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TARQOQ PARAMETRLI NOChIZIQ MAGNIT ZANJIRLARDA YUQORI GARMONIKALAR TAHLILI

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Annotatsiya. Maqolada tarqoq parametrli nochiziq magnit zanjirlardagi yuqori garmonikalar tahlili ko‘rib chiqilgan. Asosan garmonik tahlil uchunchi garmonika uchun ko‘rilgan bo‘lib variatsiyalash usuli asosida magnit zanjirlardagi jarayonlarni tavsiflovchi murakkab differensial tenglamalar yechimlari hosil qilingan. Tarqoq parametrli nochiziq magnit zanjirlarda asosiy garmonika buzulish koeffitsiyentining o‘rtacha qiymati 5,69 % ekanligi aniqlangan. O‘zgartgichlar va o‘lchash qurilmalarida qo‘llanib kelinayotgan tarqoq parmetrli zanjirlarda yuqori garmonikalarni hisobga olish ularning o‘zgartirish va o‘lchash xatoliklarini aniqlash aniqligini oshirish imkoniyatini yaratadi.

Kalit so‘zlar: Asosiy garmonika, uchunchi garmonika, variatsiyalash usuli, magnit oqimi, magnit induksiyasi, garmonika buzulish koeffitsiyenti.

Аннотация. В статье выполнен анализ влияния высших гармоник на нелинейные магнитные цепи с распределёнными параметрами. При проведении гармонического анализа основное внимание уделено третьей гармонике, а для описания протекающих процессов применён метод вариации, позволивший получить решения сложных дифференциальных уравнений, характеризующих поведение указанных магнитных цепей. Установлено, что среднее значение коэффициента искажения основной гармоники в нелинейных магнитных цепях с распределёнными параметрами составляет 5,69 %. Показано, что учёт высших гармоник в таких цепях, используемых в преобразователях и измерительных устройствах, позволяет повысить точность определения погрешности преобразования и измерения.

Ключевые слова: Основная гармоника, третья гармоника, метод вариации, магнитный поток, магнитная индукция, коэффициент гармонического искажения.

Abstract. The article considers the analysis of higher harmonics affecting distributed-parameter nonlinear magnetic circuits. Mainly, in the harmonic analysis, the third harmonic is considered, and solutions of complex differential

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equations characterizing the processes in magnetic circuits were found based on the variation method. It was determined that the average value of the fundamental harmonic distortion coefficient in distributed-parameter nonlinear magnetic circuits is 5.69%. Taking higher harmonics into account in distributed-parameter circuits used in converters and measuring devices increases their operating accuracy and reduces measurement errors.

Keywords: Fundamental harmonic, third harmonic, variation, magnetic flux, magnetic induction, harmonic distortion coefficient.

KIRISH.

Ferromagnit elementli elektromagnit tizimlarni tadqiq etishda tarqoq parametrli nochiziq magnit zanjir(TPNMZ)lar alohida ilmiy ahamiyatga ega, chunki bunday zanjirlarda magnit oqimi vaqt bo‘yicha ham, fazo bo‘yicha ham murakkab tarzda o‘zgaradi. Ayniqsa, qo‘zg‘aluvchan qism mavjud bo‘lganda tizim parametrlari o‘zgaruvchan tus oladi va bu magnit maydonning taqsimlanishi hamda garmonik tarkibiga sezilarli ta’sir ko‘rsatadi. Nochiziqlik sababli sinusoidal qo‘zg‘atishda ham magnit oqimi sof sinusoidal qonun bo‘yicha o‘zgarmaydi, natijada yuqori garmonikalar, xususan ta’siri sezilarli bo‘lgan uchinchi garmonika hosil bo‘ladi. Bu esa magnit tizimlarning ish rejimi, energiya yo‘qotishlari va dinamik tavsiflarini baholashda garmonik tahlilni muhim masalaga aylantiradi. Shu bois ushbu maqolada TPNMZ da magnit oqimining vaqt va koordinata bo‘yicha o‘zgarishi asosida birinchi va uchinchi garmonikalar tahlil qilinadi hamda ularning magnit zanjiri parametrlari va chegaraviy shartlarga bog‘liqligi yoritiladi.

ADABIYOTLAR TAHLILI. TPNMZ larni tadqiq etishga bag‘ishlangan ilmiy ishlar asosan uch yo‘nalishda rivojlangan: umumiy matematik modellashtirish, magnit ekvivalent sxema asosidagi tezkor hisoblash usullari hamda garmonik rejimlarni garmonik balans va chekli elementlar usullari orqali tahlil qilish. Chaban va uning hammualliflari nochiziq elektromagnit zanjirlar uchun modifikatsiyalangan Hamilton–Ostrogradskiy prinsipi asosida matematik model taklif qilib, elektromagnit jarayonlarni variatsion yondashuv orqali ifodalash imkonini ko‘rsatishgan [1]. Bu yondashuv magnit zanjirlarning umumiy matematik tavsifini qurishda muhim nazariy asos bo‘lsa-da, unda yuqori garmonikalar fazoviy-vaqt bo‘yicha alohida ajratib tahlil qilinmagan.

Magnit ekvivalent sxema (MES) asosidagi ishlarda asosiy e’tibor magnit maydon taqsimotini tezkor va yetarlicha aniq hisoblashga qaratilgan. Wang va uning hammualliflari NVNMC (Nonlinear Varying-Network Magnetic Circuit - O‘zgaruvchan tarmoqli nochiziqi magnit zanjiri) modeli yordamida magnit to‘yinishi va sizib chiqish oqimini hisobga olgan holda 2D model orqali 3D mashina tavsiflarini baholash mumkinligini ko‘rsatishgan [2]. Kara va Celik

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ishlab chiqqan nochiziq MES modelida material nochiziqligi, sochilgan magnit oqimi va chekka qismlarida magnit oqimini yoyilishi hisobga olinib, FEA(chekli elementlar tahlili) bilan solishtirganda maksimal nisbiy xatolik 10.2%, o‘rtacha esa xatolik 5.2% bo‘lganligi qayd etilgan [3]. Seol va uning hammualliflari esa 3D nochiziq MES modelini taklif qilib, o‘q bo‘ylab magnit oqimi yo‘llari va sochilgan magnit oqimi komponentlarni hisobga olish natijasida WRSM(Wound Rotor Synchronous Machine - Chulg‘amli rotor rusumidagi sinxron mashina) tizimlarni aniqroq tavsiflash mumkinligini ko‘rsatishgan [4]. Mazkur ishlar magnit oqimining fazoviy taqsimotini hisoblashda samarali bo‘lsa-da, birinchi va uchinchi garmonikalarni analitik ko‘rinishda ajratishga yetarli e’tibor bermaydi.

Garmonik tahlil yo‘nalishida garmonik balans sullari alohida ahamiyatga ega. Gyselinck va uning hammualliflari chekli garmonik balans - element modeling usulini elektromagnit qurilmalar uchun taklif qilib, keyinchalik uni harakatni hisobga oluvchi 2D modellarga kengaytiririshgan [5]. Ularning ishida, ayniqsa, asosiy va past tartibli garmonikalar qiziqtirganda garmonik balans yondashuvi vaqt sohasidagi hisoblashga nisbatan samarali ekanligi ko‘rsatilgan [5]. Scolaro va uning hammualliflari esa 2D nochiziq chekli element magnit modelga harakat va zanjir bog‘lanishini qo‘shib, garmonik balans usuli bilan THD(Total Harmonic Distortion - umumiy garmonik buzilish) bo‘yicha 3% dan kichik, RMS(Root Mean Square - o‘rtacha kvadratik qiymat) bo‘yicha esa 1% dan kichik xatolik bilan natija olishgan [6]. Bu ishlar garmonik tarkibni sonli usullar yordamida aniqlashda muhim natija beradi, biroq TPNMZ ning bosh differensial tenglamasi asosida uchinchi garmonikani analitik hosil qilish masalasi ularda markaziy o‘rin egallamaydi.

Harakatlanuvchi qismlar mavjud bo‘lgan elektromagnit tizimlarda garmonik buzilish masalasi Tsai va Huang tomonidan balans armaturali aktuator misolida o‘rganilgan [7]. Ular assimetrik magnit oqimi mavjud bo‘lganda toq garmonikalar bilan birga juft garmonikalar ham paydo bo‘lishini ko‘rsatgan va geometrik parametrlarni o‘zgartirish orqali garmonik buzilishni kamaytirish mumkinligini aniqlagan [7]. Bu natijalar qo‘zg‘aluvchan qism va geometrik omillar garmonik tarkibga kuchli ta’sir qilishini tasdiqlaydi.

TADQIQOT METODOLOGIYASI. O‘zgaruvchan tok zanjirida ferromagnit elementning qo‘llanilishi ularda yuqori garmonikalar tahlilini ko‘rib chiqish masalasini qo‘yadi. Shu sababdan TPNMZ ni xarakterlovchi asosiy differensial tenglamani garmonik tahlil asosida hisoblash tartibini ko‘rib chiqamiz. Quyidagi boshlang‘ich shartlarni kiritamiz: Qo‘zg‘atuvchi chulg‘am yig‘iq parametrli va nodifferensial magnit zanjiri, unda magnit oqimi magnit o‘tkazgich uzunligi bo‘ylab o‘zgaradi va vaqt bo‘yicha. Ushbu shartlar asosida TPNMZ larni xarakterlovchi asosiy tenglamani qiyidagicha yozamiz [8,10].

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$$\frac{\partial^2 Q_\mu}{\partial x^2} - A\left(Q_\mu + \frac{a}{3!}Q_\mu^3 + \cdots\right) - B\frac{\partial Q_\mu}{\partial t} = 0, \qquad (1)$$

bu yerda Q_μ – magnit oqimi; $B = (\alpha_a + \alpha_b)C_x$ - chastotaga bog‘liq o‘zgaruvchi kattalik; A va a hamda α_a va α_b - o‘zgarmas kattaliklar; C_x – magnit maydon o‘tkazuvchanlik.

Tadqiq etilayotgan TPNMZ uchun quyidagi chegaraviy shartlar o‘rinli:

$$x = 0,\ Q_\mu(x,t) = Q_{\mu 0} sin\omega t, \qquad (2)$$

$$x = l,\ \frac{\partial Q_\mu(x,t)}{\partial x} = -C_{\mu l} Q_\mu(l,t), \qquad (3)$$

bu yerda $C_l = \frac{\mu_0 S}{l}$ - havo oralig‘ining magnit o‘tkazuvchanligi.

TPNMZ larda magnit maydonining magnit o‘tkazgich uzunligi bo‘ylab tarqalishi magnit maydoni kuchlanganligiga nochiziq bog‘liqligi magnit oqimini vaqt bo‘yicha nosinusoidal o‘zgarishiga olib keladi. Shu sababdan (1) tenglama yechimini quyidagi qator ko‘rinishida izlash mantiqan to‘g‘ri bo‘ladi [9]:

$$Q_\mu(x,t) = \sum_{n=1}^{\infty} Q_{\mu n}(x)\, e^{jn\omega t}. \qquad (4)$$

(4) ni (1) ga qo‘yib, kompleks amplitudalar uchun quyidagi differensial tenglamalar sistemasini hosil qilamiz:

birinchi garmonika uchun:

$$\frac{\partial^2 Q_{\mu 1x}}{\partial x^2} - AQ_{\mu 1x} - B_1 j\omega Q_{\mu 1x} = 0, \qquad (5)$$

uchinchi garmonika uchun:

$$\frac{\partial^2 Q_{\mu 3x}}{\partial x^2} - AQ_{\mu 3x} - jB_3 3\omega Q_{\mu 3x} = \frac{Aa}{3!}Q_{\mu 1x}^3. \qquad (6)$$

Yuqorida qayd etilgan chegaraviy shartlar asosida quyidagilarni yozishimiz mumkin:

$$x = 0, Q_{\mu 1} = Q_{\mu 0};\ Q_{\mu l} = 0, \qquad Q_{\mu 3} = 0;$$

$$x = l, \qquad -\frac{1}{C_{\mu x}}\frac{\partial Q_{\mu ln}}{\partial x} = C_l Q_{\mu l}\ .$$

(5) differensial tenglamaning yechimi quyidagi ko‘rinishda bo‘ladi [9]:

$$Q_{\mu 1x} = A_1 e^{kx} + A_2 e^{-kx}, \qquad (7)$$

bu yerda $k = \sqrt{A + j\omega B}$ – magnit oqimini TPMZ bo‘ylab tarqalish koeffitsiyenti; A_1 va A_2 – integrallash doimiylari. $k = \sqrt{A + j\omega B} = (A + j\omega B)^{\frac{1}{2}} = \left(\sqrt{A^2 - \omega^2 B^2}\cdot e^{jarctg\left(\frac{\omega B}{A}\right)}\right)^{\frac{1}{2}} = \sqrt[4]{A^2 - \omega^2 B^2}\, e^{j\frac{1}{2}arctg\ \frac{\omega B}{A}\right)}$

$$k = k_1 + jk_2 = Ze^{j\varphi},\ Z = \sqrt[4]{A^2 - \omega^2 B^2},\ \varphi = \frac{1}{2}arctg\left(\frac{\omega B}{A}\right) \qquad (8)$$

$$k_1 = \sqrt[4]{A^2 - \omega^2 B^2}\cos\left(\frac{1}{2}arctg\left(\frac{\omega B}{A}\right)\right),\ k_2 = \sqrt[4]{A^2 - \omega^2 B^2}\sin\left(\frac{1}{2}arctg\left(\frac{\omega B}{A}\right)\right).$$

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Yuqoridagilarni inobatga olib, (7) tenglamani quyidagi ko‘rinishda yozamiz:

$$Q_{\mu 1x} = (A_1 e^{k_1 x} + A_2 e^{-k_1 x})cosk_2 x + j(A_1 e^{k_1 x} - A_2 e^{-k_1 x})sink_2 x. \quad (9)$$

A_1 va A_2 integrallash doimiylarini yuqorida keltirilgan chegaraviy shartlardan (4) ni hisobga olgan holda aniqlaymiz.

Haqiqiy qismini ajratib va ayrim algebraik o‘zgartrishlardan so‘ng quyidagi tenglikni hosil qilamiz:

$$Q_\mu(x,t) = D_0\{[(D_1 e^{k_1 x} + D_2 e^{-k_1 x})cosk_2 x - 2D_3 ch(k_1 x)\sin(k_2 x)]cos\omega t - [2D_3 sh(k_1 x)\cos(k_2 x) + (D_1 e^{k_1 x} - D_2 e^{-k_1 x})\sin(k_2 x)]cos\omega t\}, \quad (10)$$

bu yerda $D_0 = \frac{Q_{\mu 0}}{D_1 + D_2}$, $D_1 = \frac{d_1}{d_5} + d_3 d_6 + d_4 d_7$, $D_2 = d_2 d_5 + d_3 d_6 + d_4 d_7$,

$D_3 = d_4 d_6 - d_3 d_7$, $d_1 = [(k_1 - d)^2 + k_2^2]$, $d_2 = [(k_1 + d)^2 + k_2^2]$,

$d_3 = k_1^2 + k_2^2 - d^2$, $d_4 = 2k_2 d$, $d_5 = e^{k_1 l}$, $d_6 = \cos 2k_2 l$, $d_7 = \sin 2k_2 l$,

$k_1 = rcos\varphi$, $k_2 = rsin\varphi$, $r = \sqrt[4]{A^2 - \omega^2 B^2}$, $\varphi = arctg\frac{\omega B_1}{A}$, $d = C_{\mu x} C_l$.

Bir jinsli bo‘lmagan (6) tenglama yechimini istalgan o‘zgarmas miqdorlarni variatsiyalash usuli yordamida quyidagi ko‘rinishda izlaymiz:

$$Q_{\mu 3x}(x) = A_1(x)e^{mx} + A_2(x)e^{-mx}, \quad (11)$$

bu yerda $A_1(x)$ va $A_2(x)$ - x ga bo‘g‘liq bo‘lgan noma’lum funksiyalar.

$$m = A + j3\omega B_3 = m_1 + jm_2 = Te^{j\psi}, \quad (11)$$

bu yerda

$$T = \sqrt{A^2 - 3\omega^2 B_3^2}, \quad (12)$$

$$\psi = arctg\frac{3\omega B_3}{A}. \quad (13)$$

(12) va (13) ni (10) ga qo‘yib, quyidagi tengliklarni hosil qilamiz:

$$m_1 = \sqrt{A^2 - 3\omega^2 B_3^2}cos\left(arctg\left(\frac{3\omega B_3}{A}\right)\right),$$

$$m_2 = \sqrt{A^2 - 3\omega^2 B_3^2}sin\left(arctg\left(\frac{3\omega B_3}{A}\right)\right).$$

Istalgan o‘zgarmas miqdorlarni variatsiyalash tenglamalari quyidagi ko‘rinishda yoziladi:

$$\begin{cases} A_1'(x)e^{mx} + A_2'(x)e^{-mx} = 0, \\ mA_1'(x)e^{mx} - mA_2'(x)e^{-mx} = \varepsilon Q_{\mu 1}^3, \end{cases} \quad (14)$$

bu yerda $\varepsilon = \frac{Aa}{3!}$; $A_1'(x)$ va $A_2'(x)$ - $A_1(x)$ va $A_2(x)$ funksialar hosilalari.

(14) tenglamalar sistemaning quyidagi yechimini topamiz:

$$A_1(x) = \frac{\varepsilon}{2m}\int (A_1 e^{kx} + A_2 e^{-kx})^3 e^{-mx} dx + A_3 =$$

$$= \frac{\varepsilon}{2m}\int (A_1^3 e^{3kx} + 3A_1^2 A_2 e^{kx} + 3A_1 A_2^2 e^{-kx} + A_1^3 e^{-3kx})e^{-mx} dx + A_3 = \frac{\varepsilon}{2m}\cdot$$

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$$\cdot\left[\frac{A_1^3}{3k-m}e^{(3k-m)x}+\frac{3A_1^2A_2}{k-m}e^{(k-m)x}-\frac{3A_1A_2^2}{k+m}e^{-(k+m)x}-\frac{A_1^3}{3k+m}e^{-(3k+m)x}\right]+A_3. \quad (15)$$

Xuddi shu tartibda:

$$A_2(x)=\frac{\varepsilon}{2m}\left[\frac{A_1^3}{3k+m}e^{(3k+m)x}+\frac{3A_1^2A_2}{k+m}e^{(k+m)x}-\frac{3A_1A_2^2}{k-m}e^{-(k-m)x}-\frac{A_1^3}{3k-m}e^{-(3k-m)x}\right]+A_4. \quad (16)$$

Agar (15) va (16) larni (10) ga qo‘ysak, u holda quyidagi tenglamani hosil qilamiz:

$$Q_{\mu 3x}(x)=\varepsilon\left[\frac{A_1^3}{9k^2-m^2}e^{3kx}+\frac{A_2^3}{9k^2-m^2}e^{-3kx}+\frac{3A_1A_2}{k^2+m^2}(A_1e^{kx}+A_2e^{-kx})\right]+A_3e^{mx}+A_4e^{-m}. \quad (17)$$

Integrallash doimiylari A_3 va A_4 ni yuqoridagi chegaraviy shartlar asosida topamiz.

$$\begin{cases}A_3+A_4=C_1\\(m+d)e^{ml}A_3-(m-d)e^{-ml}A_4=C_2'\end{cases} \quad (18)$$

bu yerda

$$C_1=-\varepsilon\left[\frac{A_1^3+A_2^3}{9k^2-m^2}+\frac{3A_1A_2(A_1+A_2)}{k^2-m^2}\right], \quad (19)$$

$$C_2=-\varepsilon\left[\frac{(3k+d)A_1^3}{9k^2-m^2}e^{3kl}-\frac{(3k-d)A_2^3}{9k^2-m^2}e^{-3kl}+\frac{3A_1A_2}{k^2-m^2}\left((k+d)A_1e^{kl}-(k-d)A_2e^{-k}\right).\right] \quad (20)$$

(18) sistemaning yechimi quyidagi ko‘rinishda bo‘ladi:

$$A_3=\frac{(m-d)e^{-m}C_1+C_2}{(m-d)e^{-ml}+(m+d)e^{ml}}, \quad (21)$$

$$A_4=\frac{(m+d)e^{-ml}C_1+C_2}{(m-d)e^{-ml}+(m+d)e^{ml}}. \quad (22)$$

Shunday qilib, (17) tenglamadagi barcha integrallash doimiylari topildi. Ushbu integrallash doimiylari va koeffitsiyentlar tenglamaning haqiqiy va mavhum qismlarini tavsiflovchi kattaliklarni kompleks qiymatlarini hisoblaymiz.

$$k=k_1+jk_2,\ m=m_1+jm_2,\ A_1=A_1'+jA_1''$$

$A_2=A_2'+jA_2'',\ A_3=A_3'+jA_4'',\ A_4=A_4'+jA_4''$. (булар нима учун керак!).

$$Q_{\mu 3x}(x)=\varepsilon\left[\frac{A_1^3}{9k^2-m^2}e^{3kx}+\frac{A_2^3}{9k^2-m^2}e^{-3kx}+\frac{3A_1A_2}{k^2+m^2}(A_1e^{kx}+A_2e^{-kx})\right]+A_3e^{mx}+A_4e^{-mx}$$

(17) ifodani yoyish uchun zarur.

$$A_1^3=(A_1'+jA_1'')^3=[(A_1')^3-3A_1'(A_1'')^2]+j[3A_1''(A_1')^2-(A_1'')^3]$$

$$A_2^3=(A_2'+jA_2'')^3=[(A_2')^3-3A_2'(A_2'')^2]+j[3A_2''(A_2')^2-(A_2'')^3]$$

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$$A_1A_2 = (A_1'A_2' - A_1''A_2'') + j(A_1'A_2'' + A_1''A_2')$$
$$e^{kx} = e^{(k_1+jk_2)x} = e^{k_1x}(cosk_2x + jsink_2x)$$
$$e^{-kx} = e^{-(k_1+jk_2)x} = e^{-k_1x}(cosk_2x - jsink_2x)$$
$$e^{3kx} = e^{3(k_1+jk_2)x} = e^{3k_1x}(cos3k_2x + jsin3k_2x)$$
$$e^{-3kx} = e^{-3(k_1+jk_2)x} = e^{-3k_1x}(cos3k_2x - jsin3k_2x)$$
$$e^{mx} = e^{(m_1+j\ \ )x} = e^{m_1x}(cosm_2x + jsinm_2x)$$
$$e^{-m\ \ } = e^{-(m_1+jm_2)x} = e^{-m_1x}(cosm_2x - jsinm_2x)$$
$$k^2 = (k_1 + jk_2)^2 = (k_1^2 - k_2^2) + j2k_1k_2$$
$$m^2 = (m_1 + jm_2)^2 = (m_1^2 - m_2^2) + j2m_1m_2$$
$$9k^2 - m^2 = D_1 + jD_2$$
$$D_1 = 9(k_1^2 - k_2^2) - (m_1^2 - m_2^2)$$
$$D_2 = 18k_1k_2 - 2m_1m_2$$
$$\frac{1}{9k^2 - m^2} = \frac{D_1 - jD_2}{D_1^2 + D_2^2}$$
$$k^2 + m^2 = E_1 + jE_2$$
$$E_1 = (k_1^2 - k_2^2) + (m_1^2 - m_2^2)$$
$$E_2 = 2k_1k_2 + 2m_1m_2$$
$$\frac{1}{k^2 + m^2} = \frac{E_1 - jE_2}{E_1^2 + E_2^2}$$

Agar (17) ga (4) ni qo‘ysak va uni haqiqiy qismga ajratsak, u holda tegishli algebraik o‘zgartirishlardan so‘ng magnit oqimining uchinchi garmonik tashkil etuvchisi uchun quyidagi ifodani yozish mumkin:

$$Q_{\mu 3}(x,t) = \varepsilon[(E_1'e^{3k_1x} + E_2'e^{-3k_1x})cos3k_2x - (E_1''e^{3k_1x} + E_2''e^{-3k_1x})sin3k_2x + (E_3'e^{k_1x} + E_4'e^{-k_1x})cosk_2x - (E_3''e^{k_1x} + E_4''e^{-k_1x})sink_2x + (E_5'e^{m_1x} + E_6'e^{-m_1x})cosm_2x - (E_5''e^{m_1x} + E_6''e^{-m_1x})sinm_2x]cos3\omega t - \varepsilon[(E_1''e^{3k_1x} + E_2''e^{-3k_1x})cos3k_2x + (E_1'e^{3k_1x} - E_2'e^{-3k_1x})sin3k_2x + (E_3'e^{k_1x} - E_4'e^{-k_1x})sink_2x + (E_5''e^{m_1x} + E_6''e^{-m_1x})cosm_2x + (E_5'e^{m_1x} - E_6'e^{-m_1x})sinm_2x]sin3\omega t, \qquad (23)$$

bu yerda $E_1' = \frac{a_1a_2+b_1b_2}{a_1^2-b_1^2}$; $E_1'' = \frac{a_1b_2+a_2b_1}{a_1^2-b_1^2}$; $E_2' = \frac{a_1a_3+b_1b_3}{a_1^2-b_1^2}$; $E_2'' = \frac{a_1b_3-a_3b_1}{a_1^2-b_1^2}$; $E_3' = \frac{a_4a_5+b_4b_5}{a_4^2-b_4^2}$; $E_3'' = \frac{a_4b_5-a_5b_4}{a_4^2-b_4^2}$; $E_4' = \frac{a_4a_6-b_4b_5}{a_4^2-b_4^2}$; $E_4'' = \frac{a_4b_6-a_6b_4}{a_4^2-b_4^2}$; $a_1 = [9(k_1^2 - k_2^2) - (m_1^2 - m_2^2)]$; $b_1 = 9(2k_1k_2 - m_1m_2)$; $a_2 = D^3(D_1^3 - 3D_1D_3^2)$; $b_2 = D^3(D_2^3 - 3D_1^2D_3)$; $a_3 = D^3(D_2^3 - 3D_2D_3^2)$, $b_3 = D^3(D_3^2 - 3D_2^2D_3)$, $a_4 = (k_1^2 - k_2^2) - (m_1^2 - m_2^2)$; $b_4 = 2(k_1k_2 - m_1m_2)$; $a_5 = 3D^3[(D_1^2 - D_3^2)D_2 + 2D_1D_3^2]$; $b_5 = 3D^3[2D_1D_2D_3 - D_3(D_1^2 - D_3^2)]$; $a_6 = 3D^3[(D_1^2 - D_3^2)D_1 + 2D_2D_3^2]$; $b_6 = 3D^3[D_3(D_2^2 - D_3^2) - 2D_1D_2D_3]$; $\varepsilon_5' = -(\alpha'\varepsilon_1' - \alpha''\varepsilon_1'')$; $\varepsilon_5'' =$

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$$-(\alpha'\varepsilon_1'' + \alpha''\varepsilon_1'); \varepsilon_6' = -(\alpha'\varepsilon_2' - \alpha''\varepsilon_2''); \varepsilon_6'' = -(\alpha'\varepsilon_2'' + \alpha''\varepsilon_2'); \alpha' = \frac{\alpha_1' + \alpha_2'}{\gamma};$$

$$\alpha'' = \frac{\alpha_1'' + \alpha_2''}{\gamma}; \gamma = (\alpha_1' + \alpha_2')^2 - (\alpha_1'' + \alpha_2'')^2; \varepsilon_1' = \alpha_1'\delta_1 - \alpha_1''\delta_2 + \delta_1 - \delta_2;$$

$$\varepsilon_1'' = \alpha_1'\delta_2 - \alpha_1''\delta_1 + \delta_3 + \delta_4; \varepsilon_2' = \alpha_2'\delta_1 + \alpha_2''\delta_2 - \delta_1 + \delta_2; \varepsilon_2'' = \alpha_2'\delta_2 + \alpha_2''\delta_1 - \delta_3 - \delta_4;$$

$$\delta_1 = E_1' + E_2' + E_3' + E_4', \delta_2 = E_1'' + E_2'' + E_3'' + E_4'';$$

$$\delta_1 = \beta_1'E_1' - \beta_2'E_2' + \beta_3'E_3' - \beta_4'E_4'; \delta_2 = \beta_1''E_1'' - \beta_2''E_2'' + \beta_3''E_3'' - \beta_4''E_4'';$$

$$\delta_3 = \beta_1'E_1'' - \beta_2'E_2'' + \beta_3'E_3'' - \beta_4'E_4''; \delta_4 = \beta_1''E_1' - \beta_2''E_2' + \beta_3''E_3' - \beta_4''E_4';$$

$$\alpha_1' = \frac{1}{\gamma_1}[\gamma_{10}\gamma_4 + m_2\gamma_5]; \alpha_1'' = \frac{1}{\gamma_1}[-\gamma_{10}\gamma_5 + m_2\gamma_4];$$

$$\alpha_2' = \gamma_1[\gamma_{11}\gamma_4 - m_2\gamma_5]; \alpha_2'' = \gamma_1[\gamma_{11}\gamma_5 + m_2\gamma_4];$$

$$\beta_1' = \gamma_2[\gamma_{12}\gamma_6 - 3k_2\gamma_7]; \beta_1'' = \gamma_2[\gamma_{12}\gamma_7 + 3k_2\gamma_6];$$

$$\beta_2' = \frac{1}{\gamma_2}[\gamma_{13}\gamma_6 + 3k_2\gamma_7]; \beta_2'' = \frac{1}{\gamma_2}[-\gamma_{13}\gamma_7 + 3k_2\gamma_6];$$

$$\beta_3' = \gamma_3[\gamma_{14}\gamma_6 - k_2\gamma_9]; \beta_3'' = \gamma_3[\gamma_{14}\gamma_9 + k_2\gamma_8];$$

$$\beta_4' = \frac{1}{\gamma_3}[\gamma_{15}\gamma_8 + k_2\gamma_9]; \beta_4'' = \frac{1}{\gamma_3}[-\gamma_{15}\gamma_9 + k_2\gamma_8];$$

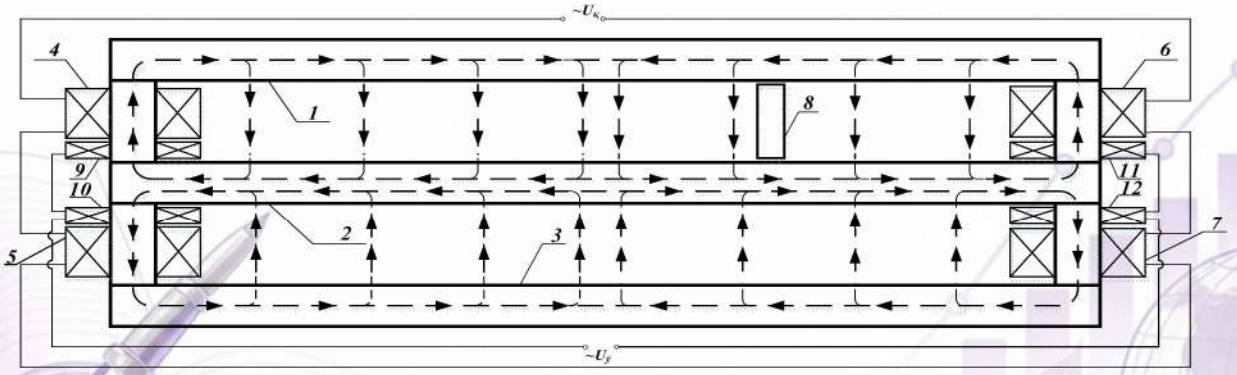
$$\gamma_1 = e^{m_1 l}; \gamma_2 = e^{3k_1 l}; \gamma_3 = e^{k_1 l}; \gamma_4 = cosm_2 l; \gamma_5 = sinm_2 l; \gamma_6 = cos3k_2 l;$$

$$\gamma_7 = sin3k_2 l; \gamma_8 = cosk_2 l; \gamma_9 = sin3k_2 l; \gamma_{10} = m - d; \gamma_{11} = m + d;$$

$$\gamma_{12} = 3k_1 + d; \gamma_{13} = 3k_1 - d; \gamma_{14} = k_1 + d; \gamma_{15} = k_1 - d; m_1 = Scos\psi;$$

$$m_2 = Ssin\psi; S = \sqrt[4]{A^2 - 3\omega^2 B_3^2}; \psi = arctg\frac{3\omega B_3}{A}.$$

MUHOKAMA VA NATIJALARI. Har bir elementar qism uchun magnit zanjiri parametrlarini aniqlab 1- jadvalga kiritamiz. Dastlabki boshlang‘ich qiymatlar va magnit zanjirining o‘lchamlari: $\boldsymbol{\omega_q = 120}$ ta $\boldsymbol{I_q = 1,2\ [A]}$, $\boldsymbol{F_q = I_q \cdot w_q = 1,2 \cdot 100 = 120\ [A]}$. Bu qiymatlar simmetrik ravishda o‘ng qism uchun ham o‘rinli bo‘ladi. $\boldsymbol{\omega_{o'} = 70}$ ta $\boldsymbol{a = 0,01\ [m], h = 0,01\ [m], \delta = 0,01\ [m], X_M = 0,1\ [m]}$, $\boldsymbol{H_{\mu x_0} = \frac{U_{\mu x_0}}{X_M} = \frac{120}{0.1} = 1200\ [A]}$. $\boldsymbol{B_{\mu x_0} = 1,45\ [Tl]}$ eksprimental qiymatlar jadvalidan olindi.



1-rasm. Tarqoq parametrli nochiziq magnit zanjiri. 1,2,3 – magnit o‘tkazgich sterjenlari; 4,5,6,7 – qo‘zg‘atish chulg‘ami, 8 – qo‘zg‘aluvchi o‘zak, 9,10,11,12 – o‘lchash chulg‘ami.

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1 – jadval.

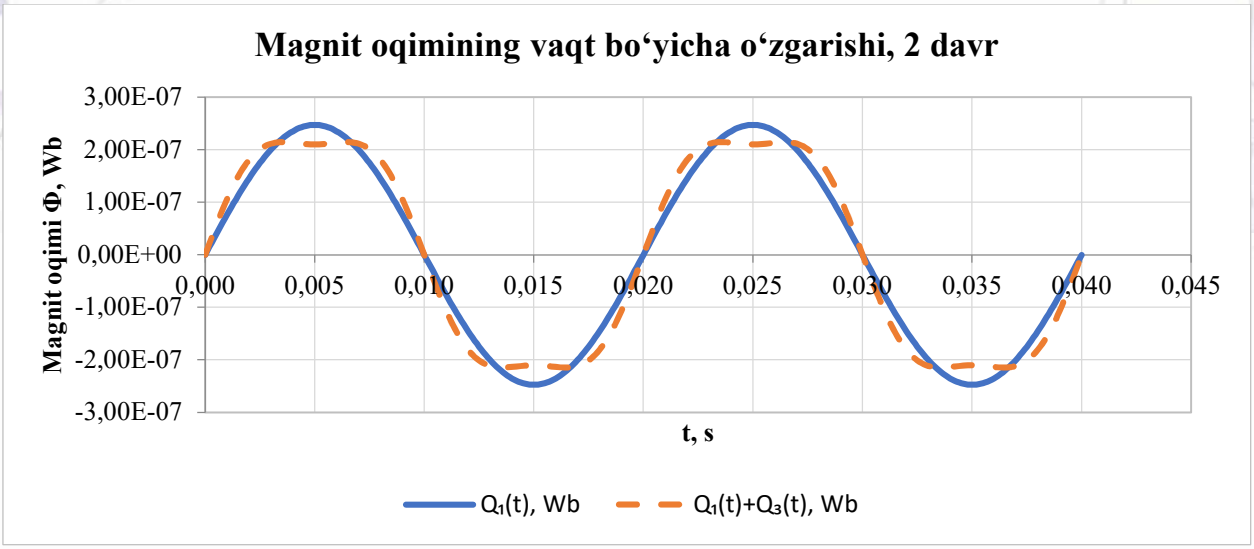
Tarqoq parametrli magnit zanjirida magnit oqimi qiymatlarini zanjir uzunligi va vaqt bo‘yicha o‘zgarishi

x, m	$Q_1(x)$, Wb	$Q_3(x)$, Wb	$Q_1(x)+Q_3(x)$, Wb	t, s	$Q_1(t)$, Wb	$Q_1(t)+Q_3(t)$, Wb
0,01	6,34E-09	6,26E-13	6,34E-09	0,0000	0,00E+00	0,00E+00
0,02	1,90E-08	1,69E-11	1,90E-08	0,0002	1,55E-08	2,25E-08
0,03	3,17E-08	7,82E-11	3,18E-08	0,0004	3,10E-08	4,47E-08
0,04	4,44E-08	2,15E-10	4,46E-08	0,0006	4,64E-08	6,62E-08
0,05	5,71E-08	4,56E-10	5,75E-08	0,0008	6,15E-08	8,69E-08
0,06	6,98E-08	8,33E-10	7,06E-08	0,0010	7,64E-08	1,06E-07
0,07	8,25E-08	1,37E-09	8,38E-08	0,0012	9,11E-08	1,25E-07
0,08	9,52E-08	2,11E-09	9,73E-08	0,0014	1,05E-07	1,41E-07
0,09	1,08E-07	3,07E-09	1,11E-07	0,0016	1,19E-07	1,56E-07
0,10	1,21E-07	4,29E-09	1,25E-07	0,0018	1,33E-07	1,69E-07
0,11	1,33E-07	5,79E-09	1,39E-07	0,0020	1,45E-07	1,81E-07
0,12	1,46E-07	7,61E-09	1,54E-07	0,0022	1,58E-07	1,90E-07
0,13	1,59E-07	9,78E-09	1,68E-07	0,0024	1,69E-07	1,98E-07
0,14	1,71E-07	1,23E-08	1,84E-07	0,0026	1,80E-07	2,04E-07
0,15	1,84E-07	1,53E-08	1,99E-07	0,0028	1,91E-07	2,08E-07
0,16	1,97E-07	1,86E-08	2,15E-07	0,0030	2,00E-07	2,12E-07

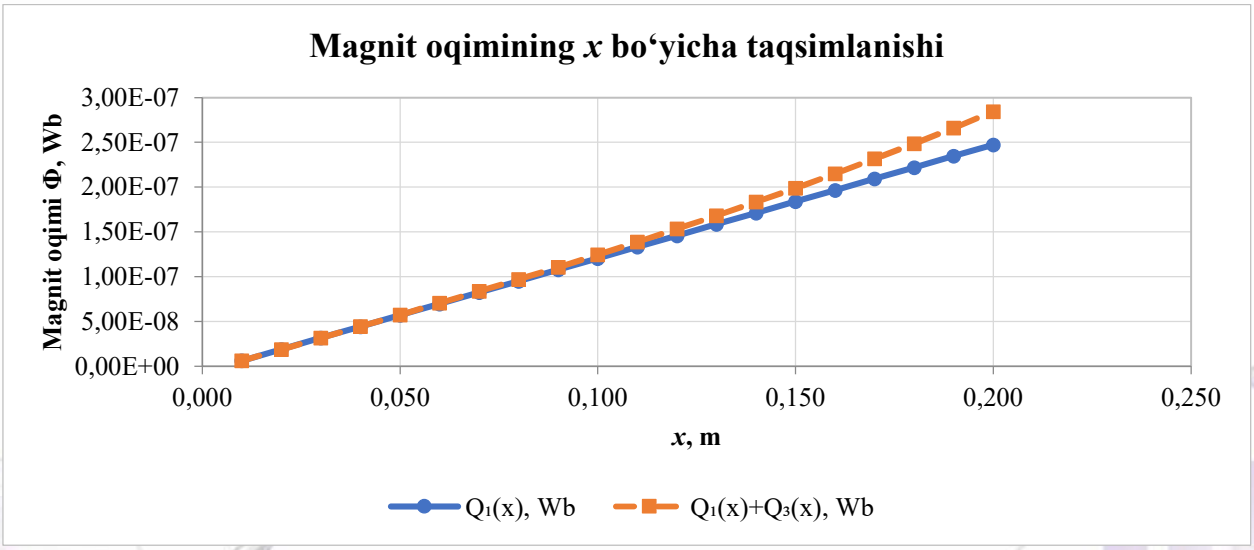
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0,17	2,09E-07	2,25E-08	2,32E-07	0,0032	2,09E-07	2,14E-07
0,18	2,22E-07	2,68E-08	2,49E-07	0,0034	2,17E-07	2,14E-07
0,19	2,35E-07	3,17E-08	2,66E-07	0,0036	2,24E-07	2,15E-07
0,20	2,47E-07	3,71E-08	2,84E-07	0,0038	2,30E-07	2,14E-07

Olingan qiymatlar asosida TPNMZ ning xarakteristikalarini qurqmiz:



2 – rasm. Tarqoq parametrli nochiziq magnit zanjirida magnit oqimini garmonikalar bo‘yicha taqsimlanishi.



3 – rasm. Tarqoq parametrli nochiziq magnit zanjirida magnit oqimini magnit o‘tkazgich uzunligi bo‘yicha taqsimlanishi

XULOSA VA TAKLIFLAR. Olingan natijalar shuni ko‘rsatadiki, qo‘zg‘aluvchan qismga ega bo‘lgan tarqoq parametrli nochiziq magnit zanjirlardagi jarayonlarni hisoblashda yuqori garmonikalarni hisoblash muhim

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bo‘lib, asosiy garmonika, asosiy bilan uchunchi garmonikani qo‘shilgandagi grafigi (2- rasm) hamda magnit zanjir uzunligi bo‘ylab magnit oqimini asosiy va asosiy bilan uchunchi garmonikani birgalikdagi grafiklari(3- rasm)da asosiy farqni yaqqol ko‘rish mumkin. Garmonikalar magnit zanjirida magnit oqimiga to‘yinishi natijasi yuzaga keladi va bu jarayonda garmonikalar buzulish koeffitsiyenti magnit zanjir uzunligi bo‘ylab 1 % dan 15 % gacha, o‘rtacha qiymati esa 5,69 % ni tashkil etadi. Garmonikalarni hisobga olish tarqoq parametrli nochiziq magnit zanjirlar qo‘llanib kelayotgan o‘zgartgichlar va o‘lchash qurilmalari xarakteristikalari aniqligini oshiradi.

FOYDALANILGAN ADABIYOTLAR.

1. Chaban, A. va boshqalar. Mathematical Model of a Nonlinear Electromagnetic Circuit Based on the Modified Hamilton–Ostrogradsky Principle. Energies, 2024, 17(21), 5365.
2. Wang, H. va boshqalar. Nonlinear Varying-Network Magnetic Circuit Analysis of Consequent-Pole Permanent-Magnet Motor for Electric Vehicles. Energies, 2021.
3. Kara, O., Çelik, H.H. A Novel Nonlinear Magnetic Equivalent Circuit Model for Magnetic Flux Leakage System. Applied Sciences, 2024, 14, 4071.
4. Seol, H.S. va boshqalar. Advanced 3D Nonlinear Magnetic Equivalent Circuit Model for Overhang-Type WRSM Design. Electronics, 2025, 14(7), 1304.
5. Gyselinck, J., Vandevelde, L., Oliveira, A.M., Dular, P., Melkebeek, J., Kuo-Peng, P. Two-Dimensional Harmonic Balance Finite Element Modelling of Electrical Machines Taking Motion into Account. ICEM 2002 Conference Record, 2002; shuningdek harmonic-balance yondashuvining dastlabki asoslari uchun: Gyselinck, J., Dular, P., Geuzaine, C., Legros, W. Harmonic-balance finite-element modeling of electromagnetic devices: A novel approach. IEEE Transactions on Magnetics, 2002, 38(2), 521–524.
6. Scolaro, E., Alberti, L., Sabariego, R.V., Gyselinck, J. Harmonic Balance Applied to a 2D Nonlinear Finite-Element Magnetic Model with Motion and Circuit Coupling. International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, 2024, 37(4), e3275.
7. Tsai, Y.-T., Huang, J.H. A Study of Nonlinear Harmonic Distortion in a Balanced Armature Actuator with Asymmetrical Magnetic Flux. Sensors and Actuators A: Physical, 2013, 203, 324–334.
8. Амиров С. Ф., Сатторов Т.А. “Магнитловчи чулғамлари бўйлама тарқоқ жойлашган дифференциал магнит занжирларининг математик моделлари” ФАН ВА ТЕХНОЛОГИУаЛАР ТАРАҚҚИЁТИ, ИЛМИЙ – ТЕХНИКАВИЙ ЖУРНАЛ 2023, № 4

ISSN 3030-3907

9. Amirov S.F., Jumayev J., Sattorov T.A., “Tarqoq parametrli magnit zanjirlarni magnitlanish egri chizig‘ini aproksimatsiyalovchi funksiyani aniqlash”, “BUXORO DAVLAT UNIVERSITETI ILMIY AXBOROTI” Ilmiy-nazariy jurnal 2024, № 2, fevral

10. Амиров С.Ф., Мамадалиев У.Ш, Каримов И.А., Сатторов Т.А., “Математические модели трансформаторных преобразователей угловых перемещений с переменной активной площадью обмотки возбуждения.”, Развитие науки и технологий. Научно – технический журнал. ISSN 2181-8193. Бухара: №6/2023. 197-205 с.