}.$$

Kuchlanishning qiymatlari Gauss va triangulyatsiya uslublari bilan olingan qiymatlarga mos keladi.

3.3. INSIDENSIYA MATRITSASINING TUZILISHI VA TARMOQ SHAHOBCHALARIDAGI TOKLARNI ANIQLASH

2.2-rasmdagi sxemada quyidagi shahobcha yo‘nalishlarini qabul qilamiz: 0-1, 1-2, 1-3, 2-3. U holda C insidensiya matritsasi quyidagi holatda aniqlanadi (3.3-jadval).

3.3-jadval

tugun / shahobcha	**0-1**	**1-2**	**1-3**	**2-3**
0	1	0	0	0
1	-1	1	1	0
2	0	-1	0	1
3	0	0	-1	-1

Demak, C matritsa quyidagiga teng:

$$C = \begin{vmatrix} 1 & 0 & 0 & 0 \\ -1 & 1 & 1 & 0 \\ 0 & -1 & 0 & 1 \\ 0 & 0 & -1 & -1 \end{vmatrix}.$$

(2.41) bo‘yicha tarmoq shahobchalarida kuchlanish tushuvlarini aniqlaymiz:

$$\Delta U^{в} = C^{T} \cdot U = \begin{vmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{vmatrix} \cdot \begin{vmatrix} 110 \\ 105{,}00015 \\ 104{,}0774 \\ 94{,}84655 \end{vmatrix} = \begin{vmatrix} 4{,}99985 \\ -0{,}92275 \\ 10{,}1536 \\ 9{,}23085 \end{vmatrix} \text{[kV]}.$$

Shahobchalar qarshiliklari matritsasi quyidagiga teng:

$$Z^{в} = \begin{vmatrix} Z^{в}_{01} & 0 & 0 & 0 \\ 0 & Z^{в}_{12} & 0 & 0 \\ 0 & 0 & Z^{в}_{13} & 0 \\ 0 & 0 & 0 & Z^{в}_{23} \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 6 & 0 \\ 0 & 0 & 0 & 4 \end{vmatrix} \text{ [Om]},$$

$Z^{в}$ ga nisbatan teskari matritsa

$$(Z^{в})^{-1} = \begin{vmatrix} 1/Z^{в}_{01} & 0 & 0 & 0 \\ 0 & 1/Z^{в}_{12} & 0 & 0 \\ 0 & 0 & 1/Z^{в}_{13} & 0 \\ 0 & 0 & 0 & 1/Z^{в}_{23} \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 0{,}33333 & 0 & 0 \\ 0 & 0 & 0{,}16667 & 0 \\ 0 & 0 & 0 & 0{,}25 \end{vmatrix} \text{ [Sim].}$$

U holda shahobchalardagi tok vektori $J^{в}$ quyidagiga teng:

$$J^{в} = \begin{vmatrix} J^{в}_{01} \\ J^{в}_{12} \\ J^{в}_{13} \\ J^{в}_{23} \end{vmatrix} = (\dot{Z}^{в})^{-1} \cdot \Delta\dot{U}^{в} = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 0{,}5 & 0 & 0 \\ 0 & 0 & 0{,}2 & 0 \\ 0 & 0 & 0 & 0{,}333 \end{vmatrix} \cdot \begin{vmatrix} 4{,}99985 \\ -0{,}92275 \\ 10{,}1536 \\ 9{,}23085 \end{vmatrix} = \begin{vmatrix} 4{,}99985 \\ -0{,}461375 \\ 2{,}03072 \\ 3{,}073873 \end{vmatrix} \text{ [kA]}$$

3.4. TUGUNLARDAGI QUVVATLARNI VA ELEKTR TARMOG‘IDAGI UMUMIY QUVVAT ISROFINI ANIQLASH

Balanslovchi tugundagi tok I_0 quyidagiga teng:

$$I_0 = -(I_1 + I_2 + I_3) = -(3 + (-2) + 4) = -5 \text{ kA.}$$

Tugunlardagi quvvatlar quyidagicha aniqlanadi:

$$P_0 = U_0 \cdot I_0 = 110\cdot(-5) = -550 \text{ MVt,}$$

$$P_1 = U_1 \cdot I_1 = 105{,}00015 \cdot 3 = 315{,}00045 \text{ MVt},$$
$$P_2 = U_2 \cdot I_2 = 104{,}0774 \cdot (-2) = -208{,}1548 \text{ MVt},$$
$$P_3 = U_3 \cdot I_3 = 94{,}84655 \cdot 4 = 379{,}3862 \text{ MVt}.$$

Tarmoqdagi umumiy quvvat isrofi quyidagiga teng:

$$\pi = I^T \cdot Z \cdot I = \begin{vmatrix} I_1 & I_2 & I_3 \end{vmatrix} \cdot \begin{vmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{vmatrix} \cdot \begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix} =$$

$$= \begin{vmatrix} 3 & -2 & 4 \end{vmatrix} \cdot \begin{vmatrix} 1 & 1 & 1 \\ 1 & 3{,}30769 & 2{,}38462 \\ 1 & 2{,}38462 & 4{,}23077 \end{vmatrix} \cdot \begin{vmatrix} 3 \\ -2 \\ 4 \end{vmatrix} = 64{,}43074 \text{ [MVt]}$$

3.5. NOCHIZIQLI TUGUN KUCHLANISH TENGLAMALARINI YECHISH

3.5.1 Oddiy iteratsiya uslubida tugun kuchlanishlarini aniqlash

Namunadagi dastlabki ma’lumotlarni oddiy iteratsiya uslubining hisobiy formulalari (2.49) ga qo‘yib, quyidagilarni olamiz:

$$\left.\begin{aligned} U_1^{(n+1)} &= \frac{1}{1{,}5}\left(1 \cdot 110 + 0{,}3333\dot{U}_2^{(n)} + 0{,}1666\dot{U}_3^{(n)} - \frac{315}{U_1^{(n)}}\right), \\ U_2^{(n+1)} &= \frac{1}{0{,}5833}\left(0{,}3333\dot{U}_1^{(n)} + 0{,}25\dot{U}_3^{(n)} - \frac{208{,}155}{U_2^{(n)}}\right), \\ U_3^{(n+1)} &= \frac{1}{0{,}41666}\left(0{,}1666\dot{U}_1^{(n)} + 0{,}25\dot{U}_2^{(n)} - \frac{379{,}3862}{U_3^{(n)}}\right), \end{aligned}\right\} \qquad (3.7)$$

Xatoliklar qiymatlarini qabul qilamiz: ε = 0,1 kV; δ = 0,1 kA.

1. Dastlabki yaqinlashtiruvchi kuchlanishlarni qabul qilamiz:

$$U^{(0)}_1 = U^{(0)}_2 = U^{(0)}_3 = U_0 = 110 \text{ kV}.$$

2. $U=U_0$ deb qabul qilinganda hosil bo‘lgan xatoliklarni (2.52) bo‘yicha aniqlaymiz:

$$W^{(0)}_1 = 1{,}5\cdot110 - 0{,}3333\cdot110 - 0{,}1666\cdot110 - 1\cdot110 + 315/110 = \\ =2{,}87464 \text{ kA}$$

$$W^{(0)}_2 = -0{,}3333\cdot110 + 0{,}5833\cdot110 - 0{,}25\cdot110 - 208{,}155/110 = \\ = -1{,}89232 \text{ kA}$$

$$W^{(0)}_3 = -0{,}16666\cdot110 - 0{,}25\cdot110 + 0{,}41666\cdot110 + 379{,}3862/110 = \\ =3{,}448965 \text{ kA}.$$

Barcha xatoliklar ruxsat etilgan qiymatidan katta bo‘lganligi uchun hisoblashlarni davom ettiramiz.

3. Keyingi yaqinlashtiruvchi kuchlanish $U^{(1)}$ (3.7) bo‘yicha hisoblanadi:

$$U_1^{(1)} = \frac{1}{1{,}5}(1\cdot110 + 0{,}3333\cdot110 + 0{,}1666\cdot110 - \frac{315}{110}) = 108{,}0836 \text{kV};$$

$$U_2^{(1)} = \frac{1}{0{,}5833}(0{,}3333\cdot110 + 0{,}25\cdot110 + \frac{208{,}155}{110}) = 113{,}2442 \text{ kV};$$

$$U_3^{(1)} = \frac{1}{0{,}41666}(0{,}1666\cdot110 + 0{,}25\cdot110 - \frac{379{,}3862}{110}) = 101{,}7065 \text{kV}.$$

Keyingilarini 3.4-jadvalga joylashtiramiz:

3.4-jadval.

k	**$U_1^{(k)}$, kV**	**$U_2^{(k)}$, kV**	**$U_3^{(k)}$, kV**	**$W_1^{(k)}$, kA**	**$W_2^{(k)}$, kA**	**$W_3^{(k)}$, kA**
0	110	110	110	2,87464	-1,89232	3,448965
1	108,0836	113,2442	101,7065	0,351193	2,766328	-0,21701
2	107,8494	108,5016	102,2118	1,502841	-0,12862	1,199732
3	106,8476	108,7221	99,31684	0,436188	1,061556	0,21357
4	106,5568	106,9022	98,78888	0,702581	0,196318	0,517446
5	106,0884	106,5656	97,53164	0,334684	0,464273	0,205314
6	105,86520	105,7697	97,0236	0,356184	0,186677	0,250174
7	105,6278	105,4497	96,40793	0,215928	0,227089	0,138203
8	105,4838	105,0603	96,06103	0,191623	0,12739	0,129194
9	105,3561	104,8419	95,73577	0,130601	0,119767	0,082979
10	105,269	104,6366	95,52144	0,106614	0,078704	0,068412
11	105,1979	104,5017	95,34209	0,076874	0,065959	0,046733
12	105,1467	104,3886	95,21478	0,060359	0,046751	0,03582
13	105,1065	104,3085	95,11367	0,044706	0,37157	0,02467
14	105,0767	104,2448	95,03933	0,034468	0,27301	0,017706
15	105,0537	104,198	94,9817	0,025856	0,021169	0,011648

Shunday qilib, xatolik qiymati berilgan qiymatdan kam bo‘ldi, ya’ni hisoblashlar yakunlandi. Olingan kuchlanishlar qiymatlari quyidagiga teng:

$$U = \begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} 105{,}0537 \\ 104{,}198 \\ 94{,}9817 \end{vmatrix} \quad [\,\text{kV}\,]$$

3.5.2. Teskari matritsaga asoslangan TKTlardan foydalanib oddiy iteratsiya uslubida tugun kuchlanishlarini aniqlash

Namunada berilgan ma’lumotlarni oddiy iteratsiya uslubining hisoblash formulalari (2.54) ga qo‘yib, quyidagilarni olamiz:

$$\begin{aligned} U_1^{(k+1)} &= 110 - \frac{315}{U_1^{(k)}} + \frac{208{,}155}{U_2^{(k)}} - \frac{379{,}3862}{U_3^{(k)}} \\ U_2^{(k+1)} &= 110 - \frac{315}{U_1^{(k)}} + \frac{688{,}5}{U_2^{(k)}} - \frac{904{,}69}{U_3^{(k)}} \\ U_3^{(k+1)} &= 110 - \frac{315}{U_1^{(k)}} + \frac{496{,}37}{U_2^{(k)}} - \frac{1605{,}095}{U_3^{(k)}} \end{aligned} \qquad (3.8)$$

Xatoliklar qiymatlarini qabul qilamiz: ε = 0,1 kV; δ = 0,1 kA.

1. Dastlabki yaqinlashtiruvchi kuchlanishlarni qabul qilamiz:

$$U^{(0)}_1 = U^{(0)}_2 = U^{(0)}_3 = U_0 = 110 \text{ kV}.$$

2. TKT $U=U_0$ bo‘lgandagi xatoliklarni (2.58) bo‘yicha aniqlaymiz:

$$W^{(0)}_1 = 1{,}5\cdot110 - 0{,}3333\cdot110 - 0{,}1666\cdot110 - 1\cdot110 + 315/110 = =2{,}87464 \text{ kA};$$

$$W^{(0)}_2 = -0{,}3333\cdot110 + 0{,}5833\cdot110 - 0{,}25\cdot110 - 208{,}155/110 = = -1{,}89232 \text{ kA};$$

$$W^{(0)}_3 = -0{,}16666\cdot110 - 0{,}25\cdot110 + 0{,}41666\cdot110 + 379{,}3862/110 = =3{,}448965 \text{ kA}.$$

Demak, barcha xatoliklar ruxsat etilganidan katta, shuning uchun hisoblashlar davom ettiriladi.

4. Keyingi yaqinlashtiruvchi kuchlanish $U^{(1)}$ (3.8) bo'yicha hisoblanadi:

$U_1^{(1)}$ = 110 – 315/110 + 208,155/110 – 379,3862/110 =
=105,5797 kV,

$U_2^{(1)}$ = 110 – 315/110 + 688,5/110 – 904,69/110 = 105,171 kV,

$U_3^{(1)}$ = 110 – 315/110 + 496,37/110 – 1605,095/110 =
=97,05704 kV.

Keyingilarini 3.5-jadvalga joylashtiramiz.

3.5-jadval.

k	**$U_1^{(k)}$, kV**	**$U_2^{(k)}$, kV**	**$U_3^{(k)}$, kV**	**$W_1^{(k)}$, kA**	**$W_2^{(k)}$, kA**	**$W_3^{(k)}$, kA**
0	110	110	110	2,8746405	-1,892316	3,4489655
1	105,5797	105,171	97,05704	0,129902	-0,08694	0,460021
2	105,0868	104,2417	95,19846	0,023852	-0,01768	0,076412
3	105,0141	104,1041	94,90368	0,011908	-0,00268	0,012478
4	105,0023	104,0813	94,85552	0,010167	-0,00048	0,002129
5	105,0004	104,0775	94,84765	0,009884	-0,00011	0,000432

Shunday qilib, xatolik qiymati berilgan qiymatdan kam bo'ldi, ya'ni hisoblashlar yakunlandi. Olingan kuchlanishlar qiymatlari quyidagiga teng:

$$U = \begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} 105{,}0004 \\ 104{,}0775 \\ 94{,}84765 \end{vmatrix} \quad [\text{kV}].$$

3.5.3. O‘tkazuvchanlik matritsa shaklida berilgan TKTlarni Gauss-Zeydel uslubi asosida yechish

Namunada berilgan ma’lumotlarni Gauss-Zeydel uslubini hisoblash formulalari (2.61) ga qo‘yib, quyidagilarni olamiz:

$$\left.\begin{aligned}
U_1^{(k+1)} &= \frac{110 + 0{,}3333 \cdot U_2^{(k)} + 0{,}1666 \cdot U_3^{(k)} - 315 / U_1^{(k)}}{1{,}5}, \\
U_2^{(k+1)} &= \frac{0{,}3333 \cdot U_1^{(k+1)} + 0{,}25 \cdot U_3^{(k)} + 208{,}155 / U_2^{(k)}}{0{,}5833}, \\
U_3^{(k+1)} &= \frac{0{,}1666 \cdot U_1^{(k+1)} + 0{,}25 \cdot U_2^{(k+1)} - 379{,}3862 / U_3^{(k)}}{0{,}41666}.
\end{aligned}\right\} \qquad (3.9)$$

Hisoblashlar ε=0,1 kV va δ=0,1 kA gacha davom etadi.

1. Dastlabki yaqinlashtiruvchi kuchlanishlarni qabul qilamiz:

$$U_1^{(0)} = U_2^{(0)} = U_3^{(0)} = U_0 = 110 \text{ kV}.$$

2. TKT ning xatoliklar qiymatlari $U = U_0$ bo‘lganda, xuddi oddiy iteratsiya uslubiga o‘xshab aniqlanadi:

$$W_1^{(0)} = 2{,}874640455 \text{ kA};$$

$$W_2^{(0)} = -1{,}892316364 \text{ kA};$$

$$W_3^{(0)} = 3{,}448965455 \text{ kA}.$$

3. Keyingi yaqinlashtiruvchi kuchlanish $U^{(1)}$ (3.10) bo‘yicha hisoblanadi:

$$\left.\begin{aligned}
U_1^{(k+1)} &= \frac{110 + 0{,}3333 \cdot 110 + 0{,}1666 \cdot 110 - 315/110}{1{,}5} = 108{,}0836\,\text{kV} \\
U_2^{(k+1)} &= \frac{0{,}3333 \cdot 108{,}0836 + 0{,}25 \cdot 110 + 208{,}155/110}{0{,}5833} = 112{,}1491\,\text{kV} \\
U_3^{(k+1)} &= \frac{0{,}1666 \cdot 108{,}0836 + 0{,}25 \cdot 112{,}1491 - 379{,}3862/110}{0{,}41666} = 102{,}2297\,\text{kV}
\end{aligned}\right\}$$

Keyingilarini 3.6-jadvalga joylashtiramiz:

3.6-jadval.

k	**$U_1^{(k)}$, kV**	**$U_2^{(k)}$, kV**	**$U_3^{(k)}$, kV**	**$W_1^{(k)}$, kA**	**$W_2^{(k)}$, kA**	**$W_3^{(k)}$, kA**
0	110	110	110	2,87464	-1,89232	3,44897
1	108,0836	112,11491	102,2297	0,62901	1,97883	0,25566
2	107,6642	108,517	99,25359	1,71775	0,68191	0,10482
3	106,5191	106,6936	97,43456	0,94225	0,42197	0,06197
4	105,8909	105,6112	96,3627	0,55687	0,24797	0,03696
5	105,5197	104,974	95,72795	0,32861	0,14672	0,01977
6	105,3006	104,5973	95,35167	0,19446	0,08693	0,00932
7	105,1709	104,3742	95,12843	0,11524	0,05156	0,00303
8	105,0941	104,2419	94,99593	0,06836	0,03059	-0,00074
9	105,0485	104,1634	94,91726	0,04057	0,01816	-0,00299
10	105,0215	104,1168	94,87055	0,024083	0,010784	-0,00433

Shunday qilib, xatolik qiymati berilgan qiymatdan kam bo‘ldi, ya’ni hisoblashlar yakunlandi. Olingan kuchlanishlar qiymatlari quyidagiga teng:

$$U = \begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} 105{,}0215 \\ 104{,}1168 \\ 94{,}87055 \end{vmatrix} \quad [\text{kV}].$$

3.5.4.Tugun o‘tkazuvchanlik matritsasining diagonal elementlari kuchaytirilganda Gauss-Zeydel uslubini qo‘llash

Misolda berilgan ma’lumotlarni diagonal elementlari kuchaytirilganda Gauss-Zeydel uslubining hisoblash formulalari (2.66) ga qo‘yamiz. 2-generatsiyalovchi, 1 va 3- yuklama tugunlari ekanligini hisobga olgan holda tegishli diagonal elementlarini kuchaytiramiz va quyidagi tenglamalarni hosil qailamiz:

$$\left.\begin{aligned} U_1^{(k+1)} &= \frac{110 + 0{,}3333 \cdot U_2^{(k)} + 0{,}1666 \cdot U_3^{(k)}}{1{,}5 + 315/\left(U_1^{(k)}\right)^2}, \\ U_2^{(k+1)} &= \frac{0{,}3333 \cdot U_1^{(k+1)} + 0{,}25 \cdot U_3^{(k)} + 208{,}155/U_2^{(k)}}{0{,}5833}, \\ U_3^{(k+1)} &= \frac{0{,}1666 \cdot U_1^{(k+1)} + 0{,}25 \cdot U_2^{(k+1)}}{0{,}41666 + 379{,}3862/\left(U_3^{(k)}\right)^2}. \end{aligned}\right\} \quad (3.10)$$

Hisoblashlar ε=0,1 kV va δ=0,1 kA gacha davom etadi.

1. Dastlabki yaqinlashtiruvchi kuchlanishlarni qabul qilamiz

$$U_1^{(0)} = U_2^{(0)} = U_3^{(0)} = U_0 = 110 \text{ kV}.$$

2. TKT ning xatoliklar qiymatlari U = U_0 bo‘lganda, xuddi oddiy iteratsiya uslubiga o’xshab aniqlanadi:

$$W_1^{(0)} = 2{,}874640455 \text{ kA};$$

$$W_2^{(0)} = -1{,}892316364 \text{ kA};$$

$$W_3^{(0)} = 3{,}448965455 \text{ kA}.$$

3. Keyingi yaqinlashtiruvchi kuchlanish $U^{(1)}$ (3.10) bo‘yicha hisoblanadi:

$$\left.\begin{aligned}
U_1^{(k+1)} &= \frac{110+0{,}3333\cdot 110+0{,}1666\cdot 110}{1{,}5+315/110^2}=108{,}1205909\text{kV}\\
U_2^{(k+1)} &= \frac{0{,}3333\cdot 108{,}1205909+0{,}25\cdot 110+208{,}155/110}{0{,}5833}=112{,}1702543\text{kV}\\
U_3^{(k+1)} &= \frac{0{,}1666\cdot 108{,}1205909+0{,}25\cdot 112{,}1702543}{0{,}41666+379{,}3862/110^2}=102{,}8135671\text{kV}
\end{aligned}\right\}$$

Keyingilarini 3.7-jadvalga joylashtiramiz:

3.7-jadval.

k	**$U_1^{(k)}$, kV**	**$U_2^{(k)}$, kV**	**$U_3^{(k)}$, kV**	**$W_1^{(k)}$, kA**	**$W_2^{(k)}$, kA**	**$W_3^{(k)}$, kA**
0	110	110	110	2,87464	-1,89232	3,44897
1	108,12059	112,17025	102,81357	0,57922	1,83322	0,46640
2	107,74530	108,81297	99,79011	1,64912	0,69861	0,22032
3	106,66934	107,00048	97,91492	0,98118	0,43639	0,14425
4	106,03092	105,88754	96,75567	0,60540	0,26937	0,09230
5	105,63852	105,20152	96,03562	0,37645	0,16719	0,05858
6	105,39596	104,77628	95,58714	0,23592	0,10409	0,03698
7	105,24535	104,51178	95,30731	0,14906	0,06493	0,02327
8	105,15157	104,34687	95,13252	0,09514	0,04055	0,01461
9	105,09306	104,24393	95,02327	0,06156	0,02534	0,00917
10	105,05651	104,17960	94,95494	0,04061	0,01585	0,00574

Shunday qilib, xatolik qiymati berilgan qiymatdan kam bo‘ldi, ya’ni hisoblashlar yakunlandi. Olingan kuchlanishlar qiymatlari quyidagiga teng:

$$U = \begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} 105{,}05651 \\ 104{,}17960 \\ 94{,}95494 \end{vmatrix} \quad [\text{kV}].$$

3.5.5. Nyuton-Rafson uslubida tugun kuchlanishlarini aniqlash

Namunada berilgan ma’lumotlarni Nyuton-Rafson uslubining hisoblash formulalari (2.78) va (2.79) ga qo‘yib, quyidagilarni olamiz:

$$W^{(k)} = \begin{cases} W_1^{(k)} = 1{,}5 \cdot U_1^{(k)} - 0{,}3333 \cdot U_2^{(k)} - 0{,}1666 \cdot U_3^{(k)} - 110 + 315/U_1^{(k)} \\ W_2^{(k)} = -0{,}3333 \cdot U_1^{(k)} + 0{,}5833 \cdot U_2^{(k)} - 0{,}25 \cdot U_3^{(k)} - 208{,}155/U_2^{(k)} \\ W_3^{(k)} = -0{,}16666 \cdot U_1^{(k)} - 0{,}25 \cdot U_2^{(k)} + 0{,}41666 \cdot U_3^{(k)} + 379{,}3862/U_3^{(k)} \end{cases} \tag{3.11}$$

$$\left(\left| \frac{\partial W}{\partial U} \right| \right)^{(k)} = \begin{vmatrix} (1{,}5 - 315/(U_1^{(k)})^2 & -0{,}3333 & -0{,}1666 \\ -0{,}3333 & (0{,}5833 + 208{,}155/(U_2^{(k)})^2 & -0{,}25 \\ -0{,}16666 & -0{,}25 & (0{,}41666 - 379{,}3862/(U_3^{(k)})^2 \end{vmatrix} \tag{3.12}$$

Hisoblashlar ε=0,1 kV va δ=0,1 kA gacha davom etadi.

1. Dastlabki yaqinlashtiruvchi kuchlanishlarni qabul qilamiz:

$$U_1^{(0)} = U_2^{(0)} = U_3^{(0)} = U_0 = 110 \text{ kV}.$$

2. (3.11) bo‘yicha $W_i^{(0)}(i=1,3)$ funksiya qiymatlarini hisoblaymiz:

$$W_1^{(0)} = 1{,}5\cdot110 - 0{,}3333\cdot110 - 0{,}1666\cdot110 - 1\cdot110 + 315/110 = =2{,}87464 \text{ kA};$$

$$W_2^{(0)} = -0{,}3333\cdot110 + 0{,}5833\cdot110 - 0{,}25\cdot110 - 208{,}155/110 = = -1{,}89232 \text{ kA};$$

$$W_3^{(0)} = -0{,}16666\cdot110 - 0{,}25\cdot110 + 0{,}41666\cdot110 + 379{,}3862/110 = =3{,}448965 \text{ kA}.$$

3. (3.12) bo‘yicha $\left(\left|\frac{\partial W}{\partial U}\right|\right)^{(0)}$ matritsa diagonal elementlar qiymatlarini aniqlaymiz:

$$\left(\frac{\partial W_1}{\partial U_1}\right)^{(0)} = 1{,}5 - 315/110^2 = 1{,}473967;$$

$$\left(\frac{\partial W_2}{\partial U_2}\right)^{(0)} = 0{,}5833 + 208{,}155/110^2 = 0{,}600536;$$

$$\left(\frac{\partial W_3}{\partial U_3}\right)^{(0)} = 0{,}41666 - 379{,}3862/110^2 = 0{,}385312.$$

4. (2.80) bo‘yicha to‘g‘ri chiziqli tenglamalar sistemasini olamiz:

$$\begin{vmatrix} 1{,}473967 & -0{,}3333 & -0{,}1666 \\ -0{,}3333 & 0{,}600536 & -0{,}25 \\ -0{,}1666 & -0{,}25 & 0{,}385312 \end{vmatrix} \cdot \begin{vmatrix} \Delta U_1^{(0)} \\ \Delta U_2^{(0)} \\ \Delta U_3^{(0)} \end{vmatrix} = \begin{vmatrix} -2{,}87464 \\ 1{,}89232 \\ -3{,}448965 \end{vmatrix} \qquad (3.13)$$

5. Olingan (3.13) tenglamalar sistemasini Gauss uslubining 3.8-jadval shaklida yechamiz:

3.8-jadval.

Etap №	1	2	3	4	Σ
I	1,473967	-0,33333	-0,16667	-2,87464	-1,90067
	-0,33333	0,600536	-0,25	1,892316	1,909519
	-0,16667	-0,25	0,385312	-3,44897	-3,48032
	1	-0,22615	-0,11307	-1,95027	-1,2895
II		0,525154	-0,28769	1,242225	1,479687
		-0,28769	0,366467	-3,77401	-3,69524
		1	-0,54782	2,365449	2,817627
III			0,208863	-3,09349	-2,88463
			1	-14,8111	-13,8111
			1	-14,8111	-13,8111
		1		-5,74841	-4,74841
	1			-4,925	-3,925

Demak, hisoblangan kuchlanishlar quyidagiga teng:

$\Delta U_1^{(0)}$ = - 4,925 kV,
$\Delta U_2^{(0)}$ = - 5,74841 kV,
$\Delta U_3^{(0)}$ = - 14,8111 kV.

6. Keyingi yaqinlashtiruvchi kuchlanish $U^{(1)}$ (2.81) bo‘yicha hisoblanadi:

$$U_1^{(1)} = U_1^{(0)} + \Delta U_1^{(0)} = 110 + (-4{,}925) = 105{,}075 \text{ kV};$$
$$U_2^{(1)} = U_2^{(0)} + \Delta U_2^{(0)} = 110 + (-5{,}74841) = 104{,}2516 \text{ kV};$$
$$U_3^{(1)} = U_3^{(0)} + \Delta U_3^{(0)} = 110 + (-14{,}8111) = 95{,}1889 \text{ kV}.$$

Keyingilarini 3.9-jadvalga joylashtiramiz:

3.9-jadval

k	**0**	**1**	**2**
$U_1^{(k)}$, **kV**	110	105,0865	104,9858
$U_2^{(k)}$, **kV**	110	104,263166	104,051008
$U_3^{(k)}$, **kV**	110	95,20138	94,78807
$W_1^{(k)}$, **kV**	2,86364045	0,005980853	-0,00262
$W_2^{(k)}$, **кА**	-1,892316364	-0,005430186	0,003641
$W_3^{(k)}$, **кА**	3,44896545	0,072126594	-0,01288

Shunday qilib, xatolik qiymati berilgan qiymatdan kam bo‘ldi, ya’ni hisoblashlar yakunlandi. Olingan kuchlanishlar qiymatlari quyidagiga teng:

$$U = \begin{vmatrix} U_1 \\ U_2 \\ U_3 \end{vmatrix} = \begin{vmatrix} 104{,}9858 \\ 104{,}051 \\ 94{,}7881 \end{vmatrix} \quad [\text{kV}].$$

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