ISNN 3030-3907

2025/4
VOLUME 6

DEVELOPMENT OF SCIENCE

ILMIY JURNAL



Development of science

Ilmiy jurnal

2026/4 VOLUME 6

ISSN 3030 -3907

Ilmiy jurnal OAK rayosatining 2024 yil 27 sentabrdagi 361-son qaroriga asosan 02.00.00 kimyo fanlari hamda 2025 yil 12 fevral 367- son qaroriga asosan 05.00.00 texnika fanlari bo‘yicha falsafa doktori (PhD) va fan doktori (DSc) ilmiy darajasiga talabgorlarning dissertatsiya ishlari yuzasidan dissertatsiyalari asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro‘yxatiga kiritilgan.

BOSH MUHARRIR:
Temirov Alisher Hoshim o‘g‘li – texnika fanlari falsafa doktori (PhD),Dotsent.
TAHRIRIYAT KENGASH RAISI:
Fozilov Sadriddin Fayzullayevich – texnika fanlari doktori, professor
TAHRIRIYAT KENGASH A’ZOLARI

TEXNIKA FANLARI/ TECHNICAL SCIENCES/ ТЕХНИЧЕСКИЕ НАУКИ

Bozorov G‘ayrat Rashidovich
Buxoro Davlat Texnika Universiteti, professor
Abdurahmonov Olim Rustamovich
Buxoro Davlat Texnika Universiteti, professor
Adizov Bobur Zamirovich
O‘zbekiston Respublikasi Fanlar akademiyasi Umumiy va noorganik kimyo instituti, professor
Hayitov Ruslan Rustamjonovich
Buxoro Davlat Texnika Universiteti, professor
Jumayev Qayum Karimovich
Buxoro Davlat Texnika Universiteti, professor.
Berdiyev Dorob Murodovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor
Maxmudov Rafiq Amonovich
Buxoro Davlat Texnika Universiteti, professor.
Tilloyev Lochin Ismatilloyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Raxmonov Qahramon Sanakulovich
Buxoro Davlat Texnika Universiteti, dotsent.
Barakayev Nusratullo Rajabovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor.
Jo‘rayev Xayrullo Fayziyevich
Buxoro Davlat Texnika Universiteti, professor.
Panoyev Erali Rajabboyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Ataullayev Sherzod Nabiullyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Malik Negmurodovich
Buxoro Davlat Texnika Universiteti, dotsent.
Axmedova Ozoda Bahronovna
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti.
Safarov Bahri Jumayevich
Buxoro Davlat Texnika Universiteti, dotsent.
Xaydarov Axtam Amonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Safarov Jasur Alijon o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.
Асадова Раъно Дилмуратовна
Тошкент Давлат техника университети доценти

KIMYO FANLARI/ CHEMICAL SCIENCES/ ХИМИЧЕСКИЕ НАУКИ

Axmedov Voxid Nizomovich
Buxoro Davlat Texnika Universiteti, professor
Umarov Baqo Bafoyevich
Buxoro Davlat Universiteti, professor
Kodirov Abduaxad Abduraximovich
Qarshi davlat Universiteti, professor
Qurbonov Mingniqul Jumagulovich
Qarshi davlat Universiteti, dotsent
Turemuratov Sharibay Naurizbaevich
O‘zbekiston Respublikasi Fanlar akademiyasi Qoraqalpog‘iston bo‘limi Bosh ilmiy kotibi, professor
Tursunov Kaxor Shonazarovich
Qarshi davlat Universiteti, professor
Do‘stov Hamro
Buxoro Davlat Texnika Universiteti, professor
Panoyev Nodir Shavkatovich
Buxoro Davlat Texnika Universiteti, dotsent.
Olimov Bobur Bahodir o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.
Kasimov Sherzod Abduazimovich
Termiz Davlat Universiteti, professor.
Aliqulov Rustam Valiyevich
Termiz Davlat Universiteti, professor
Tropov Xamza Tursunovich
Samarqand Davlat Universiteti, professor

IQTISODIYOT FANLARI/ ECONOMICS/ ЭКОНОМИЧЕСКИЕ НАУКИ

Nizamov Aslitdin Badreddinovich
Buxoro Davlat Texnika Universiteti, professor.
Boboyev Akmal Choriyevich
Buxoro Davlat Texnika Universiteti, professor.
Ergashxojayeva Shaxnoza Djasurovna
Toshkent davlat iqtisodiyot universiteti, professor
Saidaxmedova Nodira Ilxomovna
Toshkent davlat iqtisodiyot universiteti, professor
Muxsinov Bekzod Toxirovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shakarov Qulmat Ashirovich
Renessans ta'lim universiteti,dotsent.
Jumaeva Zulfiya Qayumovna
Buxoro Davlat Texnika Universiteti, dotsent.
Norova Salomat Yusupovna
Buxoro Davlat Texnika Universiteti, dotsent.
Avezova Shaxnoza Maxmudjonovna
Buxoro Davlat Texnika Universiteti, dotsent.
Jalilov Jamshid G‘anijonovich
Toshkent davlat iqtisodiyot universiteti, dotsent
Xasanova Gulruh Djumanazarovna
Buxoro Davlat Texnika Universiteti, dotsent.

PEDAGOGIKA FANLARI/ PEDAGOGICAL SCIENCES / ПЕДАГОГИЧЕСКИЕ НАУКИ

Siddiqova Sadoqat G‘afforovna
Buxoro Davlat Texnika Universiteti, dotsent.
Zoyirov Erkin Xalilovich
Buxoro Davlat Texnika Universiteti, DSc, professor
Gaffarov Feruz Hasanovich
Puchon Universiteti, *professor*
Ruziyev Davron Yuldashevich
Buxoro Davlat Universiteti, professor
Muradova Firuza Rashidovna
Buxoro Davlat Texnika Universiteti, professor.
Yunusova Gulandon Samiyevna
Buxoro Davlat Texnika Universiteti, professor.
To‘xtayeva Zebo Sharifovna
Buxoro Davlat Texnika Universiteti, professor.
Navro‘zova Gulchixra Nigmatovna
Buxoro Davlat Texnika Universiteti, dotsent.
Uzoqova Laylo Polvonovna
Buxoro muhandislik – texnologiya instituti, dotsent.
To‘raqulova Marjona Qiyom qizi
Buxoro Davlat Texnika Universiteti, dotsent.
Muradova Zarina Rashidovna
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Sanjar Aslonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shodiyev Jahongir Jo‘raqulovich
Buxoro Davlat Texnika Universiteti, dotsent
Gaffarov Laziz Hasanovich
Buxoro muhandislik – texnologiya instituti, dotsent.

Tahririyat a’zolarning to‘liq ro‘yxati jurnalning www.devos.uz saytida keltirilgan.

Tahririyat hay’ati a’zolarining tarkibini o‘zgartirish hamda qo‘shimcha kiritish yoki tahririyat a’zoligidan chiqarish bosh muharrir tomonidan amalga oshiriladi.

ISSN 3030-3907

Development of science ilmiy jurnali 2024 yil 15 aprel kuni №256445 sonli guvohnoma bilan Davlat ro‘yxatidan o‘tgan.

To‘plam elektron ko‘rinishda (pdf formatida) mualliflarga taqdim etiladi. To‘plamga kiritiladigan maqolalarning mazmuni, ulardagi statistik ma’lumotlar va me’yoriy hujjatlarning to‘g‘riligiga hamda har qanday fikr - mulohazalarga mualliflarning o‘zlari mas’ul hisoblanadilar. Talablarga javob bermaydigan maqolalar to‘plamga kiritilmaydi. Tashkiliy qo‘mita maqola matnini qisqartirish, qisman tuzatish kiritish, seksiyalarga joylashtirish huquqiga ega.

ISSN 3030-3907

INDIRECT FIELD-ORIENTED CONTROL (IFOC) OF ASYNCHRONOUS TRACTION MOTORS FOR O'Z-ELR ELECTRIC LOCOMOTIVES IN THE FLUX-WEAKENING REGION

Sobirov N.Q.

PhD student, Electric rolling stock department, Tashkent State Transport University

E-mail: nizomiddinsobirov999@gmail.com _

Annotatsiya. Bilvosita maydon yo‘naltirilgan boshqaruv— bu asinxron tortuv dvigatellarda (ATD) keng qo‘llaniladigan yuqori samarali vektor boshqaruv usuli hisoblanadi. Magnit maydon susayish sohasida (asosiy tezlikdan yuqorida) tezlik diapazonini kengaytirish bilan birga invertor kuchlanish chegarasiga moslashish uchun rotor magnit oqimini kamaytirish talab etiladi. Ushbu maqolada magnit maydon susayish sohasida bilvosita maydon yo‘naltirilgan boshqaruvi usuli batafsil yoritilgan, unda klassik va zamonaviy strategiyalar, standart blok diagramma, odatiy MATLAB/Simulink modeli tuzilmasi hamda namunaviy simulyatsiya natijalari keltirilgan. Tadqiqot natijalari shuni ko‘rsatadiki, oddiy 1/ω usuli yaxshi boshlang‘ich nuqta bo‘lsa-da, kuchlanish bo‘yicha qayta aloqa qo‘llanilishi tizimning barqarorligini va moment imkoniyatlarini sezilarli darajada yaxshilaydi. Tok cheklovlarini to‘g‘ri qo‘llash esa barcha ish rejimlarida xavfsiz ishlashni ta’minlaydi.

Kalit so‘zlar: avtonom kuchlanish invertori,tortuv tizimlari,asinxron tortuv dvigateli,impuls kenglik modulatsiyasi

Аннотация. Косвенное векторное управление является высокоэффективным методом векторного управления, широко применяемым для асинхронных двигателей (АД). В области ослабления поля (выше базовой скорости) для расширения диапазона скоростей при ограничении напряжения инвертора необходимо уменьшать магнитный поток ротора. В данной статье представлено подробное описание метода косвенное векторное управление в ослабления поля , включая классические и современные стратегии, стандартную блок-схему, типичную структуру модели в MATLAB/Simulink, а также примеры результатов моделирования. Результаты исследования показывают, что, несмотря на то что простой метод 1/ω является хорошей отправной точкой, использование обратной связи по напряжению значительно повышает устойчивость системы и её тяговые характеристики в области ослабления поля. Правильное ограничение токов обеспечивает безопасную работу системы во всех режимах эксплуатации.

ISSN 3030-3907

Ключевые слова: автономный инвертор напряжения (АИН), системы электрической тяги, асинхронные тяговые двигатели, (PWM) широтно-импульсная модуляция

Abstract. Indirect Field-Oriented Control (IFOC) is a high-performance vector control technique widely used for induction motors (IM). In the flux-weakening (FW) region (above base speed), the rotor flux must be reduced to respect the inverter voltage limit while extending the speed range. This article presents a detailed explanation of IFOC in the FW region, including classical and advanced strategies, a standard block diagram, a typical MATLAB/Simulink implementation structure, and example simulation waveforms. The study highlights that while the simple 1/ω method provides an excellent starting point, incorporating voltage-feedback control significantly improves robustness and torque capability in the flux-weakening region. Proper enforcement of current limits ensures safe operation under all conditions.

Keywords: voltage source inverter, traction systems, induction motors, (PWM) pulse width modulation

1. INTRODUCTION.

Induction motors are robust and cost-effective but face voltage limitations at high speeds. When the back-EMF approaches the maximum inverter voltage V_{max} (typically $\frac{V_{dc}}{\sqrt{2}}$), further speed increase requires **flux weakening** — deliberately reducing the rotor flux λ_r by lowering the d-axis current i_{sd}^*.IFOC achieves decoupled control of flux i_{sd} and torque i_{sq} in the rotor-flux-oriented d-q frame. In the constant-torque region (below base speed ω_b), flux is kept at rated value. In the FW region ($\omega_r > \omega_b$), flux is reduced (classically as $\frac{1}{\omega}$) to maintain voltage margin and enable constant-power operation.[1]

2. Key Principles of IFOC in Flux-Weakening

There are two operating regions of the induction motor. Below the base speed, the drive operates in the constant torque region, where stator voltage increases with speed and rotor flux remains constant. Above the base speed, the inverter voltage reaches its limit, and flux weakening is applied, resulting in reduced torque while maintaining approximately constant power. Fig.1

ISSN 3030-3907

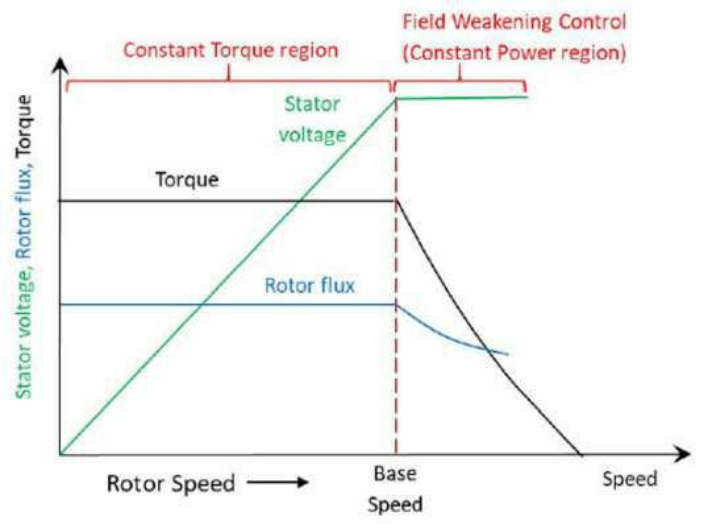


Fig.1 Induction Motor Operating Regions: Constant Torque and Flux-Weakening (Constant Power) Characteristics

Rotor flux (steady state):

$$\lambda_r = L_M i_{sd} \quad (1)$$

Electromagnetic torque:

$$T_e = \frac{3}{2} \cdot \frac{p}{2} \cdot \frac{L_m}{L_r} \cdot \lambda_r \cdot i_{sq} \quad (2)$$

Slip frequency for orientation:

$$\omega_{sl}^* = \frac{R_r \ L_m \ i_{sq}^*}{L_r \ \lambda_r^*} \quad (3)$$

Synchronous speed:

$$\omega_e = \omega_r + \omega_{slip} \quad (4)$$

In the FW region, the voltage constraint becomes critical:

$$|V_s| \approx \omega_e \sqrt{(\sigma L_s i_{sq})^2 + (L_s i_{sd})^2} \leq V_{max} \quad (5)$$

where σ is the leakage factor.

In the flux-weakening region, the rotor flux reference is adjusted inversely proportional to the rotor speed to satisfy the inverter voltage constraint. This ensures operation within the constant power region while maintaining system stability [2-3]

$$\psi^* = \begin{cases} \psi_{nom}, & \omega \leq \omega_{base} \\ \psi_{nom} \cdot \frac{\omega_{base}}{\omega}, & \omega > \omega_{base} \end{cases} \quad (6)$$

$$\text{flux}^* = \min\left(\psi_{nom}, \ \psi_{nom} \ \frac{\omega_{bas}}{\omega}\right) \quad (7)$$

In IFOC, the stator current is decomposed into i_{sd} (flux control) and torque i_{sq} (torque control) components. The inverter and motor impose a maximum allowable current $I_{s,max}$.This limit is represented as a circular boundary in the

ISSN 3030-3907

$i_{sd} - i_{sq}$ plane. Therefore, the current magnitude must satisfy $\sqrt{i_{sd}^2 + i_{sq}^2} \leq I_{s,max}$.

Rearranged for the torque-producing current, the current limit enforcement becomes:

$$i_{sq}^* \leq \sqrt{I_{s,max}^2 - (i_{sd}^*)^2} \quad . \qquad (8)$$

This formula is applied dynamically after calculating the desired i_{sq}^* from the torque reference.

The voltage-feedback uses a closed-loop controller to maintain the inverter voltage within its limit. The voltage error is defined as the difference between the maximum allowable voltage and the actual stator voltage magnitude. This error is processed by a PI controller, which reduces the d-axis current reference. As a result, the rotor flux decreases, enabling stable operation in the flux-weakening region.[4] Stator voltage magnitude is calculated as:

$$|V_s^*| = \sqrt{(u_{sd}^*)^2 + (u_{sq}^*)^2} \qquad (9)$$

To ensure safe inverter operation, the voltage must satisfy:

$$|V_s^*| \leq V_{max} \qquad (10)$$

3. Block Diagram of IFOC in the Flux-Weakening Region

The complete block diagram of the induction motor drive based on Indirect Field-Oriented Control (IFOC) with flux-weakening and current limitation is built. The control structure includes outer speed and flux control loops that generate the reference currents i_{sd}^* and i_{sq}^*, while inner current controllers regulate the corresponding stator currents. A voltage limitation block ensures that the stator voltage remains within the inverter constraint, and a current limiting mechanism maintains the stator current within safe thermal boundaries. The generated voltage references are transformed into the stationary reference frame and applied to the inverter through a PWM module. This integrated control scheme enables stable operation over a wide speed range, including both constant torque and flux-weakening regions. Fig.2

ISSN 3030-3907

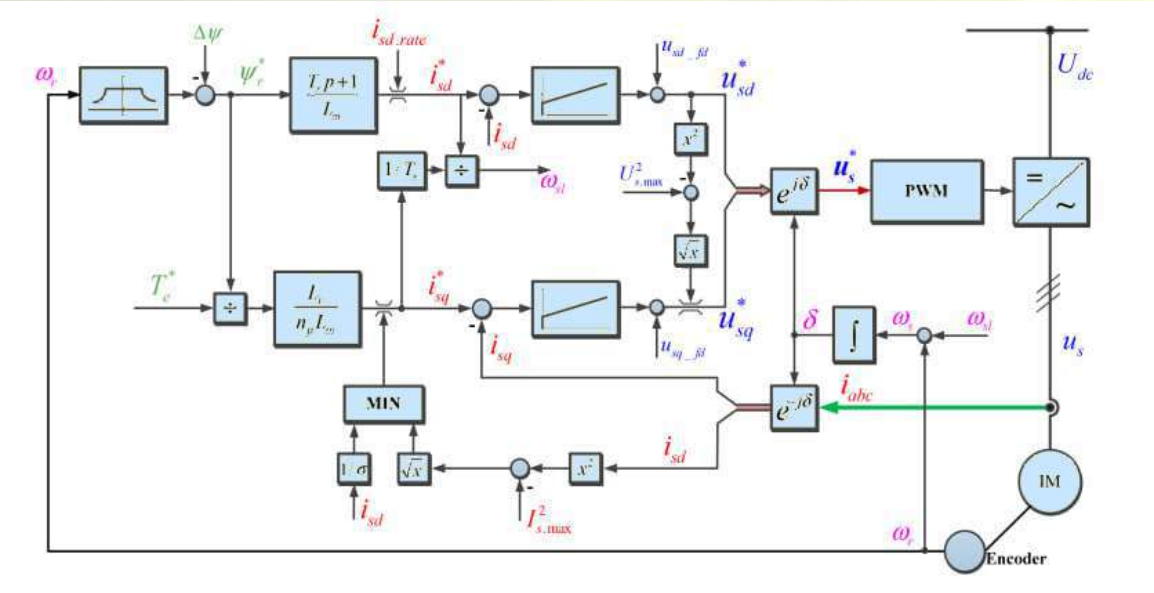


Fig.2 Block Diagram of IFOC-Based Induction Motor Drive with Flux-Weakening and Current Limitation

4. MATLAB/Simulink Implementation

The detailed Simulink implementation of the IFOC-based induction motor control system with flux-weakening, current limitation, and state estimation are given. The control structure consists of an outer speed loop that generates the torque reference, and a flux control loop that produces the d-axis current reference i_{sd}^*. Inner current control loops regulate the stator current components i_{sd}^* and i_{sq}^* through corresponding voltage references u_{sd}^* and u_{sq}^*. Saturation blocks are applied to both current and voltage signals to ensure operation within inverter and thermal limits. A flux observer and angle estimator are used to obtain the rotor flux and electrical angle, enabling accurate coordinate transformations. The generated dq voltage references are then converted to the stationary frame and supplied to the inverter. This comprehensive control scheme ensures stable and efficient operation of the induction motor across both constant torque and flux-weakening regions. Fig.3 [5]

ISSN 3030-3907

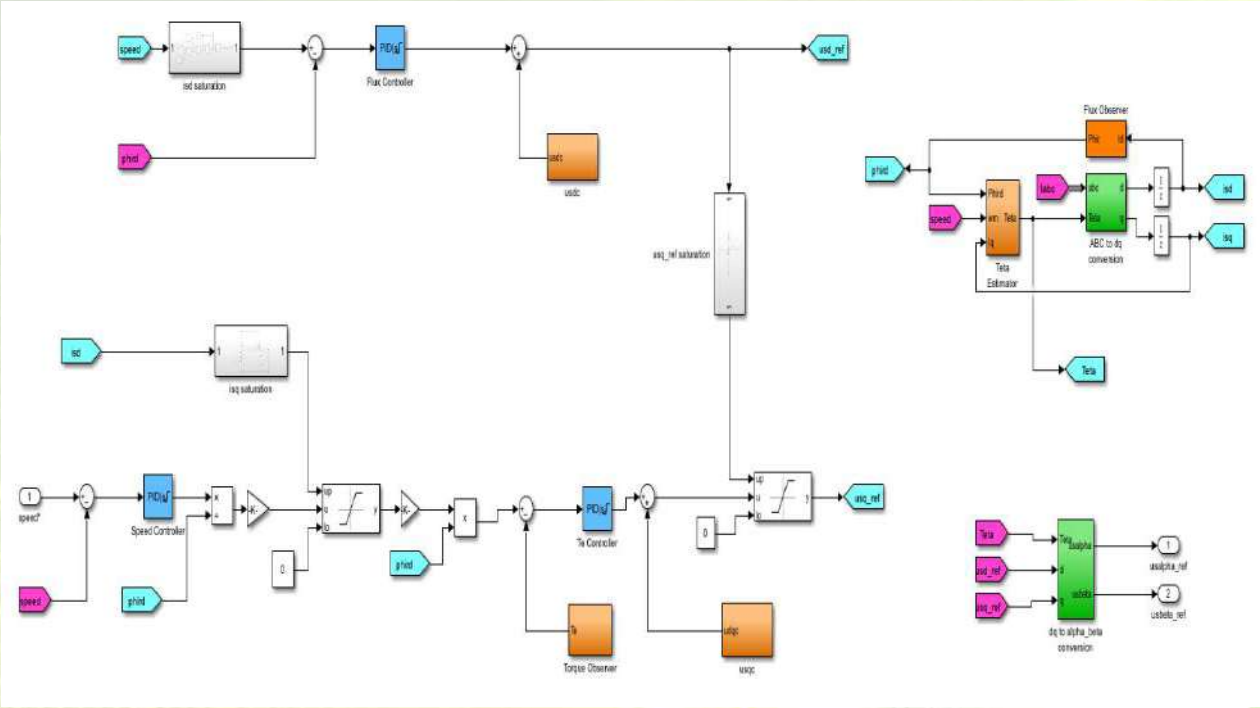


Fig.3 Detailed Simulink Model of IFOC-Based Induction Motor Drive in a full-speed region

The Simulink model of the IFOC system operating in a full-speed region was developed using the parameter values provided in the tables below.

Table.1

Induction motor parameters

U_N=2150 V	f_N=46 Hz	P_N=1.25 MW	R_s=0.062 Ω
R_r=0.045 Ω	L_s=0.0008478 H	L_r=0.00067824 H	
L_m=0.038 H	p=2 (pole pairs)	J=108 kg× m^2	

Table.2

O'Z-ELR electric locomotives characteristics

Function Point	Unit	Initial point	Nominal point	Maximum Speed
Stator frequency	Hz	0.9	46	86
voltage	V	91,4	2150	2150
Stator current	A	510,7	390	410
Power	kWt	0	1250	1250
Locomotive speed	km / h	0	65	120
Torque	kN	558,5	412,9	221,5

5. Simulation Results

The simulation results validate the effectiveness of Indirect Field-Oriented Control (IFOC) with flux-weakening for asynchronous traction motors used in O'Z-ELR electric locomotives.

ISSN 3030-3907

Stator phase voltage: The voltage waveform remains sinusoidal with its amplitude approaching the inverter's maximum limit. This confirms that the flux-weakening strategy (classical 1/ω or voltage-feedback) successfully maintains the voltage constraint.[7]

Stator phase currents I_{abc}: The three-phase currents are well-balanced and stable, with amplitudes staying within the permissible current limits. The increase in frequency with rising speed is clearly visible. Rotor speed: The speed gradually increases, demonstrating smooth extension into the flux-weakening region.Electromagnetic torque (Te): The average torque is maintained around 8500–9000 N·m with acceptable high-frequency ripple caused by PWM and current regulation. The torque remains relatively smooth and close to the reference value. Fig.4

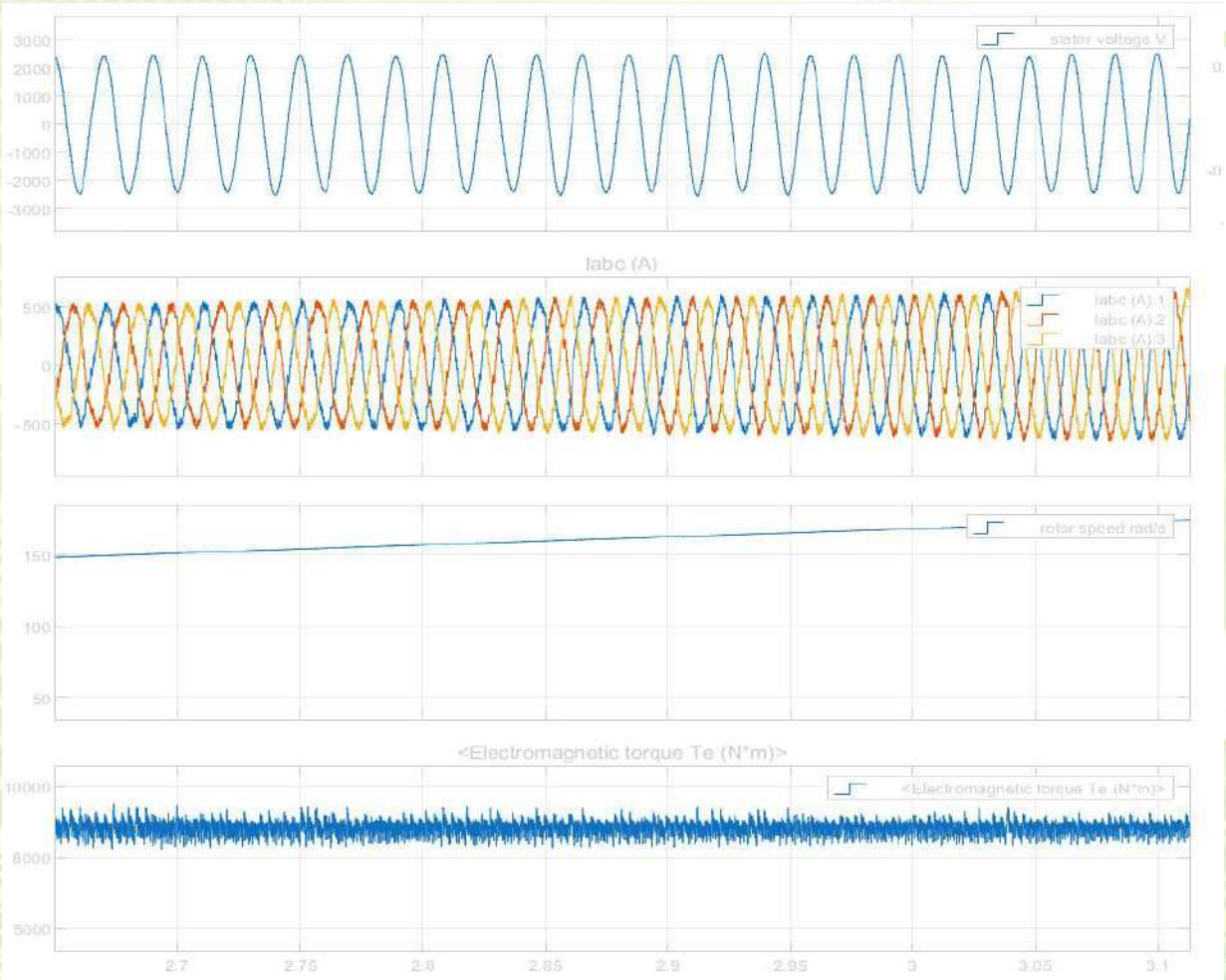


Fig.4 Simulation Results of IFOC-Based Induction Motor Drive in Full Speed Range (Voltage, Current, Speed, and Torque Responses)

These waveforms confirm that the IFOC system preserves field orientation, respects voltage and current limits, and delivers usable torque even at high speeds.

6. CONCLUSION.

ISSN 3030-3907

This article has thoroughly examined the application of Indirect Field-Oriented Control (IFOC) for induction motors operating in the flux-weakening region. The theoretical foundations, mathematical models, classical 1/ω flux-weakening method, voltage-feedback technique, and current limit enforcement strategies were presented in detail, supported by practical block diagrams and MATLAB/Simulink implementation structures.

Simulation studies confirmed the effectiveness of the control system, showing stable voltage limitation, balanced currents, and reliable torque production at elevated speeds. The study highlights that while the simple 1/ω method provides an excellent starting point, incorporating voltage-feedback control significantly improves robustness and torque capability in the flux-weakening region. Proper enforcement of current limits ensures safe operation under all conditions.[8]

Overall, IFOC with flux weakening represents a mature and reliable control strategy that successfully addresses the voltage constraint challenge in high-speed induction motor drives. Its successful validation against real O'Z-ELR locomotive parameters reinforces its potential for practical deployment in electrical traction systems.

Future research directions include adaptive parameter estimation algorithms, and maximum torque per volt (MTPV) optimization techniques to further enhance performance in deep flux-weakening operation.

REFERENCES

1. Prof. Dr.-Ing. Andreas Steimel. Electric Traction - Motion Power and Energy Supply: Basics and Practical Experience, 2008. 197–206 c.
2. Assoc. Prof. Gonzalo Abad. Power Electronics and Electric Drives for Traction Applications, Mondragon University, Spain, 2017 264-276 c.
3. Burkov, A.T., Valinsky, O.S., Evstaf'ev, A.M. et al. Modern Locomotive Traction Drive Control Systems. Russ. Electr. Engin. 90, 692–695 (2019).
4. Nazirkhonov T. M., Radjibaev D. O. Evaluation of the efficiency of a 4q-S converter of an alternating current electric locomotive of the O'Z-ELR series using a computer simulation model //AIP Conference Proceedings. – AIP Publishing, 2023. – T. 2476. – №. 1.
5. Sang-Hoon Kim. Electric Motor Control: DC, AC, and BLDC Motors. CRC Press, 2017.
6. Ľuboš Struharňanský, Ján Vittek, Pavol Makyš, and Jaroslav Ilončiak. Vector control techniques for traction drive with induction machines – comparison. In Proceedings of TRANSCOM 2017: International Scientific Conference on Sustainable, Modern and Safe Transport, Žilina, Slovakia, 2017.

ISSN 3030-3907

7. T. M. Nazirkhonov, A. T. Lesov, and N. Q. Sobirov, “Integration of neural networks into electric rolling stock control systems,” Railway Transport: Topical Issues and Innovations, no. 1, 2025.
8. X. Fang, Z. Tian, H. Li, Z. Yang, F. Lin, and S. Hillmansen,“Current closed-loop control and field orientation analysis of an induction motor in six-step operation for railway applications,” IET Power Electronics, vol. 12, no. 6, pp. 1409–1419, 2019, doi: 10.1049/iet-pel.2018.5854.

ISSN 3030-3907