



# Ikki tomondan ta'minlangan asinxron generator asosidagi shamol energetika tizimini modellashtirish

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**Dolzarbliigi:** Iqlim o'zgarishi, energiyaga bo'lgan talabning ortishi va ekologik barqarorlikni ta'minlash maqsadida qayta tiklanuvchi energiya manbalari, xususan shamol energetikasini joriy etish dolzarb ahamiyat kasb etmoqda. Bunday tizimlarda elektr energiyasini samarali ishlab chiqarish va elektr tarmog'iga uzatish jarayonida ikki tomondan ta'minlangan asinxron generatorlar muhim rol o'ynaydi. Ushbu tizim shamol turbinalari o'zgaruvchan shamol sharoitida ham yuqori samaradorlik bilan ishlashi va reaktiv quvvatni boshqarishi mumkin bo'lgan zamonaviy yechimlardan biri hisoblanadi. Tizimi o'z ichiga ikki o'zgartirgich (rotor va tarmoq tomon boshqaruvi), o'zgarimas tok shinas va yuqori dinamik xususiyatlarga ega boshqaruv algoritmlarini o'z ichiga oladi. MATLAB/Simulink muhiti modellashtirish uchun katta ahamiyatga ega bo'lib, matematik va dinamik tamoyillar asosida tizimni shakllantirish, uni turli ish rejimlarida tahlil qilish va samarali boshqarish algoritmlarini ishlab chiqish imkonini beradi.

**Maqsad:** Ikki tomondan ta'minlangan asinxron generator asosidagi shamol energetika tizimini MATLAB/Simulink muhitida modellashtirish hamda uning elektromagnit xususiyatlari, turli shamol tezliklarida ishlash samaradorligini tahlil qilish va samarali boshqarish strategiyalarini ishlab chiqish.

**Usullari:** Ikki tomondan ta'minlangan asinxron generator tizimidagi stator va rotor chulg'amlarining elektromagnit jarayonlari Park-Klark (dq0) transformatsiyasi asosida modellashtirildi. Tizimning rotor tomonida va tarmoq tomonida boshqaruv vektorli boshqaruv usuli qo'llanildi.

**Natijalar:** Mazkur tadqiqot doirasida ikki tomondan ta'minlangan asinxron generator asosidagi shamol energetikasi tizimi MATLAB/Simulink muhitida modellashtirildi va boshqaruv algoritmlarining samaradorligi kompleks tahlil qilindi. Modellashtirish jarayonida shamol tezligi 7 m/s dan 12 m/s gacha dinamik ravishda o'zgartirildi. Natijada generator rotorining tezligi, elektromagnit momenti, stator tokini o'zgarish xarakteristikalarini olindi, shu bilan birga ushbu tizim tarmoqqa integratsiya qilindi. Bu holat generatorning tez o'zgaruvchan muhit sharoitida ishlash qobiliyati yuqori ekanini ko'rsatdi. Modellashtirish natijalarida tarmoq tomonidagi stator tokining garmonik tahlili ham amalga oshirildi, garmonik buzilish darajasi juda past bo'lib, uning ko'rsatkichi 5% dan past bo'lib, xalqaro standartlarga muvofiq ekanligi aniqlandi.

**Kalit so'zlar:** Ikki tomondan ta'minlangan asinxron generator, shamol turbinalari, elektr tarmog'i, MATLAB/Simulink, modellashtirish, simulyatsiya, vektorli boshqaruv, rotor tomon o'zgartirgichi, tarmoq tomon o'zgartirgichi.

**For citation:** Tuychiev F.N., Rashidov N.Kh. Modeling of Wind Energy System Based on Doubly-Fed Induction Generator. Scientific and technical journal of Problems of Energy and Sources Saving, 2025, no. 3, pp. 97-108.

<https://doi.org/10.5281/zenodo.16935222>

Received: 18.07.2025  
Revised: 25.07.2025  
Accepted: 15.08.2025  
Published: 23.08.2025

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## Моделирование ветроэнергетической системы на основе асинхронного генератора с двойным питанием

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**Актуальность:** В связи с изменением климата, ростом спроса на энергию и необходимостью обеспечения экологической устойчивости, внедрение возобновляемых источников энергии, в частности ветровой энергетики, приобретает особую актуальность. В таких системах асинхронные генераторы с двусторонним питанием играют важную роль в процессе эффективной выработки и передачи электроэнергии в электрическую сеть. Данная система является одним из современных решений, позволяющих ветровым турбинам работать с высокой эффективностью и управлять реактивной мощностью в условиях переменного ветра. Система включает в себя два преобразователя (управление со стороны ротора и сети), шину постоянного тока и алгоритмы управления с высокими динамическими характеристиками. Среда MATLAB/Simulink имеет большое значение для моделирования, позволяя формировать систему на основе математических и динамических принципов, проводить её анализ при разных режимах работы и разрабатывать эффективные алгоритмы управления.

**Цель:** Моделирование ветроэнергетической системы на основе асинхронного генератора двойного питания в среде MATLAB/Simulink, а также анализ её электромагнитных характеристик, эффективности работы при различных скоростях ветра и разработка эффективных стратегий управления.



**Методы:** Электромагнитные процессы в статоре и роторе генератора описаны с использованием системы дифференциальных уравнений, основанных на преобразовании Парк-Кларка (dq0). Для управления со стороны ротора и со стороны сети реализована векторная система управления.

**Результаты:** В рамках данного исследования была смоделирована система ветроэнергетики на базе асинхронного генератора с двойным питанием в среде MATLAB/Simulink и проведен комплексный анализ эффективности алгоритмов управления. В процессе моделирования скорость ветра изменялась динамически от 7 м/с до 12 м/с. В результате были получены характеристики изменения скорости ротора генератора, электромагнитного момента и тока статора, при этом система была успешно интегрирована в электрическую сеть. Это обстоятельство показало высокую работоспособность генератора в условиях быстро меняющейся среды. В результате моделирования также был проведен гармонический анализ тока статора на стороне сети, уровень гармонического искажения был очень низким, его показатель был ниже 5%, что соответствовало международным стандартам.

**Ключевые слова:** Асинхронный генератор с двойным питанием, ветровая турбина, электрическая сеть, MATLAB/Simulink, моделирование, симуляция, векторное управление, преобразователь со стороны ротора, преобразователь со стороны сети.

## Modeling of Wind Energy System Based on Doubly-Fed Induction Generator

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**Relevance:** Due to climate change, growing energy demand, and the need to ensure environmental sustainability, the implementation of renewable energy sources, particularly wind energy, is becoming increasingly important. In such systems, doubly-fed induction generators (DFIGs) play a key role in the efficient generation and transmission of electrical energy to the power grid. This system represents one of the modern solutions that allows wind turbines to operate with high efficiency and enables control of reactive power under variable wind conditions. The system includes two converters (grid-side and rotor-side control), a DC-link, and control algorithms with high dynamic performance. The MATLAB/Simulink environment is of great importance for modeling, as it allows the creation of systems based on mathematical and dynamic principles, their analysis under various operating conditions, and the development of effective control algorithms.

**Aim:** To model a wind energy system based on a doubly-fed induction generator (DFIG) in MATLAB/Simulink, analyze its electromagnetic characteristics and efficiency under varying wind speeds, and develop effective control strategies.

**Methods:** The electromagnetic processes in the stator and rotor of the generator are described using a system of differential equations based on Park-Clarke (dq0) transformation. Vector control systems were implemented for both rotor-side and grid-side converters.

**Results:** In this study, a wind energy system based on a doubly-fed induction generator was modeled in MATLAB/Simulink, and a comprehensive analysis of the effectiveness of control algorithms was conducted. During the simulation, wind speed dynamically varied from 7 m/s to 12 m/s. As a result, the characteristics of rotor speed variation, electromagnetic torque, and stator current were obtained, and the system was successfully integrated into the electrical grid. This demonstrated the generator's high performance under rapidly changing environmental conditions. Harmonic analysis of the stator current on the grid side was also performed, showing that the total harmonic distortion (THD) was below 5%, which complies with international standards.

**Keywords:** Doubly-fed induction generator, wind turbine, power grid, MATLAB/Simulink, modeling, simulation, vector control, rotor-side converter, grid-side converter.

### 1. Kirish (Introduction)

Energiya inson sivilizatsiyasining texnologik rivoji va barqaror taraqqiyoti uchun muhim manba hisoblanib, ayniqsa XXI asrda elektr energiyasiga bo'lgan talab ortib borishi, ishlab chiqarish korxonalari va aholi sonining keskin ko'payishi global darajada energiya tanqisligini keltirib chiqardi. Elektr energiyasiga ehtiyoj ortib borayotgan bir paytda, an'anaviy energiya manbalariga bog'liqlik kamaymoqda, shu sababli shamol, quyosh va boshqa qayta tiklanuvchi manbalar orqali energiya ishlab chiqarishni oshirish zaruriyati paydo bo'ldi [1,2].

Shamol energiyasi, chiqindilar hosil qilmasligi tufayli, barcha qayta tiklanadigan manbalar orasida eng toza va ekologik xavfsiz "yashil" energiya turi sifatida alohida ahamiyatga ega hisoblanadi [3]. Shamol energetikasi dunyoda qayta tiklanuvchi energetikaning eng jadal sur'atlarda rivojlanayotgan tarmoqlaridan biridir. Global shamol energetikasi kengashining (GWEC) yangi hisobotiga ko'ra, 2024 yilda jahon shamol energetikasi rekord darajadagi 117 GW yangi quvvatlarni o'rnatdi, bu 2023 yilga nisbatan biroz ko'proq, o'tgan yili 109 GW quuruqlik va 8 GW dengiz shamol energiyasi quvvatlari qo'shildi, natijada dunyodagi shamol energiyasining umumiy quvvati 1136 GW ga yetdi [4].

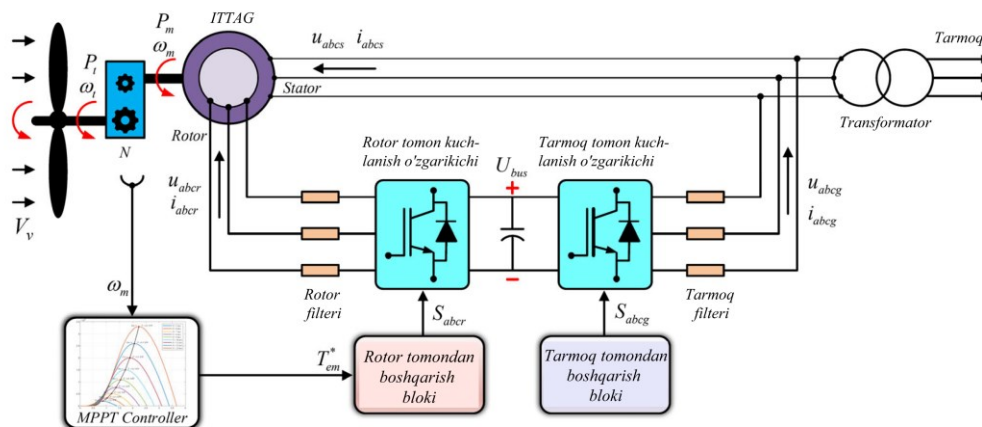
O‘zbekiston respublikasida shamol energetikasi zaxirasi yuqori, ayniqsa respublikaning shimoliy-g‘arbiy va janubiy-g‘arbiy hududlarida shamol energetikasi bo‘yicha yuqori salohiyatga ega, ba‘zi taxminlarga ko‘ra 22 dan 4090 mlrd kW·soat gacha, texnik tomondan 9,9 mlrd kW·soat bo‘lib, eng yuqori ko‘rsatkich Qoraqalpog‘iston (4,4 mlrd kW·soat), Navoiy (2,9 mlrd kW·soat), Buxoro (1 mlrd kW·soat) viloyatlarida tashkil etadi. Shamol energetikasi salohiyatini ro‘yobga chiqarish yiliga 3,3 mlrd. kub. m tabiiy gazni tejash imkonini beradi. So‘nggi paytlarda ushbu yo‘nalishda ishlab chiqarish quvvati 11,3 mlrd kW·soatga (3,1 GW) teng bo‘lgan 3,6 mlrd dollarga 7 ta loyihasi amalga oshirilmoqda [5, 6].

1990 yillarning o‘rtalariga qadar o‘rnatilgan shamol turbinalarining aksariyati to‘g‘ridan-to‘g‘ri tarmoqqa ulangan qisqa tutashtirilgan rotorli asinxron motorlarga asoslangan doimiy aylanish tezligiga ega shamol turbinalari bo‘lib, elektr energiyasini ishlab chiqarish faqatgina doimiy tezlik bo‘lganda amalga oshirilgan. Bugungi kunda o‘rnatilgan shamol turbinalarining nisbatan kam miqdorda faza rotorli sinxron generatorlar (FRSG) va doimiy magnitli sinxron generatorlarga (DMSG) asoslangan yangi modellar bilan bir qatorda bozorda nisbatan katta miqdordagi ikki tomondan ta‘minlanuvchi asinxron generatorlarga (ITTAG) asoslangan boshqariladigan aylanish tezligiga ega turbinalar muhim o‘ringa ega. Generatorlarning bu barcha variantlari rostanadigan aylanish tezligi bilan elektr energiyasini ishlab chiqarish imkonini beradi [7-9].

ITTAG asosidagi shamol energiyasini o‘zgartirish tizimlari hozirgi kunda eng samarali tizim bo‘lib dunyo bo‘ylab keng ko‘lamda qo‘llanilmoqda. Bunday tizimlar sirpanuvchi halqali asinxron motor yoki faza rotorli asinxron mashinadan tashkil topgan elektr quvvatini o‘zgartirish qurilmasi sifatida ishlab, ular ikki tomondan ta‘minlanuvchi asinxron generator deb ataladigan [10-12]. Ular elektron o‘zgartirgichlar yordamida boshqariladi, bu esa rotorning aylanish tezligi va quvvatini nazorat qilish imkonini beradi. Faza rotorli asinxron mashinaning statori to‘g‘ridan-to‘g‘ri elektr tarmog‘iga, ketma-ket teskari o‘zgartirgichlar esa rotor chulg‘amlariga ulanadi. Bunday mashina ITTAG deb ataladi, chunki u elektr energiyasining ikkala yo‘nalishda ham oqishiga imkon beradi: generator o‘ta sinxron tezlikda ishlaganda energiya tarmoqqa uzatiladi, generator subsinxron tezlikda ishlaganda esa energiya rotorga yuboriladi [13]. Rotor zanjiri va elektr tarmog‘i o‘rtasida joylashgan ikki tomonlama o‘zgaruvchan/o‘zgarmas/o‘zgaruvchan o‘zgartirgichlar generatorning aylanish tezligini sinxron tezlikdan yuqori darajada boshqarish imkonini beradi va natijada elektr energiyasi ham stator, ham rotor orqali ishlab chiqariladi [14-16].

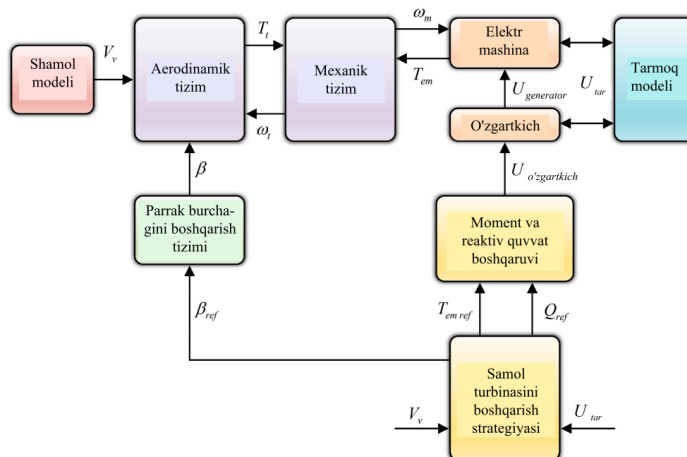
## 2. ITTAG tizimining tuzilishi va modellashtirish (System Configuration and Modeling of DFIG)

Tarmoqqa ulangan ITTAG asosidagi shamol energiyasini o‘zgartirish tizimining tuzilishi 1-rasmda keltirilgan. Tizim quyidagi asosiy elementlardan iborat: shamol turbini, ikki tomondan ta‘minlangan asinxron generator (ITTAG), rotor tomoni uchun filtr, tarmoq tomoni uchun filtr, maksimal quvvat nuqtasini kuzatish kontrolleri, o‘zgarmas tok zvenosi kondensatori va ikki tomonlama ulangan uch fazali impuls kengligi modulyatsiyasi asosidagi kuchlanish manbasi o‘zgartirgichi hamda ularning boshqaruv bloklari. Rotor chulg‘amiga rotor filtri orqali ulangan kuchlanish o‘zgartirgichi rotor tomoni o‘zgartirgichi deb nomlanadi. Stator chulg‘ami esa bevosita elektr tarmog‘iga ulangan bo‘lib, kuchlanish o‘zgartirgichi tarmoq o‘zgartirgichi tomonidagi ulanish nuqtasida birlashtirilgan. Rotor va tarmoq o‘zgartirgichlar ITTAG ning turli ish rejimlarini amalga oshirish uchun mas‘ul hisoblanadi. Taklif etilgan tizimning blok-sxemasi 2-rasmda keltirilgan.



1-rasm. ITTAG bilan ta‘minlangan shamol turbinasining tuzilishi

Fig 1. Configuration of variable speed wind turbine with DFIG



**2-rasm.** Tarmoqqa ulangan DFIG tizimining blok-sxemasi

**Fig 2.** Block diagram of a grid-connected DFIG

### *Shamol turbinasini modellashtirish.*

Shamol turbinasi bu shamol oqimining kinetik energiyasini aylanma harakat energiyasiga o'zgartiruvchi qurilma bo'lib, uning asosiy vazifasi shamolning harakat energiyasini mexanik aylanma momentga o'zgartirishdan iborat. Bu jarayonda turbina parraklari shamol oqimi ta'sirida aylana boshlaydi va shu orqali valga mexanik quvvat uzatiladi.

Shamolning muayyan tezlikdagi harakatidan olinadigan energiya miqdori atmosfera oqimidagi havo massasi va uning harakat tezligiga bog'liq. Shamol oqimi quvvatining miqdori quyidagi tenglama bilan ifodalanadi:

$$P_v = \frac{1}{2} \rho A V_v^3 \quad (1)$$

bu yerda,  $A$ -turbina parraklarining qamrab oluvchi maydoni,  $m^2$ ;  $\rho$ -havo zichligi (odatda 1.225 qabul qilinadi),  $kg/m^3$ ;  $V_v$ -shamol tezligi,  $m/s$ .

Ushbu formula shamol turbinasiga tushayotgan umumiy quvvat miqdorini hisoblash imkonini beradi, lekin amaliyotda aerodinamik va konstruktiv yo'qotishlar sababli faqatgina ma'lum bir qismi elektr energiyasiga aylantirilishi mumkin. Shuning uchun shamoldagi mavjud quvvatdan turbina tomonidan olinadigan quvvat (2) tenglama bilan ifodalanadi

$$P_t = \frac{1}{2} \rho \pi R^2 V_v^3 C_p(\lambda, \beta) \quad (2)$$

bu yerda,  $R$  - turbina rotorining radiusi ( $m$ );  $C_p(\lambda, \beta)$  - quvvat koeffitsienti;  $C_p$  - shamol turbinasining aerodinamik samaradorlik koeffitsienti, parrak uchining burchak tezligi ( $\lambda$ ) ning parrak burchagi ( $\beta$ ) ga nisbatining funksiyasidir.

$C_p(\lambda, \beta)$  quyidagi (3) va (4) formulalar orqali ifodalanadi.

$$C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda_i} - c_3 \beta - c_4 \beta^{c_5} - c_6 \right) e^{-\frac{c_7}{\lambda_i}} \quad (3)$$

bu yerda,  $c_1 = 0.73$ ;  $c_2 = 151$ ;  $c_3 = 0.58$ ;  $c_4 = 0.002$ ;  $c_5 = 2.4$ ;  $c_6 = 13.2$ ;  $c_7 = 18.4$

$$C_p(\lambda, \beta) = 0.73 \left( \frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.4} - 13.2 \right) e^{-\frac{18.4}{\lambda_i}} \quad (4)$$

$$\lambda_i = \frac{1}{\lambda + 0.02\beta} - \frac{0.003}{\beta^3 + 1} \quad (5)$$

Bes chegarasiga muvofiq,  $C_p$  koeffitsientining eng yuqori nazariy qiymati (6) formula orqali ifodalanadi:

$$C_{p \max} = 0.593 = 59.3\% \quad (6)$$

Shamol turbinasi orqali olinishi mumkin bo'lgan eng yuqori nazariy samaradorlik darajasi bo'lib, turbina shamoldagi energiyaning ko'pi bilan 59.3% ni foydalana olishi mumkin.

Parrak uchi tezligining shamol tezligiga nisbati quyidagi formula orqali ifodalanadi

$$\lambda = \frac{R \omega_t}{V_v} \quad (7)$$

Turbina tomonidan hosil qilinadigan aylantiruvchi moment quyidagi formula orqali ifodalanadi:

$$T_t = \frac{P_t}{\omega_t} \quad (8)$$

$\omega_t$  - shamol turbinasi rotorining burchak aylanish tezligi ( $rad/s$ ).

### *ITTAG ni modellashtirish.*

ITTAG stator va rotor chulg'amlaridan tashkil topgan bo'lib, u sirpanuvchi halqalarga ega. Uch

fazali izolyasiyalangan chulg'amlar statorga o'rnatilgan bo'lib, uch fazali transformator orqali tarmoqqa ulangan. Rotor ham xuddi stator kabi uch fazali izolyasiyalangan chulg'amlardan tashkil topgan. Sirpanuvchi halqalar va cho'tkalar to'plami rotor chulg'amlarini tashqi statsionar zanjir bilan bog'laydi. Bu qismlar rotor chulg'amlariga rotorning boshqaruvchi tokini kiritish yoki olish imkonini beradi [15].

ITTAG ning dinamik modelini ifodalashda to'g'ri va teskari almashtirishdan foydalaniladi. Fazoviy vektorlar nazariyasidan foydalanib, rotor va statorning uchta chulg'amini quyidagicha tasvirlash mumkin: stator uchun ikkita  $\alpha\beta$  chulg'am qo'zg'almas holatda bo'ladi, rotor uchun esa  $dq$  chulg'am aylanma harakatda bo'ladi.

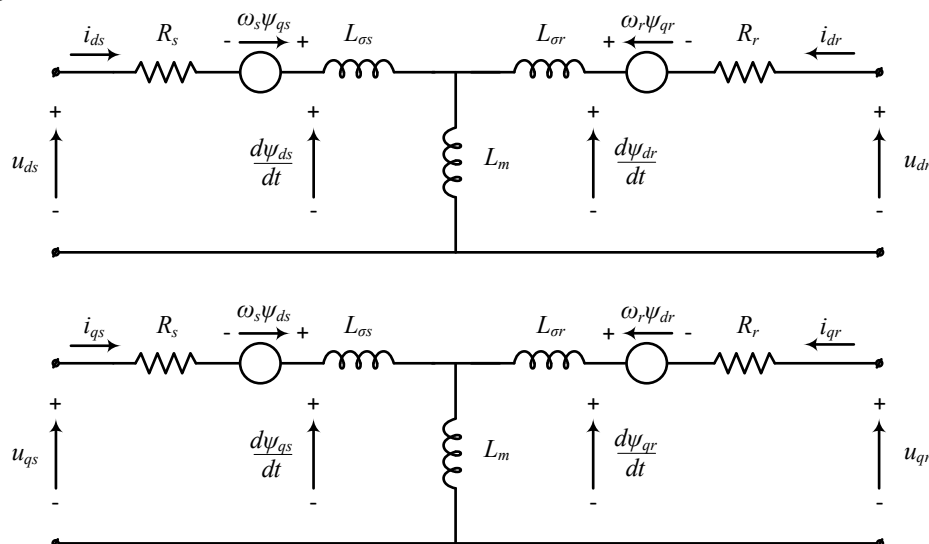
Stator va rotor kuchlanish vektorlari quyidagicha ifodalanadi:

$$\vec{u}_s \Rightarrow \begin{cases} u_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \\ u_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \end{cases} \quad (9)$$

$$\vec{u}_r \Rightarrow \begin{cases} u_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r \psi_{qr} \\ u_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_r \psi_{dr} \end{cases} \quad (10)$$

bu yerda,  $u_{ds}, u_{qs}, u_{dr}, u_{qr}$  - mos ravishda,  $dq$  koordinata tizimida stator va rotor kuchlanishlari;  $i_{ds}, i_{qs}, i_{dr}, i_{qr}$  - mos ravishda,  $dq$  koordinata tizimida stator va rotor toklari;  $R_s, R_r$  - stator va rotor faza qarshiliklari;  $\omega_s, \omega_r$  - stator va rotor burchak tezligi.

(9) va (10) tenglamalar asosida  $dq$  koordinata tizimidagi almashtirish elektr sxemasi 3-rasmda ko'rsatilgan.



3-rasm. ITTAG uchun  $dq$  tizimidagi almashtirish sxemasi

Fig 3. DFIG dq equivalent circuit

Stator va rotorning magnit oqim vektorlari mos ravishda (11) va (12) tenglamalar bilan ifodalanadi:

$$\vec{\psi}_s \Rightarrow \begin{cases} \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} = L_s i_{qs} + L_m i_{qr} \end{cases} \quad (11)$$

$$\vec{\psi}_r \Rightarrow \begin{cases} \psi_{dr} = L_m i_{ds} + L_r i_{dr} \\ \psi_{qr} = L_m i_{qs} + L_r i_{qr} \end{cases} \quad (12)$$

bu yerda,  $\psi_s, \psi_r$  - mos ravishda, stator va rotorning magnit oqim vektorlari;  $\psi_{ds}, \psi_{qs}$  - statorning  $dq$  koordinata o'qlari bo'yicha magnit oqimlari;  $\psi_{dr}, \psi_{qr}$  - rotorning  $dq$  koordinata o'qlari bo'yicha magnit oqimlari;  $L_s, L_r$  - mos ravishda, stator va rotor faza sochilish induktivliklari;  $L_m$  - stator va rotor o'rtasidagi o'zaro induktivlik,  $p$  - generatorning juft qutblar soni.

Elektromagnit aylanuvchi momenti ifodasi (13) tenglamada keltirilgan:

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_s} (\psi_{qs} i_{dr} - \psi_{ds} i_{qr}) \quad (13)$$

Stator va rotorning aktiv va reaktiv quvvat tenglamalari mos ravishda (14) va (15) tenglamalarda keltirilgan:



$$\begin{cases} P_s = \frac{3}{2}(u_{ds}i_{ds} + u_{qs}i_{qs}) \\ Q_s = \frac{3}{2}(u_{qs}i_{ds} - u_{ds}i_{qs}) \end{cases} \quad (14)$$

$$\begin{cases} P_r = \frac{3}{2}(u_{dr}i_{dr} + u_{qr}i_{qr}) \\ Q_r = \frac{3}{2}(u_{qr}i_{dr} - u_{dr}i_{qr}) \end{cases} \quad (15)$$

bu yerda,  $P_s, Q_s$  - mos ravishda statorning aktiv va reaktiv quvvati;  $P_r, Q_r$  - mos ravishda rotorning aktiv va reaktiv quvvati;  $T_{em}$  - elektromagnit moment.

Aylantiruvchi (elektromagnit) momentni aniqlovchi asosiy tenglama (16) formula orqali ifodalanadi:

$$T_{em} - T_{load} = j \frac{d\omega_m}{dt} \quad (16)$$

bu yerda,  $J$  - rotorning inersiya momenti;  $T_{load}$  - rotor valiga tushgan yuklamaning momenti,  $\omega_m$  - rotor tezligi.

*Rotor va tarmoq o'zgartkichlari uchun boshqaruv strategiyasi.*

Uch fazali elektr tarmog'idan ITTAG stator chulg'amiga kelayotgan kuchlanish doimiy qiymat va chastotada beriladi. Aksincha, ITTAG ning turli ish sharoitlariga erishish uchun Rotor tomon o'zgartkichi rotorga o'zgaruvchan chastota va amplitudada kuchlanish bilan ta'minlaydi. Bu boshqaruv strategiyasi generatorning optimal ishlash nuqtasini tanlashga va shamol energiyasini yuqori samaradorlik bilan elektr energiyasiga aylantirishga yordam beradi.

Rotor tomon o'zgartkichi rotor chulg'amiga kuchlanish beradi. (11) va (12) tenglamalarni (10) tenglamaga qo'yish orqali  $dq$  koordinatsion tizimidagi kuchlanish tenglamalari hosil qilinadi.  $\psi_{qs} = 0$  deb hisobga olsak, quyidagi kuchlanish ifodalari kelib chiqadi.

$$\begin{cases} u_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \omega_r \sigma L_r i_{qr} + \frac{L_m}{L_s} \frac{d\vec{\psi}_s}{dt} \\ u_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_r \sigma L_r i_{dr} + \omega_r \frac{L_m}{L_s} \frac{d\vec{\psi}_s}{dt} \end{cases} \quad (17)$$

bu yerda  $\sigma = L_m^2 / (L_s L_r)$ . Tarmoq parametrlari doimiy bo'lgani sababli,  $d\psi_s/dt$  nolga yaqinlashadi, ya'ni statordagi oqimning o'zgarishini juda kichik deb hisoblash mumkin. Shuning uchun, stator chulg'amidagi aktiv qarshilikdan kelib chiqadigan kuchlanish tushuvini hisobga olmaslik va stator magnit oqimi doimiy deb olish mumkin. (17) tenglamadan ko'rinib turibdiki, rostlagichlar rotor tokining  $dq$  tashkil etuvchilarini boshqarish uchun ishlatilishi mumkin.

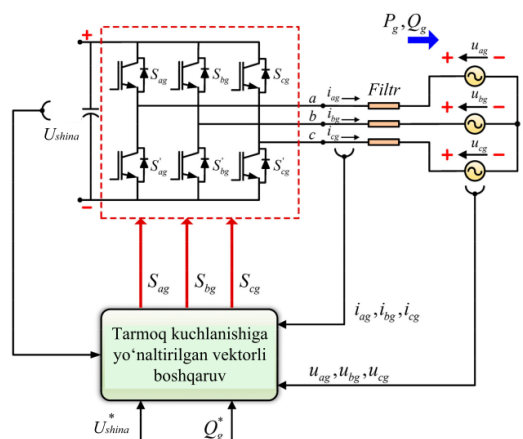
ITTAG asosidagi shamol turbinalarida elektr energiyasini samarali tarmoqqa uzatish va barqaror ishlashini ta'minlashda tarmoq tomonidan boshqaruv asosiy vazifani bajaradi. Bu boshqaruv konturi generatorning rotor tomoniga ulangan inverter bilan birgalikda ishlaydigan ikkinchi invertorni o'z ichiga oladi va u o'zgarimas tok shinasi orqali bog'langan bo'ladi. Tarmoq tomonidagi boshqaruvda odatda  $dq$  koordinatalar tizimiga asoslangan vektorli boshqaruv usuli qo'llaniladi. Bu usulda uch fazali kattaliklar ( $ABC$ ) ikki fazali stasionar ( $\alpha\beta$ ) va aylanuvchi ( $dq$ ) koordinatalarga o'tkaziladi.

Filtrodagi kuchlanishning  $dq$  tashkil etuvchilari (18) tenglama bilan, tarmoq bilan aktiv va reaktiv quvvat almashinuvi ifodasi esa (19) tenglama bilan ifodalanishi mumkin.

$$\begin{cases} u_{df} = R_f i_{dg} + L_f \frac{di_{dg}}{dt} + u_{dg} - \omega_s L_f i_{qg} \\ u_{qf} = R_f i_{qg} + L_f \frac{di_{qg}}{dt} + \omega_s L_f i_{dg} \end{cases} \quad (18)$$

$$\begin{cases} P_g = \frac{3}{2}(u_{dg}i_{dg} + u_{qg}i_{qg}) \Rightarrow P_g = \frac{3}{2}u_{dg}i_{dg} \\ Q_g = \frac{3}{2}(u_{qg}i_{dg} - u_{dg}i_{qg}) \Rightarrow Q_g = -\frac{3}{2}u_{dg}i_{qg} \end{cases} \quad (19)$$

(19) tenglamaga ko'ra,  $i_{dg}$  tok tashkil etuvchisi  $P_g$  (tarmoqqa uzatiladigan aktiv quvvat) ni boshqarsa,  $i_{qg}$  tok tashkil etuvchisi  $Q_g$  (reaktiv quvvat) ni boshqaradi. 4-rasmda tarmoq tomonidagi o'zgartirgich boshqaruvining blok-sxemasini ko'rsatilgan. O'zgarimas tok shinasi kondensator orqali tashkil etilgan bo'lib, aktiv quvvat rotor tomon o'zgartkichi-kondensator-tarmoq tomon o'zgartkichi orqali elektr tarmog'iga uzatiladi. Demak,  $V_{shina}$  kuchlanishni o'zgarimas darajada ushlab turish aktiv quvvatni uzatishda rotor va tarmoq tomon o'zgartkichlarining to'g'ri ishlashini ta'minlaydi. Reaktiv quvvatni tarmoqqa uzatish ham xuddi shu tartibda ta'minlanadi. Demak, elektr tarmog'ida reaktiv quvvat almashinuvi ham shunday yo'l bilan ta'minlanadi.



4-rasm. Tarmoq tomondagi tizimning blok-sxemasi

Fig 4. Block diagram of grid-side system

### 3. Modellashtirish natijalar va muhokama (Simulation results and discussion)

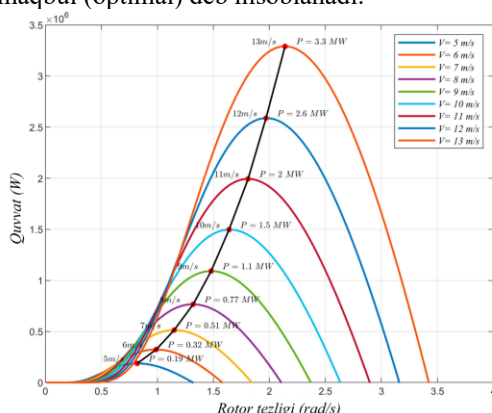
Taklif etilgan ITTAG modellashtirishi hamda rotor tomon o'zgartkichi va tarmoq tomon o'zgartkichi orqali boshqaruv tizimi MATLAB/Simulink muhitlarida amalga oshirildi va simulyasiya qilindi. Ushbu bo'limda shamol tezligining o'zgarishi davomida taklif etilgan tizimning ishlash samaradorligi tahlil qilinadi. Tizimning modellashtirish parametrlari 1-jadvalda keltirilgan.

1-jadval. Modelni asosiy parametrlari

Table 1. Main parameters of the model

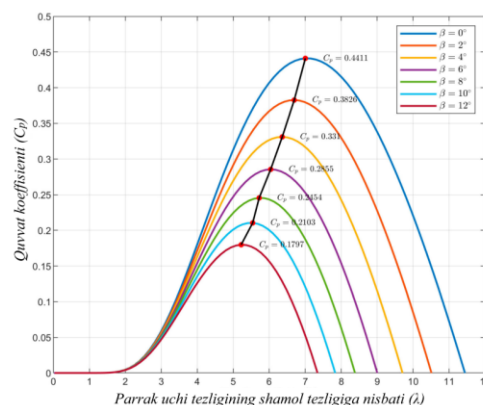
Parametr nomi	Qiymati	Parametr nomi	Qiymati
Nominal shamol tezligi	11 m/s	Aylanish tezligi diapazoni	9-18 ayl/min
Havo zichligi	1.225 kg/m <sup>3</sup>	Nominal moment	12732 Nm
Parrak uchi tezligi nisbati	7.2	Juft qutblar soni	2
Parrak burilish burchagi	0°	Stator kuchlanishi	690 V
Eng yuqori samaradorlik ko'effitsienti	0.44	Tishli uzatma nisbati	100
Nominal quvvat	2 MW	Turbina radiusi	42 m

Ushbu tadqiqotda paraklarning  $\beta$  burchagi nolga teng qilib olingan va hisob-kitoblarni shamolning nominal 11 m/s tezligi uchun amalga oshirilgan.  $\beta = 0^\circ$  bo'lgan holatda shamolning turli tezliklari uchun modellashtirilgan quvvat xarakteristikalarini 3-rasmda keltirilgan.  $C_p-\lambda_i$  (quvvat ko'effitsienti va tezlik nisbati) xarakteristikalarini  $\beta$  parametrining turli qiymatlarida 5-rasmda tasvirlangan. Tadqiqot natijalariga ko'ra, konstruksiyaning eng yuqori quvvat ko'effitsienti  $C_{p\max} = 0,44$  ga teng bo'lib, unga mos keladigan  $\lambda$  qiymati 7.2 ni tashkil qiladi. Bu parametrlar  $\beta = 0^\circ$  da 6-rasmda aks ettirilgan. Keltirilgan  $C_{p\max}$  va  $\lambda$  qiymatlari mavjud shamol energiyasidan maksimal quvvatni olish uchun eng maqbul (optimal) deb hisoblanadi.



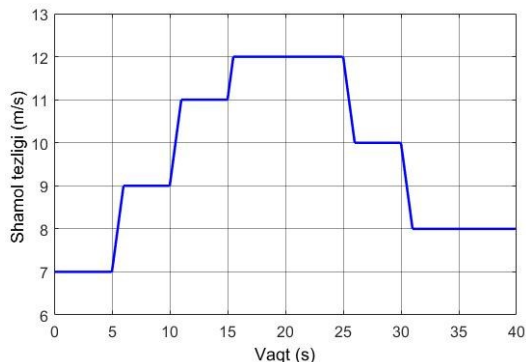
5-rasm. Shamol turbinasining turli shamol tezliklaridagi quvvat va rotor aylanish tezligi xarakteristikalarini

Fig 5. Power and rotor speed characteristics of WT at different wind speed

6-rasm. Parraklarning burilish burchagi ( $\beta$ ) o'zgarandagi xarakteristikalarFig 6. Characteristics with variation in pitch angle ( $\beta$ )

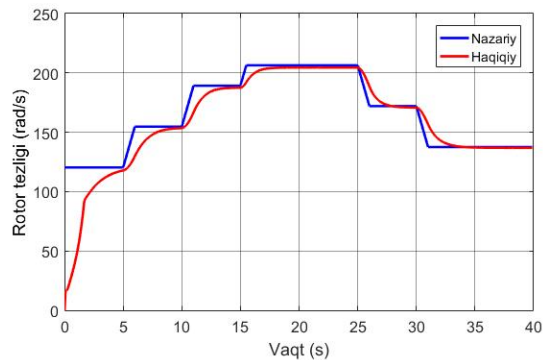


Tizimga qo'llanilgan shamol tezligi 10-rasmda keltirilgan, bunda shamol tezligi 7 m/s dan 12 m/s gacha bo'lgan keng oraliqda o'zgaruvchan tezlikka ega. Ushbu modellashtirish tadqiqotida shamol tezligining pog'onali bosqichma-bosqich ortishi va pasayishi ko'rib chiqiladi. Modellashtirishning boshlanishida shamol tezligi 7 m/s etib belgilangan va tizim to'xtab turgan holatdan ishga tusha boshlaydi, maksimal tezlik 12 m/s gacha oshirib borildi. 11-rasmda shamol tezligidagi o'zgarishga bog'liq holda rotorning nazariy va haqiqiy aylanish tezligini o'zgarish natijalari keltirilgan. Generator rotorining tezligi haqiqiy (ko'k chiziq) va nazariy (qizil chiziq) dinamikasi vaqt bo'yicha o'zgaradi, nazariy tezlik haqiqiy tezlikdan orasidagi muayyan farq bo'lsada, umuman olganda ikkala tezlik o'zaro mutanosib hisoblanadi.



**10-rasm.** Tizimga berilgan shamol tezligining o'zgarishi

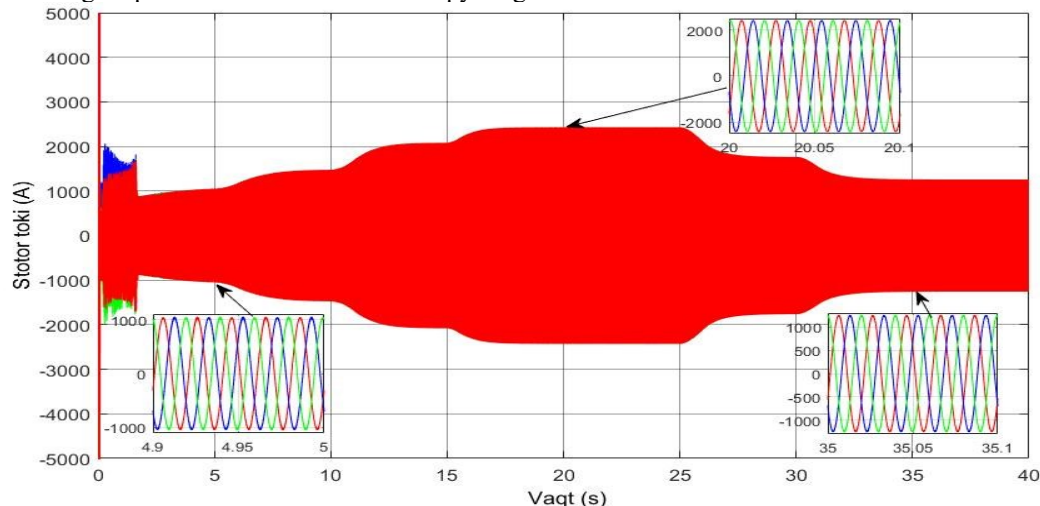
**Fig 10.** Wind speed variation input to the system



**11-rasm.** Rotorning haqiqiy va nazariy tezligining o'zgarishi

**Fig 11.** Change of real and theoretical rotor speed

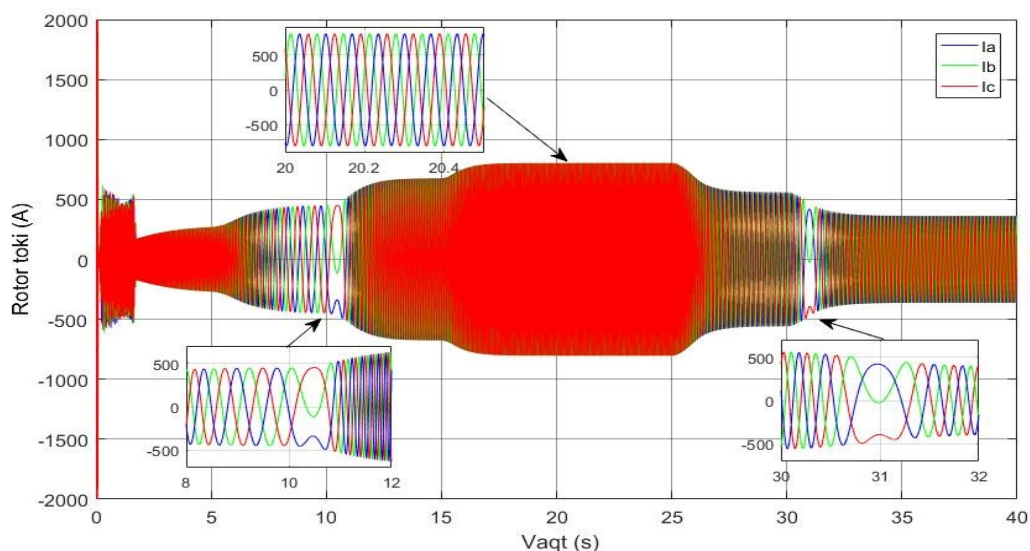
12-rasmda stator toklarining vaqt bo'yicha o'zgarishi aniq ko'rsatilgan bo'lib, turli ranglarda ko'rsatilgan fazalar ( $I_a$  – ko'k,  $I_b$  – yashil,  $I_c$  – qizil) sinusoidal shaklga ega va ularning orasidagi fazaviy farq  $120^\circ$  ni tashkil etadi. Bu o'zaro simmetrik fazaviy toklar shakllanishi va elektr energiyasining sifatli ishlab chiqarilishini ta'minlaydi. Tahlillardan ko'rinib turibdiki, ITTAG generatori turli shamol tezliklari sharoitida tok amplitudasini moslashtirish va fazaviy simmetriyani saqlash qobiliyatiga ega. 17-25 s orasida, ya'ni shamol tezligida 12 m/s ga erishganda stator toklarining amplitudasi taxminan  $\pm 2440$  A qiymatga erishadi.



**12-rasm.** ITTAG stator tokining o'zgarishi

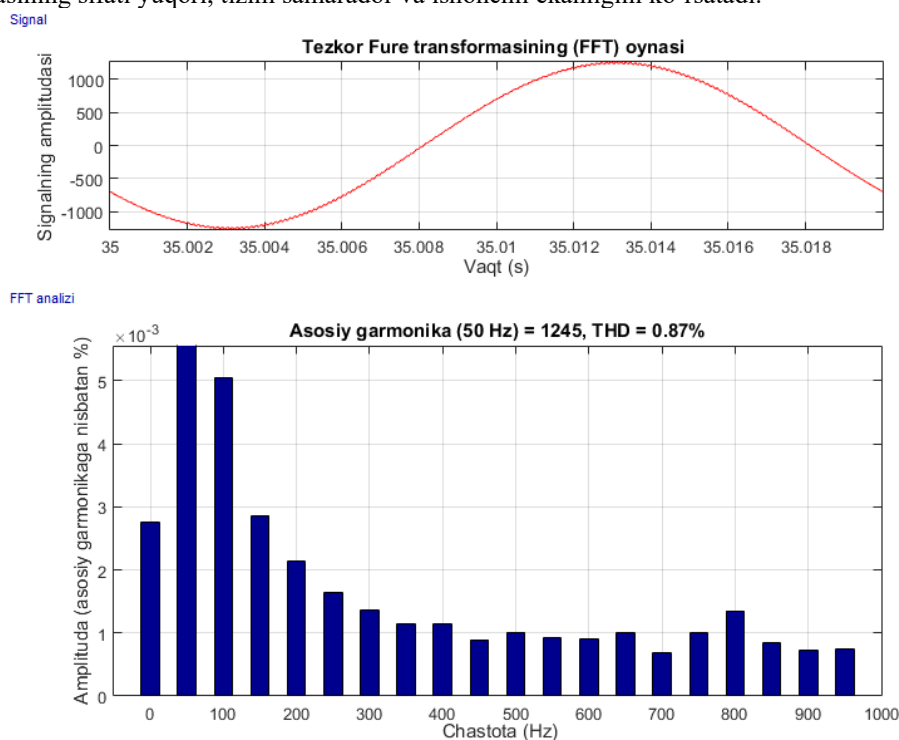
**Fig 12.** DFIG stator current variation

13-rasmda elektr tarmog'iga ulangan ITTAG tizimida uch fazali  $I_a$ ,  $I_b$ , va  $I_c$  rotor tokining vaqt bo'yicha o'zgarishi aks ettirilgan. Ushbu faza toklari bir-biridan o'zaro  $120^\circ$  fazaviy burchakka burilgan va sinusoidal ko'rinishda va generatorning dinamik holatdagi toklarning ish rejimiga barqarorligini ko'rsatadi. Grafikda rotor tokining 0 dan 40 sekundgacha bo'lgan intervaldagi o'zgarishi berilgan, uning amplituda qiymatini o'zgarishlari  $\pm 805$  A gacha yetadi, bu esa yuqori quvvatli ish rejimlarini aks ettiradi.



**13-rasm.** ITTAG rotor tokining o'zgarishi  
**Fig 13.** DFIG rotor current variation

50 Hz asosiy chastota asosida 0 - 1 kHz diapazonda, bitta sikl davomida olingan stator toki uchun umumiy garmonik buzilish tahlili 14-rasmda keltirilgan. Tahlil natijalari shundan dalolat beradiki, generator nominal tezlikda ishlayotgan holatda stator tokidagi garmonik buzilish darajasi juda past bo'lib, uning qiymati 0.87% ni tashkil etadi. Garmonik buzilish darajasining past bo'lishi elektr energiyasining sifati yuqori, tizim samarador va ishonchli ekanligini ko'rsatadi.



**14-rasm.** Stator tokining bitta fazasini yuqori garmonik tarkibi  
**Fig 14.** Higher harmonic components of one phase of the stator current

Simulyasion tahlillar va barcha rasmlarga asoslanib, xulosa qilish mumkinki, ushbu boshqaruv tizimi shamolning turli tezliklar sharoitida elektr quvvatini samarali kuzatib borish qobiliyatiga ega. Rotor tomon o'zgartkichi va tarmoq tomon o'zgartkichi uchun vektor boshqaruv tizimi yuqori dinamik xususiyatlarni va ortiqcha rostlashsiz tayanch qiymatga aniq ergashishni ta'minlaydi. Taklif etilgan boshqaruv usullari shamoldan maksimal quvvat olish bilan birga, tizimning dinamik va o'tkinchi jarayonidagi barqarorligini ta'minlaydi.

#### 4. Xulosa (Conclusion)

Ushbu ishning asosiy maqsadi - shamol tizimini modellashtirish, boshqarish va turli shamol



tezligida ishlashini simulyasiya qilishdan iborat. Tadqiqot ishida tarmoqqa ulangan, ikki tomondan ta'minlanuvchi asinxron generator asosidagi shamol energiyasi tizimining dinamik modeli taqdim etilib modellashtirish va boshqarish usullari taklif etildi. Avvalo, shamol turbinasi va ITTAG generatorining matematik modellari ishlab chiqildi. Rotor tomoni va tarmoq tomoni o'zgartkichi uchun vektor boshqaruv strategiyasi orqali generator bilan tarmoq o'rtasidagi quvvat oqimini samarali boshqarish ta'minlandi. Simulyasiya natijalari stator kuchlanish va tok shakllarining sinusoidal va barqarorligini ko'rsatadi. Taklif etilgan boshqaruv strategiyasi tizimning shamol tezligiga nisbatan yaxshi moslashishini va barqaror ishlashini namoyon qildi. Umumiy garmonik buzilish tahliliga ko'ra, stator toki garmonikasi standartlar talabiga javob beradi. Bu model shamol turbinasining aerodinamikasi va parraklarni burilish burchaklarini boshqarish tizimi bilan integratsiya qilingan ishlaydi. Natijalar shundan dalolat beradiki, o'zgaruvchan tezlikdagi ITTAG uchun rotor oqimiga asoslangan boshqaruv tizimi shamol energetikasi sohasida istiqbolli yechim bo'la oladi.

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