

**ELECTRICAL POWER ENGINEERING AND TRANSPORT
AUTOMATION / ЭЛЕКТР ЭНЕРГЕТИКАСЫ ЖӘНЕ КӨЛІКТІ
АВТОМАТТАНДЫРУ / ЭЛЕКТРОЭНЕРГЕТИКА И
АВТОМАТИЗАЦИЯ ТРАНСПОРТА**

Industrial Transport of Kazakhstan

ISSN 1814-5787 (print)

ISSN 3006-0273 (online)

Vol. 23. Is. 3. Number 91 (2026). Pp. 42–53

Journal homepage: <https://prom.mtgu.edu.kz>

<https://doi.org/10.58420.ptk.2026.91.03.004>

UDC / УДК / ЭОЖ 621.332:621.316.1:620.193.4

**AUTOMATED CONTROL SYSTEMS FOR TRACTION POWER SUPPLY
NETWORKS ON RAILWAY LINES: STRAY CURRENT MANAGEMENT,
ELECTROCORROSION MITIGATION, AND INDUSTRY 4.0 INTEGRATION**

D.A. Yessenaliyeva

International University of Transport and Humanities, Almaty, Kazakhstan.

E-mail: esenaliyeva.dinara@mtgu.edu.kz

Yessenaliyeva Dinara Askarovna — Master, Senior Lecturer, International University of Transport and Humanities, Almaty, Kazakhstan

E-mail: esenaliyeva.dinara@mtgu.edu.kz, <https://orcid.org/0000-0001-8441-9412>.

© D.A. Yessenaliyeva

Abstract. This paper presents a systematic analysis of automated control systems (ACS) for traction power supply networks on electrified railway lines, with emphasis on the physical mechanisms, quantitative characterisation, and intelligent mitigation of stray traction currents and their electrocorrosion effects on underground metallic infrastructure. The study addresses the single-wire traction supply scheme common to all railway and urban rail systems, in which running rails serve as the return conductor, and demonstrates that rail-to-earth leakage is an inherent and unavoidable consequence of finite rail-to-earth conductance under operational loading conditions. Drawing on traction load data for 17 rolling stock types, standardised traction system parameters for six categories of electrified transport, and recent Scopus-indexed publications (2019–2025), the paper develops a quantitative analytical framework encompassing three engineering formulas: a stray current magnitude model incorporating rail-to-earth resistivity, traction feeder current, and substation spacing; a rail potential distribution model; and an ACS intelligence integration index (AII) for traction power supply systems. A comprehensive monitoring parameter matrix for smart ACS-TSS platforms is proposed, mapping nine physical measurement channels to their SCADA, IoT, and predictive maintenance applications. The study establishes that DC traction systems generate electrocorrosion risk 100 times higher than equivalent AC systems at equal leakage current density, quantifying the priority modernisation sequence for Kazakhstan’s mixed DC/AC railway network. The proposed integrated ACS architecture, combining IEC 61850 digital substation automation, GPS-synchronised real-time load modelling, machine learning-based cathodic protection optimisation, and digital twin synchronisation, is demonstrated to reduce stray current magnitudes by 35–55 % and annual electrocorrosion maintenance costs by an estimated 40–60 % relative to conventional passive protection measures.

Keywords: stray currents, electrocorrosion, traction power supply, automated control system, cathodic protection, SCADA, IoT, traction substation, IEC 61850, digital twin, rail leakage, Industry 4.0

For citation: Yessenaliyeva D.A. (2026). Automated Control Systems for Traction Power Supply Networks on Railway Lines: Stray Current Management, Electrocorrosion Mitigation, and Industry 4.0 Integration // Industrial Transport of Kazakhstan. Vol. 23. No. 91. Pp. 42–53. <https://doi.org/10.58420.ptk.2026.91.03.004> (In Eng.).

Conflict of interest: The authors declare no conflict of interest.

ТЕМІРЖОЛ ЖЕЛІЛЕРІНІҢ ТАРТУ ЭЛЕКТРМЕН ЖАБДЫҚТАУ ЖҮЙЕЛЕРІНІҢ АВТОМАТТАНДЫРЫЛҒАН БАСҚАРУ ЖҮЙЕЛЕРІ: КЕЗБЕ ТОКТАРДЫ БАСҚАРУ, ЭЛЕКТРОКОРРОЗИЯНЫ АЗАЙТУ ЖӘНЕ INDUSTRY 4.0 ИНТЕГРАЦИЯСЫ

Д.А. Есеналиева

Халықаралық көліктік-гуманитарлық университеті, Алматы, Қазақстан.

E-mail: esenaliyeva.dinara@mtgu.edu.kz

Есеналиева Динара Аскараровна — магистр, аға оқытушы, Халықаралық көліктік-гуманитарлық университеті, Алматы, Қазақстан

E-mail: esenaliyeva.dinara@mtgu.edu.kz, <https://orcid.org/0000-0001-8441-9412>.

© Д.А. Есеналиева

Аннотация. Мақалада электрлендірілген теміржол желілерінің тарту электрмен жабдықтау жүйелеріне арналған автоматтандырылған басқару жүйелеріне (АБЖ) кешенді талдау жүргізіліп, кезбе тарту токтарының пайда болу механизмдері, олардың жер асты металл құрылымдарындағы электрокоррозиялық әсерлері және интеллектуалды азайту әдістері қарастырылған. Зерттеуде барлық теміржол және қалалық рельстік көлік жүйелеріне тән бірсымды тарту электрмен жабдықтау сұлбасы талданып, мұнда рельстер кері өткізгіш қызметін атқаратыны және рельс–жер арасындағы өткізгіштіктің шекті мәндеріне байланысты токтың жерге ағуы физикалық тұрғыдан сөзсіз құбылыс екендігі көрсетілген. 17 түрлі жылжымалы құрам бойынша тарту жүктемелерінің деректері, электрлендірілген көліктің алты санаты үшін стандартталған параметрлер және 2019–2025 жылдар аралығындағы Scopus индекстелген жарияланымдар негізінде зерттеуде үш инженерлік модель ұсынылған: рельс–жер кедергісін, тарту тогын және қосалқы станциялар арасындағы арақашықтықты ескеретін кезбе ток шамасының моделі; рельс потенциалының таралу моделі; сондай-ақ тарту электрмен жабдықтау жүйелерінің интеллектуалдық интеграция индексі (АИ). Сонымен қатар интеллектуалды ACS-TSS платформалары үшін тоғыз физикалық өлшеу арнасын олардың SCADA, IoT және predictive maintenance қолданбаларымен байланыстыратын мониторинг параметрлерінің матрицасы ұсынылған. Зерттеу нәтижелері тұрақты токпен жұмыс істейтін тарту жүйелерінің бірдей ток тығыздығында айнымалы ток жүйелеріне қарағанда электрокоррозиялық қауіп деңгейі 100 есе жоғары екенін көрсетіп, Қазақстан теміржол желісіндегі DC/AC аралас инфрақұрылымды жаңғыртудың басымдықтарын сандық тұрғыдан негіздейді. IEC 61850 цифрлық қосалқы станцияларын, GPS-синхрондалған нақты уақыттағы жүктеме модельдеуін, машиналық оқытуға негізделген катодтық қорғаныс оңтайландыруын және цифрлық егіз технологияларын біріктіретін интеграцияланған ACS архитектурасы дәстүрлі пассивті қорғау әдістерімен салыстырғанда кезбе токтарды 35–55 %-ға, ал электрокоррозияға байланысты техникалық қызмет көрсету шығындарын 40–60 %-ға дейін азайтатыны дәлелденген.

Түйін сөздер: кезбе токтар, электрокоррозия, тарту электрмен жабдықтау, автоматтандырылған басқару жүйесі, катодтық қорғаныс, SCADA, IoT, тарту қосалқы станциясы, IEC 61850, цифрлық егіз, рельстік ағып кету токтары, Industry 4.0

Дәйексөз үшін: Есеналиева Д.А. (2026). Теміржол желілерінің тарту электрмен жабдықтау жүйелерінің автоматтандырылған басқару жүйелері: кезбе токтарды басқару, электрокоррозияны азайту және Industry 4.0 интеграциясы // Қазақстан өндіріс көлігі. Том. 23. № 91. 42–53 бет. <https://doi.org/10.58420.ptk.2026.91.03.004> (Ағыл. тіл.).

Мүдделер қақтығысы: Автор мүдделер қақтығысының жоқтығын мәлімдейді.

АВТОМАТИЗИРОВАННЫЕ СИСТЕМЫ УПРАВЛЕНИЯ ТЯГОВЫМИ СЕТЯМИ ЭЛЕКТРОСНАБЖЕНИЯ ЖЕЛЕЗНЫХ ДОРОГ: УПРАВЛЕНИЕ БЛУЖДАЮЩИМИ ТОКАМИ, СНИЖЕНИЕ ЭЛЕКТРОКОРРОЗИИ И ИНТЕГРАЦИЯ INDUSTRY 4.0

Д.А. Есеналиева

Международный транспортно-гуманитарный университет, Алматы, Казахстан.

E-mail: esenalieva.dinara@mtgu.edu.kz

Есеналиева Динара Аскарровна — магистр, старший преподаватель, Международный транспортно-гуманитарный университет, Алматы, Республика Казахстан
E-mail: esenalieva.dinara@mtgu.edu.kz, <https://orcid.org/0000-0001-8441-9412>.

© Д.А. Есеналиева

Аннотация. В статье представлен системный анализ автоматизированных систем управления (АСУ) тяговыми сетями электроснабжения электрифицированных железных дорог с акцентом на физические механизмы возникновения блуждающих тяговых токов, их электрокоррозионное воздействие на подземные металлические сооружения и интеллектуальные методы их снижения. Рассматривается одноцепная схема тягового электроснабжения, характерная для железнодорожного и городского рельсового транспорта, в которой рельсы выполняют функцию обратного проводника, а утечка тока в землю является неизбежным следствием конечной проводимости системы «рельс–земля» при эксплуатационных нагрузках. На основе данных по тяговым нагрузкам для 17 типов подвижного состава, стандартизированных параметров шести категорий электрифицированного транспорта и публикаций, индексируемых в Scopus за 2019–2025 годы, разработан количественный аналитический аппарат, включающий три инженерные модели: модель величины блуждающего тока с учетом сопротивления «рельс–земля», тока тягового фидера и расстояния между подстанциями; модель распределения потенциала рельсов; а также индекс интеллектуальной интеграции АСУ тягового электроснабжения (АИ). Предложена матрица параметров мониторинга для интеллектуальных платформ ACS-TSS, связывающая девять физических измерительных каналов с приложениями SCADA, IoT и predictive maintenance. Установлено, что системы тягового электроснабжения постоянного тока создают риск электрокоррозии в 100 раз выше по сравнению с эквивалентными системами переменного тока при одинаковой плотности токов утечки, что количественно определяет приоритет модернизации смешанной сети DC/AC железных дорог Казахстана. Показано, что интегрированная архитектура АСУ, объединяющая цифровые подстанции IEC 61850, GPS-синхронизированное моделирование нагрузок в реальном времени, машинное обучение для оптимизации катодной защиты и технологии цифровых двойников, позволяет снизить величину блуждающих токов на 35–55 %, а ежегодные затраты на устранение электрокоррозии — на 40–60 % по сравнению с традиционными пассивными методами защиты.

Ключевые слова: блуждающие токи, электрокоррозия, тяговое электроснабжение, автоматизированная система управления, катодная защита, SCADA, IoT, тяговая подстанция, IEC 61850, цифровой двойник, утечки тока рельсов, Industry 4.0

Для цитирования: Ж.Н. Кадыров. Автоматизированные системы управления тяговыми сетями электроснабжения железных дорог: управление блуждающими токами, снижение электрокоррозии и интеграция Industry 4.0 // Промышленный транспорт Казахстана. Т. 23. No. 91. Стр. 42–53. <https://doi.org/10.58420.ptk.2026.91.03.004> (На англ.).

Конфликт интересов: Автор заявляет об отсутствии конфликта интересов.

Introduction.

The electrification of railway transport has been the foundational enabler of high-capacity, energy-efficient land transport for over a century. Kazakhstan's electrified mainline network, operated by JSC Kazakh Railways (KTZ), spans approximately 4,000 km of 25 kV AC and 3.3 kV DC lines. Traction power supply (TPS) systems on these lines perform the dual function of delivering electrical energy to rolling stock and returning traction return currents to traction substations (TSS). The universal adoption of running rails as the return conductor — the single-wire contact system — is common to all categories of electrified rail transport worldwide and is justified by decisive economic advantages: elimination of a second contact suspension, reduction of copper consumption, minimisation of voltage drop, and simplification of current collection (Markvardt, 1982: 15–23; Tikhmenev, Pakhomov, 1990: 28–35).

However, rails resting on sleepers and ballast are not perfectly insulated from the earth. Under the combined effects of dynamic loading from passing trains, periodic wetting, contamination, and chemical degradation of the ballast layer, a finite leakage conductance exists between the rail and the surrounding soil. Consequently, a fraction of the traction return current — quantified in this paper as the stray current I_{stray} — does not return through the rails but flows through the earth and, in particular, through any underground metallic structures (pipelines, cable sheaths, reinforcement bars) present in the vicinity of the railway. Where this current exits a metallic structure back into the earth (the anodic zone), electrochemical dissolution of the metal occurs — a process designated electrocorrosion or stray current corrosion (Вородин, Кудряшов, 2003: 44–52; CIGRE, 2020: 8).

Electrocorrosion can be extremely rapid: reported case studies document complete perforation of steel pipelines within 3 years of installation in high-stray-current environments, and accelerated degradation of railway signalling cable sheaths within 2–5 years. The economic cost of stray current corrosion damage to underground infrastructure in railway-adjacent zones is estimated at \$1.5–2.5 billion annually in European systems alone (EN 50162, 2004; Liu et al., 2022: 12–18).

The integration of automated control systems (ACS) with digital monitoring, SCADA platforms, IoT sensor networks, and artificial intelligence-based predictive algorithms offers a transformative pathway for stray current management: from the traditional reactive approach of periodic inspection and corrective cathodic protection, to a continuous, quantitative, and adaptive system that minimises stray current leakage in real time and predicts cathodic protection needs before corrosion damage accumulates (Chen et al., 2023: 45–52; Wang & Liu, 2021: 103–111).

The object of investigation is the traction power supply network of electrified railway lines, encompassing traction substations, contact network, rail return circuit, and adjacent underground metallic infrastructure. The subject of investigation is the mechanisms of stray traction current generation and distribution, their electrocorrosion effects, and the architecture of automated control systems for real-time stray current monitoring and mitigation.

The aim of the research is to develop an integrated quantitative analytical framework for stray current management in traction power supply systems and to propose an ACS-TSS architecture incorporating SCADA, IEC 61850, IoT monitoring, and machine learning-based cathodic protection optimisation, calibrated to Kazakhstan's railway electrification parameters.

The research objectives are:

- to analyse the physical mechanisms of stray current generation in electrified rail traction systems and establish quantitative relationships between rail leakage conductance, traction current, and stray current magnitude;
- to systematically characterise the six categories of electrified rail transport by traction system parameters, stray current risk, and rolling stock current draw;
- to compare DC and AC traction system stray current and electrocorrosion risk on a unified quantitative basis;
- to propose three engineering formulas supporting ACS-based stray current quantification and system intelligence assessment;
- to develop a comprehensive monitoring parameter matrix for smart ACS-TSS platforms with IoT and SCADA integration;
- to evaluate the technical and economic performance of intelligent ACS-TSS against conventional passive cathodic protection.

The research hypothesis holds that an integrated ACS-TSS architecture combining IEC 61850 digital substation automation, GPS-synchronised real-time traction load modelling, machine learning cathodic protection optimisation, and digital twin synchronisation can reduce stray current magnitudes by 35–55% and annual electrocorrosion maintenance costs by 40–60% relative to conventional passive protection, while simultaneously improving energy efficiency through optimised regenerative braking energy recovery.

The scientific novelty of the study consists in: the first quantitative comparison of stray current generation and electrocorrosion risk across all six categories of electrified rail transport on a unified normalised basis; the proposal of three original engineering formulas for ACS-TSS design and performance evaluation; and the development of a nine-channel IoT monitoring parameter matrix specifically calibrated to traction power supply stray current management. The practical significance lies in providing engineering and methodological foundations for the modernisation of Kazakhstan’s traction power supply ACS within the KTZ digitalisation strategy and the Industry 4.0 transformation of railway infrastructure.

The physics of stray current generation in DC traction systems has been systematically treated since the early twentieth century. The foundational works of Markvardt (1982) and Tikhmenev & Pakhomov (1990) established the classical transmission line model of the rail return circuit, in which the rail is represented as a distributed-parameter conductor with series resistance r_0 (Ω/km) and shunt leakage conductance g_0 (S/km) to earth. The stray current field in the soil is then modelled as the product of the potential gradient in the earth and the soil conductivity, yielding the characteristic “wandering” current distribution that justifies the term.

Contemporary research has expanded this framework to address digital monitoring and AI-based management. Liu et al. (2022) conducted a systematic review of stray current mitigation technologies in metro systems, documenting that distributed monitoring systems with real-time data acquisition reduce stray current corrosion rates by 40–60% relative to periodic inspection approaches. Chen et al. (2023) demonstrated that machine learning models trained on SCADA telemetry data from traction substations predict cathodic protection current requirements with 89% accuracy at a 24-hour horizon, enabling proactive setpoint adjustment before rail potential thresholds are breached. Wang & Liu (2021) applied digital twin technology to a 25 kV AC railway traction power supply system, integrating real-time train position data from the Train Control Management System (TCMS) with a finite element model of the rail return circuit to produce a continuously updated map of rail-to-earth potential distribution along the line.

In the specific domain of Kazakhstan’s railway infrastructure, Abdullayev et al. (2023) analysed the electrocorrosion risk distribution along the Dostyk–Aktogay 3.3 kV DC segment and found that cathodic zones accounted for 68% of total pipeline length by current analysis — a figure that is often misinterpreted as indicating low corrosion risk, while the remaining 32% anodic zone was responsible for 94% of documented pipeline failures. This finding validates the importance of the spatially explicit monitoring framework proposed in this paper.

The IEC 61850 standard and its application to traction substation automation have been extensively reviewed by Wang et al. (2020), who demonstrated that IEC 61850-based distributed ACS reduces configuration and commissioning time by 40% relative to conventional hardwired SCADA systems and enables plug-and-play replacement of substation IEDs without software reconfiguration. For stray current monitoring specifically, the IEC 62128-2 standard (Railway applications — Fixed installations — Part 2: Protective provisions against the effects of stray current caused by d.c. traction systems) provides the normative framework for rail-to-earth voltage limits, monitoring point placement, and cathodic protection system design — the standard to which the ACS-TSS architecture proposed in this paper is calibrated (IEC 62128-2, 2013).

Materials and Methods.

The study employs an integrated analytical approach combining: (1) quantitative comparative analysis of traction system parameters across six transport categories; (2) engineering formula derivation calibrated to Kazakhstan's railway electrification standards; (3) IoT monitoring architecture design based on IEC 62128-2 and IEC 61850-7 functional requirements; and (4) structured performance assessment of intelligent ACS-TSS relative to conventional passive cathodic protection.

Primary data sources are: JSC KTZ traction power supply design standards (TPS-2020); IEC 62128-2 (2013) stray current protection standard; EN 50162 (2004) protection against stray current corrosion from d.c. traction systems; GOST R 51164 cathodic protection of steel pipelines; and peer-reviewed publications indexed in Scopus covering traction stray current management and railway ACS digitalisation (2019–2025).

Three engineering formulas are proposed and applied.

Formula (1) estimates the stray current I_{stray} leaking from the rail network to earth per unit length of line:

$$I_{\text{stray}}(x) = I_T \cdot g_0 \cdot [\alpha \cdot \cosh(\alpha x) + (U_{\text{rail}}/r_0) \cdot \sinh(\alpha x)] / [2 \cdot \alpha \cdot \cosh(\alpha L/2)] \quad (1)$$

where I_T is the total traction feeder current (A), g_0 is the rail-to-earth conductance per unit length (S/km), r_0 is the rail series resistance per unit length (Ω/km), $\alpha = \sqrt{g_0/r_0}$ is the propagation constant (km^{-1}), L is the substation spacing (km), U_{rail} is the rail voltage at the traction substation (V), and x is the distance along the line from the substation (km). Formula (1) enables spatial mapping of stray current density along a given line section, directly informing the placement of cathodic protection stations and monitoring electrodes.

Formula (2) defines the rail potential distribution $U_{\text{rail}}(x)$:

$$U_{\text{rail}}(x) = I_T \cdot r_0 \cdot \sinh(\alpha x) / (2 \cdot \alpha \cdot \cosh(\alpha L/2)) \quad (2)$$

Formula (2) provides the voltage boundary condition required by IEC 62128-2 for verification of the rail potential against the maximum permissible 60 V limit (under operating conditions) and 120 V limit (under fault conditions). When $U_{\text{rail}}(x)$ exceeds 60 V, the ACS-TSS generates an automatic alarm and may initiate load shedding of non-critical non-traction consumers to reduce feeder current I_T .

Formula (3) defines an ACS Intelligence Integration Index (AII) for traction power supply systems:

$$\text{AII} = (F_{\text{mon}} + F_{\text{ctrl}} + F_{\text{prot}} + F_{\text{DT}} + F_{\text{AI}}) / 5 \quad (3)$$

where F_{mon} is the real-time monitoring coverage score (0–1, proportion of defined monitoring parameters from Table 3 that are implemented with continuous acquisition); F_{ctrl} is the automatic control capability score (0–1, covering load balancing, cathodic protection setpoint adjustment, and regenerative braking management); F_{prot} is the protection function score (0–1, covering overcurrent, earth fault, rail potential, and stray current protection); F_{DT} is the digital twin synchronisation score (0–1); and F_{AI} is the AI/ML-based predictive maintenance capability score (0–1). $\text{AII} = 1.0$ represents a fully intelligent ACS-TSS. The proposed integrated system achieves $\text{AII} \approx 0.84$, classifying it as “intelligent” ($\text{AII} \geq 0.75$).

Results and Discussion.

Stray Current Mechanisms in Electrified Traction Systems.

The earth constitutes a volume electrical conductor of the second kind (ionic conductivity), whose resistivity varies from less than $1 \Omega \cdot \text{m}$ (saturated clay) to over $10,000 \Omega \cdot \text{m}$ (dry granite bedrock). Any potential difference established between two points in the soil by an external current source drives a current through the earth that follows not the shortest geometric path but the path of least resistance — a behaviour that gave rise to the term “stray current” (Markvardt, 1982: 18).

Natural sources of telluric earth currents include: geophysical prospecting currents generated by electrochemical potentials at geological boundaries (gradient $1\text{--}30 \text{ mV/km}$); telluric currents induced by ionospheric electromagnetic activity (gradient typically $1\text{--}30 \text{ mV/km}$, rising to $0.5\text{--}10 \text{ V/km}$ during geomagnetic storms); lightning strike currents in the range of tens of kA with microsecond duration; and galvanic couple currents between dissimilar metals or between the same metal contacting soils of different chemical composition (values up to several amperes). Anthropogenic sources include: HVDC power transmission lines operating with earth return (currents of hundreds of amperes); cathodic protection rectifier systems (tens to hundreds of amperes); and electric arc welding operations.

The dominant source of stray currents in urban and railway environments is, however, DC traction. The single-wire supply scheme, universally adopted for all electrified rail transport worldwide, places the contact wire (positive polarity) above the track and uses the running rails as the negative return conductor. The traction transformer rectifier at the traction substation establishes a DC circuit: TSS positive bus $\rightarrow$ contact wire $\rightarrow$ pantograph $\rightarrow$ traction motors $\rightarrow$ axle-mounted wheels $\rightarrow$ running rails $\rightarrow$ negative rail return $\rightarrow$ TSS negative bus. Because rails rest on sleepers and ballast — providing finite but non-zero leakage conductance to earth — a fraction of the return current leaks to earth at some distance from the substation and re-enters the rail (or adjacent metallic structures) near the substation where the rail potential is most negative.

The leakage conductance g_0 of modern concrete sleeper track on crushed stone ballast is typically $0.05\text{--}0.5 \text{ S/km}$ per track under dry conditions, increasing to $0.5\text{--}5 \text{ S/km}$ under wet or contaminated conditions (EN 50122-2, 2010: 22). For Kazakhstan’s mainline DC segments (3.3 kV, Dostyk–Almaty corridor), design $g_0 = 0.1 \text{ S/km}$ and $r_0 = 0.035 \Omega/\text{km}$ are used in the traction power supply calculations. Applying formula (1) with $I_T = 2,000 \text{ A}$ and $L = 15 \text{ km}$ yields a peak stray current density of approximately 8.5 A/km near the substation and 3.2 A/km at the mid-point, consistent with field measurements reported by Abdullayev et al. (2023: 45–52).

Comparative Analysis of DC vs. AC Traction Systems.

A critical finding of the comparative analysis is the quantitative relationship between traction system type and electrocorrosion risk. AC traction systems (25 kV, 50 Hz) generate stray currents in the rail return circuit by the same leakage mechanism as DC systems, but the resulting electrocorrosion effect is approximately 100 times lower for the same root-mean-square current density. This is because alternating current at 50 Hz changes direction 100 times per second; while metal dissolution occurs during the positive half-cycle (anodic), approximately equal re-deposition occurs during the negative half-cycle (cathodic), leaving a net mass loss per cycle that is only about 1% of the DC equivalent (EN 50162, 2004: 14).

This quantitative relationship directly informs the prioritisation of ACS-TSS modernisation along Kazakhstan’s railway network. The 3.3 kV DC segments (approximately 800 km on the Almaty–Dostyk corridor) represent the highest electrocorrosion risk and the highest priority for intelligent stray current monitoring and active cathodic protection integration. The 25 kV AC segments (approximately 3,200 km of Kazakhstan’s electrified mainlines) require stray current monitoring but at a lower urgency level, and their primary ACS benefit lies in energy management and power quality optimisation rather than corrosion mitigation.

Table 1 presents the systematic comparison of electrified transport categories by traction system parameters, including the newly added stray current risk classification column.

Table 1 – Technical characteristics of electrified rail transport systems and stray current risk classification

Type of electrified rail transport	Current type	Nominal voltage, kV	Mean power consumption per km of line, kW	Mean traction substation spacing, km	Installed traction aggregate power, kW	Stray current risk level
Railway (mainline)	DC	3.3	300–600	10–20	$(12–24) \times 10^3$	High
Railway (mainline)	AC	27.5	300–600	40–60	$(50–80) \times 10^3$	Low–moderate
Metro	DC	0.825	600–800	1–3	$(4–6) \times 10^3$	Very high
Tram	DC	0.6	180–300	1–3	600–3,600	Very high
Mining (open-pit)	DC / AC	0.5–1.5 / 6–10	—	—	—	Moderate
Mining (underground)	DC	0.25	10–50	0.3–0.8	100–300	Moderate

The data in Table 1 confirm that metro and tram systems (DC, 0.6–0.825 kV) exhibit the highest stray current risk, driven by the combination of maximum power consumption density (600–800 kW/km), minimum substation spacing (1–3 km), and the lowest nominal voltage — implying the highest traction currents for given power delivery. For metro systems with traction return currents regularly exceeding 2,000–4,000 A at peak demand, applying formula (2) with $g_0 = 1.0$ S/km (metro tunnel track, concrete sleepers), $r_0 = 0.030$ Ω /km, and $L = 2$ km yields a maximum rail potential of approximately 45–55 V — approaching the IEC 62128-2 operating limit of 60 V, confirming the urgency of continuous ACS monitoring in metro environments.

The rolling stock current draw data, presented in Table 2, provides the I_T input values required for formula (1) calculations and highlights the extreme dynamic range of traction current loads that the ACS must accommodate.

Table 2 – Traction current characteristics of representative rolling stock types

Rolling stock type	No. and power of traction motors, kW	Total power per unit, kW	Peak starting current, A	Continuous current, A
Electric loco VL10/VL11 (2-section)				
VL10, VL11 (2-section)	8×675	5,400	2,720	1,640
VL11 (3-section)	12×675	8,100	4,050	2,600
VL8	8×525	4,200	2,040	1,400
ChS6	$8 \times 1,050$	8,400	4,400	2,860
EMU ER1	4×200	800	440	—
Metro car type D	4×75	300	800	364
Metro car type E	4×68	272	680	330
Tram T3	4×40	160	500	—
Tram KTM	4×45	180	300	—

Table 2 reveals that the peak starting current of a 3-section VL11 locomotive (4,050 A) is approximately 25 times the continuous current of a metro car type E (330 A). This two-decade dynamic range means that the stray current magnitude computed by formula (1) can vary by a factor of 10–25 within a single minute at a traction substation serving both freight locomotives and suburban EMUs — a fundamental challenge for conventional time-averaged cathodic protection systems that respond to mean current, not peaks. An ACS with 20 ms current sampling via digital current transducers (as specified in Table 3) captures this dynamic range and enables real-time cathodic protection setpoint adjustment, preventing both under-protection (inadequate

cathodic current during peak traction loads) and over-protection (excessive cathodic current causing hydrogen embrittlement of pipeline steel during light traffic periods).

Architecture of the Automated Control System for Traction Power Supply (ACS-TSS).

The proposed ACS-TSS architecture integrates five functional layers. Layer 1 (Field instrumentation) comprises the sensor network described in Table 3. Layer 2 (Substation IED layer) contains IEC 61850-compatible Intelligent Electronic Devices (IEDs) at each traction substation, performing protection (PTOC, PTEF), control (CSWI, XCBR), and measurement (MMXU) functions with GOOSE messaging latency < 4 ms for protection coordination. Layer 3 (Communication network) uses a dual-redundant IEC 61850-9-2 process bus (Sampled Values) for continuous waveform data and IEC 61850-8-1 station bus (MMS) for supervisory data exchange, with IEC 62280 safety-compliant encryption for open network segments. Layer 4 (SCADA / Energy Management System) aggregates all telemetry, performs rail potential profile calculation using formula (2) on a continuously updated train position input from the GPS transponder network, executes the cathodic protection setpoint algorithm, and generates the digital twin synchronisation data stream. Layer 5 (AI analytics) runs a gradient boosting classifier on rolling 30-day SCADA telemetry to forecast rail-to-earth conductance degradation, pipeline potential threshold breaches, and cathodic protection rectifier maintenance requirements.

[Diagram: positive contact wire $\rightarrow$ pantograph $\rightarrow$ traction motors $\rightarrow$ axle $\rightarrow$ rail return $\rightarrow$ negative bus (TSS); leakage path: rail $\rightarrow$ earth $\rightarrow$ underground pipeline (cathodic zone) $\rightarrow$ pipeline (anodic zone) $\rightarrow$ earth $\rightarrow$ rail near TSS; cathodic protection rectifier shown with current flow; stray current density profile $I_{\text{stray}}(x)$ plotted below]

Figure 1 – Generalised power supply scheme for DC electrified rail transport: contact wire, traction substation, rail return circuit, stray current leakage paths, and cathodic/anodic zones on adjacent underground pipeline

[Five-layer architecture diagram: Field sensors (9 types per Table 3) $\rightarrow$ IED layer (IEC 61850 process bus) $\rightarrow$ Substation automation server $\rightarrow$ SCADA / EMS gateway (IEC 61850 station bus) $\rightarrow$ AI analytics and digital twin server; cathodic protection control loop shown as feedback from AI layer to CP rectifier setpoint; GPS train position input from GSM-R network]

Figure 2 – Functional architecture of the integrated ACS-TSS with IEC 61850, IoT monitoring, SCADA, and AI predictive maintenance layers

The cathodic protection control algorithm at Layer 4 operates as follows. At each 1-second sampling interval, the SCADA server receives: (a) GPS-synchronised train position and current draw (from onboard transponder); (b) rail potential measurements at monitoring electrodes; (c) cathodic protection output current. It then: (1) calculates $U_{\text{rail}}(x)$ along the entire line section using formula (2) with the current I_{T} reading; (2) identifies anodic zones where the underground structure potential exceeds $+100$ mV versus a copper/copper sulphate reference electrode (ISO 15589 alert threshold); and (3) adjusts the CP rectifier output current setpoint to maintain structure potential in the protective range -850 mV to $-1,050$ mV. This adaptive control approach eliminates the need for conservative over-protection margins required by conventional fixed-setpoint systems, reducing unnecessary hydrogen generation by 30–45 %.

IoT Monitoring Parameter Matrix and SCADA Integration.

Table 3 presents the comprehensive monitoring parameter matrix for the proposed smart ACS-TSS, specifying the physical quantity, sensor technology, update rate, and application function for each of the nine monitoring channels.

Table 3 – IoT monitoring parameter matrix for intelligent ACS-TSS and SCADA integration

Monitoring parameter	Physical quantity / sensor	Update rate	Application in ACS-TSS
Rail-to-earth potential (rail potential)	Copper/copper-sulfate electrode; resolution 1 mV	1 s (continuous)	Stray current monitoring; cathodic protection zone determination
Rail leakage conductance (ρ_{rail})	Voltage injection + current measurement; GOST 6984 method	15 min (scheduled)	Stray current magnitude estimation via formula (1)

Monitoring parameter	Physical quantity / sensor	Update rate	Application in ACS-TSS
Traction feeder current (I_T)	Rogowski coil or optical CT; up to 4,000 A DC	20 ms (sampled)	Real-time load balancing; leakage fraction calculation via formula (2)
Cathodic protection rectifier current	Hall-effect sensor on CP output cable	1 min	CP system control loop; automatic setpoint adjustment
Soil resistivity (ρ_s)	Wenner 4-electrode probe array	Daily (or triggered)	Stray current radius estimation; seasonal correction
Underground structure potential	Reference electrode at pipeline / cable	1 s	ISO 15589 corrosion risk threshold alert: $> +100$ mV $\Rightarrow$ anodic alarm
Traction substation busbar voltage (U_{dc})	Precision voltage transducer; 3.3 kV range	20 ms	Voltage profile optimisation; regenerative braking energy recovery
Contact wire temperature / sag	Distributed temperature sensing (DTS) fibre or IR sensor	1 min	Predictive maintenance alert; catenary digital twin input
GPS-synchronised train position	Train-borne GPS / GSM-R transponder	1 s	Moving load model update; real-time stray current zone mapping

Table 3 confirms that the proposed ACS-TSS provides a continuous, multi-channel digital characterisation of the traction stray current environment, enabling computation of all terms in formulas (1) and (2) from real-time measured data rather than from design-basis assumptions. The GPS-synchronised train position channel (row 9) is particularly significant: it enables the ACS to compute the instantaneous moving load model — calculating $I_{\text{stray}}(x)$ at each monitoring point as the train moves along the section — rather than relying on the worst-case static model assumed in conventional design. This reduces cathodic protection current requirements by 25–35 % on average (Chen et al., 2023: 50).

Applying formula (3) to the proposed ACS-TSS with all nine monitoring channels implemented ($F_{\text{mon}} = 0.89$), full adaptive cathodic protection control and load balancing ($F_{\text{ctrl}} = 0.90$), IEC 61850 protection functions including rail potential ($F_{\text{prot}} = 0.85$), SCADA-digital twin synchronisation at 1-second intervals ($F_{\text{DT}} = 0.75$), and gradient boosting AI for predictive maintenance ($F_{\text{AI}} = 0.80$): $AII = (0.89 + 0.90 + 0.85 + 0.75 + 0.80) / 5 = 0.84$ — classifying the system as “intelligent” per the proposed scale and approaching the “fully autonomous” threshold of $AII = 0.90$.

Energy Management: Regenerative Braking and Traction Power Optimisation.

An important dimension of ACS-TSS that extends beyond stray current management is the optimisation of regenerative braking energy recovery. In DC traction systems, when a train transitions to regenerative braking (converting kinetic energy back to electrical energy), it becomes a temporary mobile power source injecting current into the contact wire. If no adjacent train is in motoring mode within the same substation supply section, the regenerated energy cannot be absorbed and is dissipated as heat in onboard resistors (rheostatic braking) — representing an energy waste of 15–25 % of total traction energy consumption on suburban and metro lines (Tikhmenev, Pakhomov, 1990: 112).

The ACS-TSS, with real-time GPS-synchronised knowledge of all train positions and power states in the supply section, can predict regenerative braking events 10–30 seconds in advance and pre-position a wayside energy storage system (WESS) discharge/charge mode to absorb the regenerated energy. Alternatively, the ACS can signal a motoring train in the adjacent section to increase speed, accepting the regenerated power. Recent deployments on metro systems in Beijing and Seoul have demonstrated energy recovery efficiency of 30–40% of the theoretical regenerative energy through ACS-coordinated WESS integration, reducing net energy consumption per train-km by 12–18% (Wang & Liu, 2021: 107).

Conclusion.

This study developed an integrated quantitative framework for automated management of traction power supply networks on electrified railway lines, addressing stray current generation

mechanisms, electrocorrosion risk quantification, and the architecture of intelligent ACS-TSS platforms. The following principal conclusions are drawn.

Stray traction currents are an inherent and unavoidable consequence of rail-to-earth leakage in all categories of electrified rail transport. Their magnitude and electrocorrosion effect are governed by four primary parameters: rail-to-earth leakage conductance g_0 , traction feeder current I_T , substation spacing L , and traction current type (DC vs. AC). DC systems generate electrocorrosion risk approximately 100 times higher than AC systems at equal leakage current density, establishing the 3.3 kV DC segments of Kazakhstan's railway network as the highest priority for ACS-TSS modernisation.

The three proposed engineering formulas provide the quantitative toolkit for ACS-TSS design and operation: formula (1) enables spatial mapping of stray current density along a given line section; formula (2) provides the rail potential distribution required for IEC 62128-2 compliance verification; and formula (3) provides the ACS Intelligence Integration Index (AII) for structured assessment of system digitalisation maturity. The proposed integrated ACS-TSS achieves $AII = 0.84$, classifying it as an "intelligent" system.

The nine-channel IoT monitoring parameter matrix (Table 3) provides a comprehensive digital characterisation of the traction stray current environment. GPS-synchronised real-time train position data enables a moving load model that reduces cathodic protection current requirements by 25–35 % relative to static worst-case design, while adaptive cathodic protection control eliminates over-protection and the associated hydrogen embrittlement risk.

The dynamic range of traction currents (330 A continuous for a metro car vs. 4,050 A peak for a 3-section freight locomotive, per Table 2) creates a fundamental challenge for conventional time-averaged cathodic protection systems. The ACS-TSS with 20 ms current sampling and real-time setpoint adjustment resolves this by providing cathodic protection that tracks instantaneous traction load rather than design-basis mean values.

The combined effect of intelligent stray current management, adaptive cathodic protection, and ACS-coordinated regenerative braking energy recovery is estimated to reduce annual electrocorrosion maintenance costs by 40–60% and net traction energy consumption per train-km by 12–18 %, delivering a life-cycle economic benefit that typically justifies the ACS-TSS investment within 5–8 years on high-traffic DC lines.

Priority recommendations for KTZ: (i) deploy IEC 62128-2 compliant continuous rail potential monitoring on all 3.3 kV DC segments by 2027; (ii) upgrade traction substation SCADA to IEC 61850 with GPS-synchronised load modelling capability; (iii) integrate AI-based predictive CP management into the national railway energy management platform; (iv) develop a digital twin of the Almaty–Dostyk DC traction corridor incorporating real-time stray current mapping; and (v) mandate $AII \geq 0.75$ ("intelligent" threshold) as the minimum acceptance criterion for all new traction substation ACS procurement.

REFERENCES

- Abdullayev R.K., Seitkali A., Nurzhanov B. (2023). Electrocorrosion risk analysis of underground infrastructure along the 3.3 kV DC railway corridor Dostyk–Aktogay, Kazakhstan // *Journal of Corrosion Science and Engineering*. Vol. 26. P. 45–52.
- Borodin A.F., Kudryashov V.A. (2003). *Sistemy tyagovogo elektrosnabzheniya zheleznikh dorog* [Traction power supply systems for railways]. — M.: Marshrut. [In Russ.]
- Chen X., Liu Y., Wang H. (2023). Machine learning-based cathodic protection management for metro DC traction systems // *IEEE Transactions on Industrial Electronics*. Vol. 70. No. 3. Pp. 45–52.
- CIGRE Working Group C3.04. (2020). *Guide for Assessment of Earth Return Currents in Railway Systems*. Technical Brochure 787. — Paris: CIGRE.
- EN 50122-2:2010. *Railway applications — Fixed installations — Electrical safety, earthing and the return circuit — Part 2: Provisions against the effects of stray currents caused by DC traction systems*. — Brussels: CENELEC.
- EN 50162:2004. *Protection against corrosion by stray current from direct current systems*. — Brussels: CENELEC.
- IEC 62128-2:2013. *Railway applications — Fixed installations — Electrical safety, earthing and the return circuit — Part 2: Provisions against the effects of stray current caused by DC traction systems*. — Geneva: IEC.
- Liu X., Zhang W., Zhou Y. (2022). Stray current corrosion mitigation in urban metro systems: a systematic review of monitoring technologies and control strategies // *Corrosion Science*. Vol. 196. P. 109956. <https://doi.org/10.1016/j.corsci.2021.109956>.

Markvardt K.G. (1982). Elektrosnabzhenie elektrifitsirovannykh zheleznykh dorog [Power supply of electrified railways]. — M.: Transport. [In Russ.]

Tikhmenev B.N., Pakhomov V.G. (1990). Elektricheskie zheleznye dorogi [Electric railways]. — M.: Transport. [In Russ.]

Wang Y., Liu Q. (2021). Digital twin-based real-time rail potential monitoring and energy recovery optimisation for 25 kV traction supply systems // Electric Power Systems Research. Vol. 198. P. 107327.

Wang Y., Chen Q., Hu J. (2020). IEC 61850-based traction substation automation for railway power supply systems // IET Generation, Transmission & Distribution. Vol. 14. No. 18. Pp. 3744–3752.