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Assessment of the impact of resonance regimes in power supply systems on network voltage quality

Sh.I. Murtazov[1][a], **J.N. Tolipov**[1][b]
[1]Institute of Energy Problems of the Academy of Sciences of the Republic of Uzbekistan, Uzbekistan

Abstract: This article investigates the impact of resonance regimes on voltage quality in power supply systems. The study particularly analyzes voltage distortion levels, waveform deformation, and the emergence of high-frequency harmonic components under the presence of nonlinear loads and capacitor devices. Based on oscillograms and spectral analyses, the negative effects of resonance and inter-resonance conditions on voltage purity are demonstrated. Modeling results are expressed through the Total Harmonic Distortion of Voltage (THD_U), revealing its variation depending on load parameters and the presence of capacitors. The research substantiates the necessity of carefully selecting capacitors and filtering devices to improve power quality in electrical systems.

Keywords: power supply system, resonance regime, harmonic distortion, capacitor bank, nonlinear loads, waveform, voltage quality, harmonic analysis, spectral analysis, sinusoidal signal, reactive power compensation

Elektr ta’minoti tizimining rezonans rejimini tarmoq kuchlanishi sifat darajasiga ta’sirini baholash

Murtazov Sh.I.[1][a], **Tolipov J.N.**[1][b]
[1]O‘zbekiston Respublikasi Fanlar akademiyasi Energetika muammolari instituti, O‘zbekiston

Annotatsiya: Mazkur maqolada elektr ta’minoti tizimlarida rezonans rejimining kuchlanish sifatiga ta’siri o‘rganilgan. Tadqiqotda, ayniqsa, nochiziqli yuklamalar va kondensator qurilmalari mavjud holatda tarmoq kuchlanishining buzilish darajalari, kuchlanish to‘lqin shaklining o‘zgarishi va yuqori chastotali garmonik komponentlarning paydo bo‘lishi tahlil qilingan. Osillogramma va spektral tahlillar asosida rezonans va inter-rezonans holatlarning kuchlanish tozaligiga salbiy ta’siri ko‘rsatilgan. Modellashtirish natijalari THD_U (umumiy garmonik buzilishlar koeffitsienti) orqali ifodalangan bo‘lib, yuklama parametrlari va kondensatorlarning mavjudligiga bog‘liq holda qanday o‘zgarishi aniqlangan. Tadqiqot elektr energiyasi sifatini yaxshilashda kondensatorlar va filtrlash qurilmalarining ehtiyotkorlik bilan tanlanishi zarurligini asoslaydi.

Kalit so‘zlar: elektr ta’minoti tizimi, rezonans rejimi, garmonik buzilishlar, kondensator batareyasi, nochiziqli yuklamalar, to‘lqin shakli, kuchlanish sifati, garmonik tahlil, spektral analiz, sinusoidal signal, reaktiv quvvat kompensatsiyasi

1. Kirish

Elektr ta’minoti tizimlarining sifat ko‘rsatkichlari, xususan kuchlanishning sifati va uning garmonik tarkibi iste’molchilarning sifatli elektr energiyasi olishida muhim o‘rin tutadi. Zamonaviy tarmoqlarda ko‘plab elektron to‘g‘rilagichlar, invertorlar va boshqa noan’anaviy yuklamalar tufayli kuchlanishning yuqori garmonikalar darajasi ortib bormogda. Bunday garmonikalar tizimning rezonan rejimiga kirishiga, ya’ni tizim elementlarining induktivligi va kondensatorlar sig‘imi muvofiqlashtirilgan holatda rezonans chastotasida o‘zaro ta’sirlashuvi natijasida kuchlanish va tokda kuchli o‘zgarishlar hosil bolishiga olib keladi.

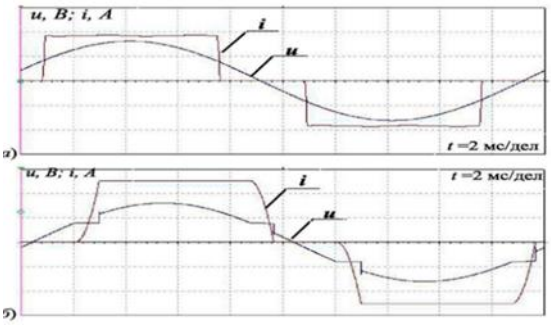
2. Tadqiqot metodologiyasi

Ushbu maqolada asosiy metodologik yondashuvi transport oqimlarini GAT texnologiyalari asosida Kondensatorlar elektr ta’minoti tizimlarida reaktiv quvvatni kompensatsiya qilish uchun keng qo‘llaniladi, biroq ular ishlashi tizimda rezonan rejimlarni kuchaytirishi mumkin. Shuning uchun kondensatorlarning mavjudligi yoki yo‘qligi, hamda ularning quvvati va holati tarmoq kuchlanishining sifat ko‘rsatkichlariga bevosita ta’sir ko‘rsatadi.

1-rasmda nochiziq yuklamalar uchun (P*d = 0,01 va P*d = 0,7) to‘g‘rilagich faza tokining va tarmoq faza kuchlanishining (ko‘k chiziq) osillogrammalari keltirilgan. Ikkinchi osillogrammadan ko‘rinib turibdiki, tokning kommutatsiya oraliqlarida kuchlanish egri chizig‘ida kuchli buzilishlar yuzaga keladi.

[a] https://orcid.org/0009-0009-2520-8995
[b] https://orcid.org/0009-0002-5095-0234

Ushbu osillogrammalarda tarmoq kuchlanishi va tokning vaqtga nisbatan o‘zgarishi ko ‘rsatilgan. Ko‘k rangda faza kuchlanishi u, qizil rangda esa to‘g‘rilagich orqali o‘tuvchi faza toki i ifodalangan[1-4].



1-rasm. To‘g‘rilagich kirishidagi faza kuchlanishi va toki osillogrammalari: a) - P*d = 0,01; b)-P*d = 0,7

a) Yuklama faktori P*d = 0,01 holatida tok va kuchlanish to‘lqinlari nisbatan sinusoidal shaklida bo‘lib, toki ham kuchlanishga yaqin silliq o‘zgarishlarga ega. Bu holatda elektr ta’minoti tizimida yuklama juda kichik bo‘lib, tarmoqda kuchlanish sifati yuqori darajada saqlanmoqda. Tok to‘lqinining to‘g‘rilagichga kirishi sezilarli buzilmasdan, aniq va nazorat ostida bo‘ladi[1-7].

b) Yuklama faktori P*d - 0,7 holatida esa tok to‘lqini sezilarli darajada o‘zgargan. Tog‘rilagichning kalitlanish momentlarida tok to‘lqini to‘rtburchak shakliga o‘xshash tarzda keskin o‘zgarib, kuchlanish egri chizig‘ida (ko‘k chiziq) katta buzilishlar paydo bo‘ladi. Bu kommutatsiya oraliqlarida kuchlanishning qattiq tebranishlari va impuls shaklidagi garmonik komponentlar yuzaga kelishiga olib keladi. Natijada, kuchlanish sifati pasayadi, kuchlanishdagi yuqori garmonikalar va nosinusoidallik ko‘payadi, bu esa elektr ta’minoti tizimining samaradorligini kamaytirishi va jihozlarning shikastlanish xavfini oshirishi mumkin.

Shu bilan birga, yuqori yuklama sharoitida tokning aniq to‘g‘rilanishi uchun tizimda rezonans rejimlari yuzaga kelishi ehtimoli oshadi, bu esa kuchlanish sifatini yanada yomonlashtiradi. Mazkur osillogrammalar elektr ta’minoti tizimlarida yuklamaning o‘zgarishi kuchlanish va tok to‘lqin shakliga qanday ta’sir qilishini aniq ko‘rsatadi va kondensator qurilmalarining mavjudligi yoki yo‘qligi sharoitida tizimning ish faoliyatini baholashda muhim ma’lumot beradi[2-6].

Ushbu tadqiqot bosqichida elektr energiyasi sifati ko‘rsatkichlariga, xususan, kuchlanishning yuqori garmonikalar darajasiga, nochiziq yuklama quvvatining ta’siri kondensator qurilmalari mavjud va mavjud bo‘lmagan holatlar uchun ko‘rib chiqilgan. Kondensatorlar o‘chirilgan holatdagi modellashtirish natijalari 1-jadvalda keltirilgan.

1-jadval

Kondensator batareyasi o‘chirilgan holatda THD_U % koeffitsientining qiymatlari

P^*_d	1	0,75	0,66	0,5	0,25
S^*_n	0	0	0	0	0
THD_U, %	10,25	9,1	7,15	6,3	3,6
P^*_d	1	0,75	0,66	0,5	0,25
$S^*_н$ (cosφ = 0,85)	0	0,25	0,33	0,5	0,75
THD_U, %	10,25	9,2	7,65	6,75	3,95

Ko‘rib chiqilayotgan rejimlar uchun tarmoq kuchlanishining garmonik tarkibiy qismlari qiymatlari hamda kuchlanishning umumiy nosinusoidallik koeffitsienti THD_U, % bilan birga 2-jadvalda keltirilgan.

2-jadval

Tarmoq kuchlanishining yuqori garmonik amplituda qiymatlari

Rejimlar		11-garmonikadagi rezonansrejimi		11 va 13-garmonikalar orasidagi inter-rezonans rejimi		7 va 11-garmonikalar orasidagi inter-rezonans rejimi	
Tarmoq parametrlari		P^*_d= 0,3, $Q_к$*=0,15, $S^*_н$=0,4		P^*_d= 0,3, $Q_к$*=0,13, $S^*_н$=0,4		P^*_d= 0,3, $Q_к$*=0,25, $S^*_н$=0,4	
n	Chastota, Hz	Kuchlanish garmonikalarining amplitudalari		Kuchlanish garmonikalarining amplitudalari		Kuchlanish garmonikalarining amplitudalari	
		V	n.b.	V	n.b.	V	n.b.
1	50	320,6	1	320,2	1	322,2	1
5	250	5,5	0,017	6,4	0,02	8,1	0,025
7	350	5,9	0,019	8	0,025	16,1	0,05
11	550	48,8	0,152	30,8	0,096	7,4	0,023
13	650	6,3	0,02	29,6	0,093	3,7	0,011
17	850	2,9	0,009	4,9	0,015	1,5	0,005
19	950	2,5	0,008	3,2	0,01	1,1	0,003
23	1150	1,9	0,006	1,7	0,005	0,6	0,002
25	1250	1,7	0,005	1,3	0,004	0,5	0,001
29	1450	1,2	0,004	0,8	0,003	0,3	0,001
31	1550	1	0,003	0,7	0,002	0,2	0,001
35	1750	0,7	0,002	0,5	0,001	0,1	>0,001
37	1850	0,5	0,002	0,4	0,001	ОД	>0,001
THD_U %		156		138		6,2	

Kondensator batareyasi ulangan holatda 11-garmonikadagi rezonans rejimi hamda 7 va 11-garmonikalar orasidagi, shuningdek 11 va 13-garmonikalar orasidagi inter-rezonans rejimlari uchun tarmoq faza kuchlanishining osillogrammalari va garmonik tarkibi olinib, ular 2–3 rasmlarda keltirilgan[3-7].

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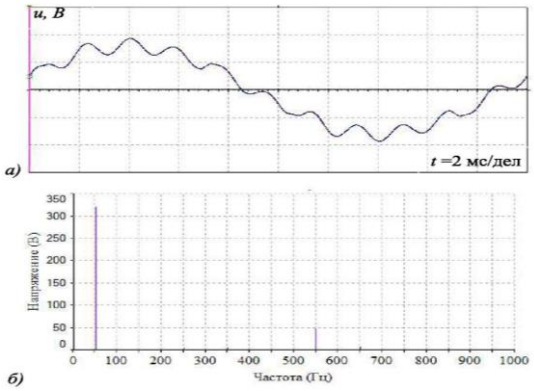
Shunday qilib, nochiziq yuklamali elektr ta’minoti tizimlarida kondensator qurilmalarining ishlashi kuchlanish sifatini yomonlashtiradi, bu ayniqsa rezonans rejimlarida yaqqol namoyon bo‘ladi.



2-rasm. Faza kuchlanishining osillogrammasi va garmonik tarkibi (P*d = 0,3; S*н = 0,4; cosφ = 0,8; QK* = 0,15; 11-garmonikadagi rezonans holati)

2-rasmda kondensator batareyasi ulangan holda 11-garmonikadagi rezonans holati yuzaga kelganida tarmoq faza kuchlanishining qanday buzilishga uchrashi ko‘rsatilgan.

a) Bu osillogrammada (yugori qismda) kuchlanish signali sof sinusoidal shakldan ancha farq qilganini ko‘rish mumkin. To‘lqin shaklida aniq tebranishlar va notekisliklar kuzatilmoqda.

Aynan bu tebranishlar yuqori garmonikalar, xususan 11-garmonik rezonans sababli yuzaga kelgan. Bu holatda kuchlanish sinusoidasi ustiga rezonans orqali kuchaytirilgan garmonikalar “qatlam” bo‘lgan va signal shaklini sezilarli darajada buzgan. Bu rezonans holati kuchlanish sifati ko'rsatkichlari, xususan THD_U (umumiy no-sinusoidallik koeffitsienti) ortishiga olib keladi va tizimdagi jihozlar uchun xavf tug‘diradi [2-5].

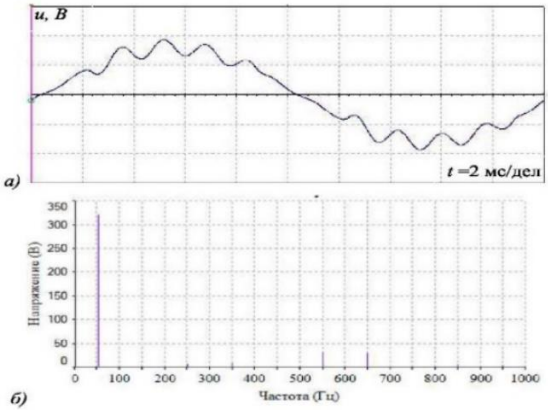
b) Quyi qismda keltirilgan grafik faza kuchlanishining chastota spektrini aks ettiradi. Unda vertikal o‘qda kuchlanishning amplitudasi (V), gorizontal o‘qda esa chastota (Hz) ko‘rsatilgan.

Bu tahlilda asosiy (1-garmonik, 50 Hz) signal bilan birga 550 Hz (11-garmonik) chastotada ancha yuqori amplitudali komponent borligi aniq ko‘zga tashlanadi. Bu aynan rezonans kuchayishi natijasida yuzaga kelgan yuqori garmonik bo‘lib, uning mavjudligi kuchlanish to‘lqinining shaklini buzib, tarmoqda sezilarli no-sinusoidallik hosil qiladi. Bu holatda asosiy kuchlanish komponenti (50 Hz) - taxminan 320 V atrofida 11-garmonik (550 Hz) - sezilarli darajada (taxminan 48-50 V) bolib, bu kuchlanish sifati uchun salbiy ko‘rsatkich hisoblanadi.

Bu osillogram va spektral tahlil quyidagilarni ko‘rsatadi: Elektr ta’minoti tizimida kondensator batareyalari mavjud holatda, ayniqsa rezonans chastotasiga yaqin bo'lganda, kuchlanish signalida sezilarli darajada buzilishlar yuzaga keladi.

Bunday holatda 11-garmonik kuchli kuchayadi, bu esa kuchlanish sifatining yomonlashuviga, jihozlarning gizib ketishiga yoki ishlamay qolishiga olib kelishi mumkin.

Shuning uchun rezonans rejimlarini aniqlash va bartaraf etish, kondensator qurilmalarini garmonik filtrlash usullari bilan to‘g‘ri loyihalash zarur.



3-rasm. Faza kuchlanishining osillogrammasi va garmonik tarkibi (P*d = 0,3; S*н = 0,4; cosφ = 0,8; QK* = 0,13; 11 va 13-garmonikalar orasidagi rezonans holati)

Ushbu 3-rasmda elektr ta’minoti tizimi yuklamasi ostida kondensator batareyasi mavjud holatda yuzaga kelgan inter-rezonans (ya’ni ikki garmonik chastota oralig‘idagi rezonans) holati tasvirlangan. Jumladan, tizimda 11 va 13-garmonikalar oralig‘ida rezonans yuzaga kelgan.

a) Faza kuchlanishining osillogrammasidagi yuqori grafiga qaraganda, kuchlanish signalining shakli an’anaviy sinusoidaldan sezilarli darajada chetlagan. To‘lqin shakli ko‘p sonli notekis tebranishlarga ega bo‘lib, ayniqsa signalning har ikki yarim davrida aniqlik bilan garmonik modulyatsiya holati kuzatiladi. Bu esa kuchlanish sifatining yomonlashganidan darak beradi. Inter-rezonans holatida kuchlanish spektrida bir nechta yuqori chastotali komponentlar kuchayadi va bu to‘lqin shaklini buzib, no-sinusoidallik koeffitsientining oshishiga olib keladi. Natijada tarmoqdagi elektr jihozlar (ayniqsa kuchlanishga sezgir elektron qurilmalar) ishdan chiqishi yoki nosoz ishlashi mumkin [4-6].

b) Garmonik tarkibi quyi grafik kuchlanish signalining spektral tahlilini ko‘rsatadi. Bunda asosiy (1-garmonik. 50 Hz) komponentning amplitudasi yuqori - taxminan 320 V atrofida 11-garmonik (550 Hz) va 13-garmonik (650 Hz) chastotalarda sezilarli garmoniklar mavjud. Bu ikki garmonik orasida rezonansli kuchayish mavjud bo‘lib, aynan kondensator batareyasi bilan yuklama parametrlari o‘zaro rezonans sharoitini hosil qilgan.

Bu holatda tizimda bir nechta yuqori garmonikalar mavjudligi sababli THD_U (umumiy garmonik buzilishlar koeffitsienti) oshadi, bu esa energiya sifatining keskin yomonlashuviga olib keladi.

3. Xulosa

Ushbu maqolada elektr ta’minoti tizimlarida rezonans va inter-rezonans rejimlarining kuchlanish sifati ko‘rsatkichlariga ta’siri modellashtirish va spektral tahlillar asosida chuqur o‘rganilgan. Tadgigot natijalari shuni ko‘rsatadiki nochiziqli yuklamalar va kondensator batareyalari mavjud bo‘lgan tizimlarda kuchlanish to‘lqin shakli sezilarli darajada buziladi hamda yuqori chastotali garmonik komponentlar kuchayadi. Ayniqsa, 11-garmonik va 11-13-garmonikalar oralig‘ida yuzaga keladigan rezonans holatlarida kuchlanish signalida nosinusoidallik ortib, THD_U koeffitsienti me’yordan ancha yuqori darajalarga yetadi.

Kondensator qurilmalarining tizimga ulanmagan va ulangan holatlaridagi taqqoslama natijalari, rezonans sharoitlari mavjud bo‘lgan holatlarda kuchlanish sifatining keskin yomonlashishini isbotlab berdi. Bu esa, o‘z navbatida, elektr ta’minoti tizimlarida energiya sifatini ta’minlashda kondensatorlar parametrlarini to‘g‘ri tanlash va garmonik filtrlash usullarini joriy etish zarurligini ko‘rsatadi. Tadqiqot natijalari elektr energiyasi sifatini yaxshilash, tizimda garmonik buzilishlar va rezonans rejimlarining oldini olish, shuningdek, elektr jihozlarining ishonchli ishlashini ta’minlash bo‘yicha xizmat qiladi.

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Mualliflar to‘g‘risida ma’lumot/ Information about the authors

Tolipov Jamshid Nurbekovich/ Jamshid Tolipov
O‘zbekiston Respublikasi Fanlar akademiyasi Energetika muammolari instituti, katta ilmiy xodimi PhD, k.i.x.
E-mail: tolipovjamshidn@gmail.com
Tel.: +99893 565-22-08
https://orcid.org/0009-0009-2520-8995

Murtazov Sherzod Isakbayevich/ Sherzod Murtazov
O‘zbekiston Respublikasi Fanlar akademiyasi Energetika muammolari instituti, mustaqil izlanuvchisi.
E-mail: shermurtazov@gmail.com
Tel.: +99893 555-10-24
https://orcid.org/0009-0002-5095-0234

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