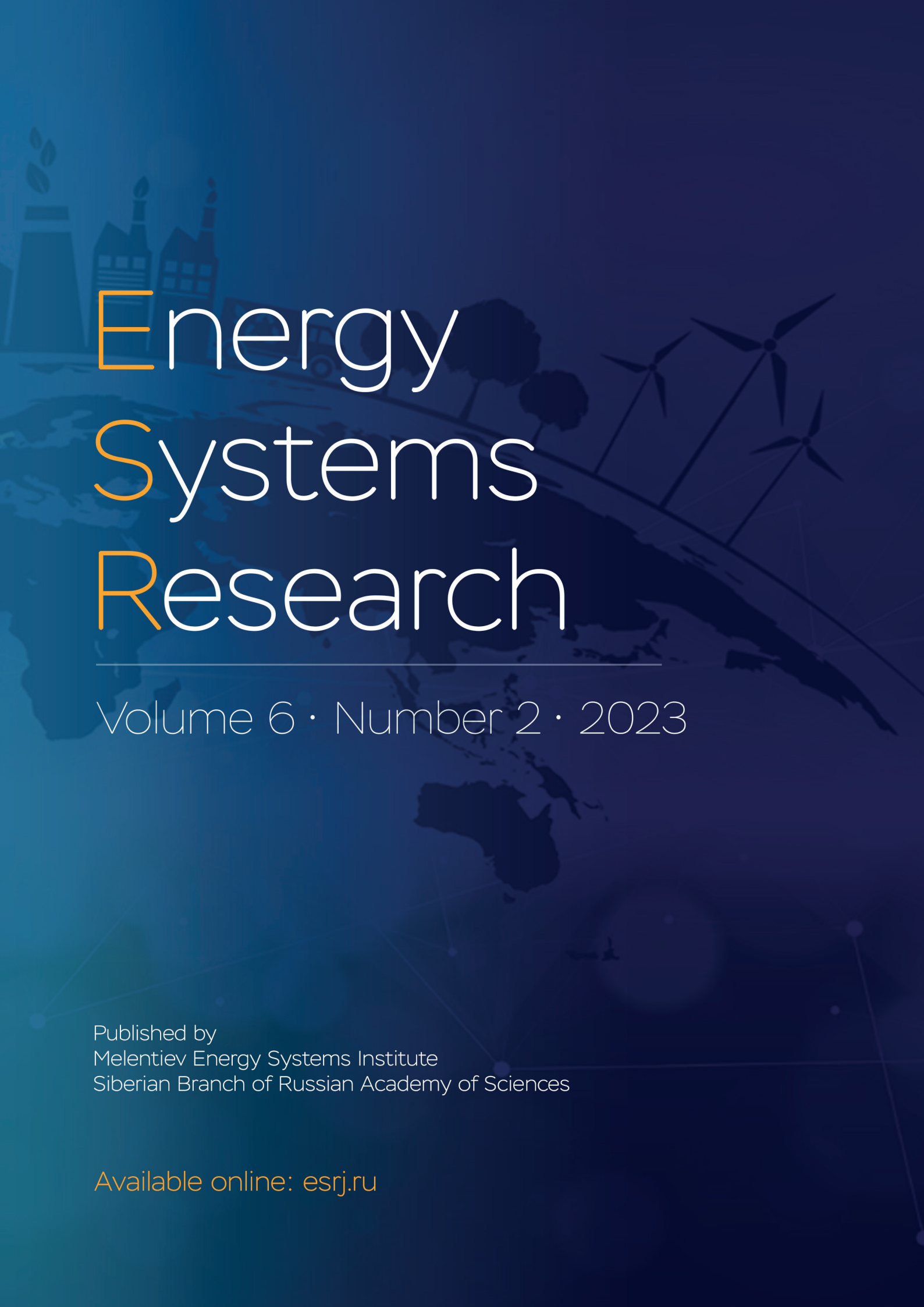




Energy Systems Research

Volume 6 · Number 2 · 2023

Published by
Melentiev Energy Systems Institute
Siberian Branch of Russian Academy of Sciences

Available online: esrj.ru

ISSN 2618-9992

Energy Systems Research

Volume 6 • Number 1 • 2023

International scientific peer-reviewed journal

Available online: <http://esrj.ru>

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Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

Energy systems research methodology is based on a systems approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of systems analysis.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

The journal welcomes papers on advances in heat and electric power industries, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technologies.

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The journal is published by Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences. The journal's ISSN is 2618-9992. There are 4 issues per year (special issues are available). All articles are available online on English as Open access articles.

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Cost Analysis of an Optimized Hybrid Energy System for a Remote Area in St. John's, NL

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Abstract — In the current energy field scenario, hybrid energy, combining both conventional and non-conventional energy, plays a significant role. With the development of technology, this new energy category has gained popularity due to its efficiency and cost-effectiveness, especially in remote places where the primary grid is located far away. This research puts forth an optimum design of a PV-diesel hybrid energy system for analysis of a remote off-grid power system in St. John's, Newfoundland, Canada, using HOMER (Hybrid Optimization Model for Electric Renewables) software. The study involves connecting a diesel generator and a PV solar panel to the bus. To ensure uninterrupted load distribution, batteries are combined as storage. A technical and economic study of the hybrid energy system is conducted by simulation through HOMER. The levelized energy cost is expected to be lower under the proposed arrangement.

Index Terms: hybrid energy, HOMER, COE, energy production, fuel consumption.

I. INTRODUCTION

Because St. John's has long relied on diesel generators to generate electricity, many residents feel excluded from upcoming developments. Furthermore, the high amount of fuel burnt has led to greenhouse gas emissions harming the environment and the health of the locals. Fossil fuel prices rise, therefore, renewable energy is necessary to produce the electrical supply. The increasing use of renewable energy connected to the grid poses considerable challenges because of its erratic power delivery. If we want to ensure a constant supply of electricity to the system, we must

discover better techniques to store energy. Due to its capacity to store energy and the potential for energy transportation, solar energy is the ultimate energy source. Since a few years ago, shifting to Renewable Energy System (RES) has been necessary to meet the world's energy needs because of rising environmental concerns caused by the depletion of fossil fuels. The deployment of RES in the commercial, industrial, and residential sectors has been drawn by its eco-friendliness, scalability, and other significant qualities. The power system's operation and control are now more unpredictable due to the ongoing trend of integrating RES. Additional resources are needed to sustain RES because of its sensitivity to unpredictable weather conditions. Energy Storage Systems (ESS) are a need in this situation as one of the many resources to assist RES penetration. The capacity of ESS, however, is constrained in terms of meeting all application needs. Therefore, a possible approach is the hybridization of several ESS to create a composite ESS. Power sharing control is essential to use the complementing qualities of each ESS while integrating them. The notable challenges faced during the integration of RES are voltage instability, load discrepancy, frequency fluctuation, poor power quality, and load-following [1]. A possible way to get around these restrictions and enable the grid to run steadily is to incorporate ESS. By integrating ESS and RES into the microgrid, power fluctuations can be avoided, power quality can be improved, frequency regulation can be enhanced, and more ancillary services may be available [2]. ESS plays a significant role in the advancement of electric energy systems and extends RES to remote power locations around the globe [3–6]. Renewable energy power generators require high initial investments and relatively low operating costs. The most important costs are generated by the battery park and then come the photovoltaic panels. The hybrid PV/wind/diesel/hydropower system is profitable if the distance from the village to the transformer station is greater than 1.90 km [7]. In many cases, hybrid energy systems have been shown to drastically lower the overall lifespan cost of stand-alone power supplies while also supplying a more dependable source of electricity thanks to the mix of energy sources [8–10].

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<http://dx.doi.org/10.25729/esr.2023.02.0001>

Received March 06, 2023. Revised April 11, 2023.

Accepted May 03, 2023. Available online June 10, 2023.

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II. METHODOLOGY

A. Description of Proposed Hybrid Energy System

Hybrid Energy: Hybrid energy combines different power and energy systems. A standard hybrid power system combines nonconventional energy, e.g., solar energy, wind energy, hydro energy, etc., with another energy source, such as diesel energy, fuel cell, battery storage system, etc., to meet the required load demand.

Photovoltaics: Photovoltaics (PV) convert light into electricity using semiconducting materials exhibiting photovoltaic effects. PV is famous for generating electricity commercially with no pollution. Solar modules of many solar cells are used in a photovoltaic system to produce electricity. PV installations can be floating, wall-mounted, rooftop-mounted, or ground-mounted.

Diesel Generator: Diesel generator combines a diesel engine with an electric generator to generate electrical energy. Diesel generating sets are used in places without connection to a power grid or as an emergency power supply if the grid fails, as well as for more complex applications such as peak-opping, grid support, and export to the power grid.

Converter: An electrical or electromechanical device for

converting electrical energy is called a power converter. A power converter can adjust the voltage or frequency of the current, convert alternating current (AC) into direct current (DC), or do any combination of these things. A power converter could be as straightforward as a transformer or incredibly sophisticated, as a resonant converter. The term can also be used to describe a group of electrical devices that change the frequency of an alternating current. Voltage regulation and redundant components are frequently used in power conversion systems.

Storage: Energy storage is the process of storing energy produced at one moment for use at a later period in order to balance out the imbalance between energy production and demand. An accumulator or battery is a term used to describe a device that stores energy. There are several different types of energy, including kinetic, latent heat, gravitational potential, chemical, electricity, and radiation. Energy storage is the process of transforming energy from forms that are challenging to store to forms that are easier or more practical to store.

B. Description of Designing Tool

HOMER (Hybrid Optimization Model for Electric Renewables) is a specialized tool for microgrid electrical

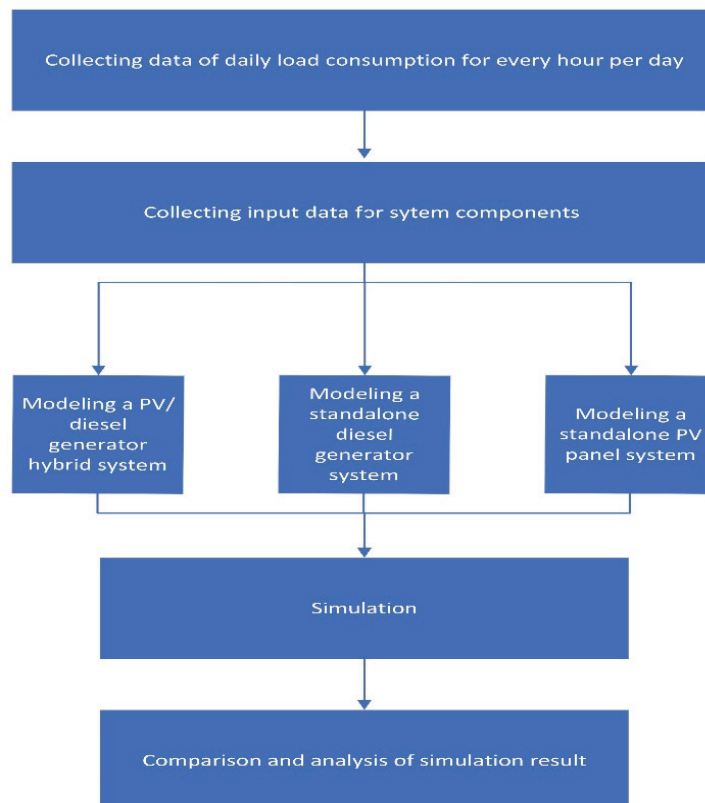


Fig. 1. Research methodology flowchart.

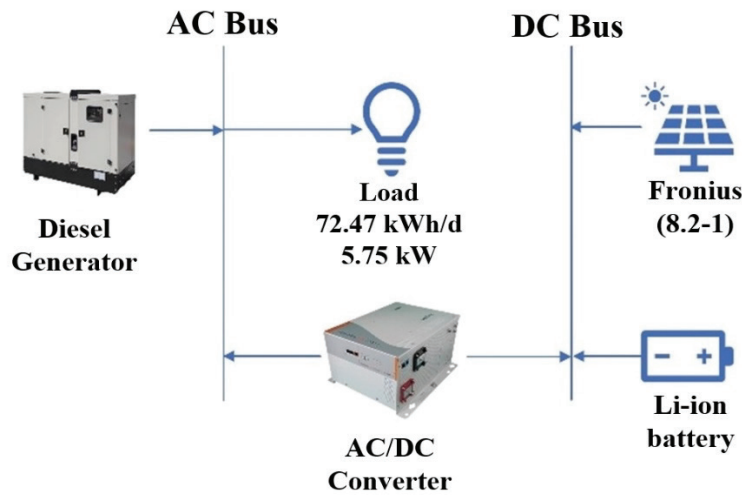


Fig. 2. Schematic diagram.

TABLE 1. Load Profile of January

Hour	Load (kWh)
0	3.4
1	3.3
2	3.3
3	3.2
4	3.1
5	3.1
6	3
7	3
8	2.93
9	2.88
10	2.83
11	2.8
12	2.77
13	2.74
14	2.73
15	2.68
16	2.63
17	2.6
18	2.58
19	3.2
20	3.3
21	3.4
22	3.5
23	3.5

power systems' design, modeling, optimization, and sensitivity analysis. HOMER navigates the complexities of building cost-effective and reliable hybrid microgrid and grid-connected systems that combine traditionally generated and renewable power, storage, and load management. This program was used to study and design hybrid energy systems utilizing both renewable and nonrenewable energy sources.

C. Step-by-Step Process

To conduct this study, we first demonstrated a load

profile for a house in St. John's, NL, with a 72.47 kWh/day and peak load of 5.75 kW in 24 hours for the month of January as January is the month when the electricity consumption is the highest in this region. After setting up the load profile, all the data for the equipment and machinery were obtained to connect with the load. After connecting the whole set up, three simulations were executed based on three different scenarios. One with the proposed hybrid model where the load is connected to the PV panel, diesel genset, and Li battery, one with the standalone diesel genset, which is considered as the base case, and the third simulation was with the standalone PV panel. The numerical results of all these simulations were analyzed and compared to obtain the best possible case with the lower Cost of Energy (COE). After the analysis, the case of standalone PV panel was eliminated as the generation of electricity was minimum.

D. Schematic Diagram

In the proposed system, a PV panel is connected to the load through a DC bus, and the conventional source, i.e., the diesel genset, is connected to the load through an AC bus. For storage and power backup purpose, a Li battery is connected to the DC bus. To convert alternating current to direct current and vice versa, a converter is also connected to the whole system. Upon gathering all the necessary data through HOMER, relevant graphs and results are generated and then used to analyze the expected result.

A load consumes energy from the microgrid. A primary load can model anything that uses electricity, such as a light bulb or a motor. Primary load is the electrical load that the system must meet immediately in order to avoid unmet load. At first, the load profile of the peak month (January) of St. John's was set up using the average hourly energy consumption of 3 kW [11].

After setting up the load profile, the data of solar Global Horizontal Irradiance (GHI) was required, which was obtained from HOMER through NASA Prediction of



Fig. 3. Solar GHI data.

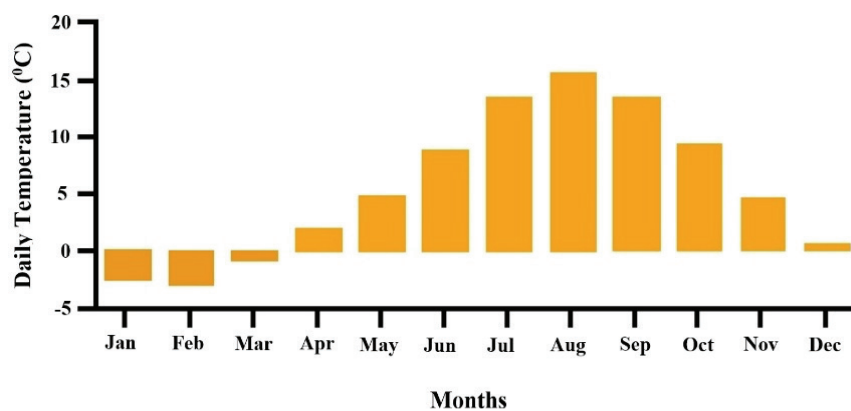


Fig. 4. Monthly average temperature.

TABLE 2. Specification of Converter

Description	Specification
Capacity	1 kW
Capital cost	300 \$
O&M cost	60 \$
Lifetime	15 years

TABLE 5. Specification of Generator

Description	Specification
Fuel	Diesel
Capital cost	500 \$
O&M cost/hr	0.03 \$
Lifetime	90 000 hrs
Minimum load ratio	30

TABLE 3. Specification of PV

Description	Specification
Capacity	8.25 kW
Capital cost	3 000 \$
O&M cost	10 \$
Lifetime	25 years

TABLE 6. Cost Summar

Description	Base Case (\$)	BI
Initial Capital	3 200	47 158
O&M	27 652/yr	18 005/yr
COE	1.05/kWh	0.819/kWh

TABLE 4. Specification of Storage

Description	Specification
Capacity	1 kW
Nominal voltage	6 V
Capital cost	550 \$
O&M cost	10 \$
Lifetime	15 years

TABLE 7. Economic Metrics

Description	Specification
IRR	23%
ROI	17.9%
Simple payback	4.1 years
Minimum load ratio	30

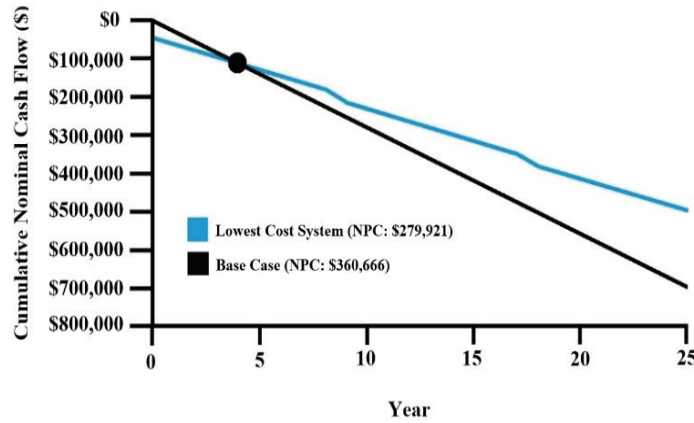


Fig. 5. Hybrid system project break-even graph.

Worldwide Energy Resource (POWER) database. GHI is the total solar radiation incident on a horizontal surface. It is the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance, and ground-reflected radiation. HOMER uses Solar GHI to compute flat-panel PV output. Solar GHI resource is used to calculate flat panel PV array output.

In addition, the monthly average temperature data was required, which was obtained from HOMER through NASA Surface Meteorology and Solar Energy database.

E. Specifications of Components

Converter: A generic 1 kW converter was selected as PV panel for the intended system. The specification (from HOMER) of the converter is given below.

PV: Fronius Primo 8.2-1 PV panel was selected for the intended system. The specification (from HOMER) of the PV is given below.

Storage: A 1kWh Li-Ion battery was selected as the storage for the intended system. The specification (from HOMER) of the storage is given below.

Generator: An auto-genset was selected as the fuel generator for the intended system. The specification of the generator is given below.

F. Numerical Analysis

The Project lifetime is the length of time over which the costs of the system occur. HOMER uses the project lifetime to calculate annualized costs from net present costs. HOMER assumes that salvage values occur at the end of the project lifetime. In this proposed project, the project lifetime is 25 years. The simple payback period at the point where the lower cost system case and the base case intersect each other in the project lifetime curve is 4.1 years.

The initial capital cost of a component is the total installed cost of that component at the beginning of the project. The Operation and Maintenance (O&M) cost of a component is the cost associated with operating and maintaining that component. The total O&M cost of the system is the sum of the O&M costs of each system

component. The annualized cost of producing electricity (i.e., the total annualized cost less the cost of supplying the thermal load) is divided by the total electric load provided by HOMER to determine the COE:

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}}, \quad (1)$$

where $C_{ann,tot}$ – total annualized cost of the system [\$/yr]; C_{boiler} – boiler marginal cost [\$/kWh]; H_{served} – total thermal load served [kWh/yr]; E_{served} – total electrical load served [kWh/yr].

The Return on Investment (ROI) is the yearly cost savings relative to the initial investment. HOMER calculates the return on investment with the following equation:

$$ROI = \frac{\sum_{i=0}^{R_{proj}} C_{i,ref} - C_i}{R_{proj} (C_{cap} - C_{cap,ref})}, \quad (2)$$

where, $C_{i,ref}$ – nominal annual cash flow for base (reference) system; C_i – nominal annual cash flow for current system; R_{proj} – project lifetime in years; C_{cap} – capital cost of the current system; $C_{cap,ref}$ – capital cost of the base (reference) system.

The ROI is the average yearly difference in nominal cash flows over the project lifetime divided by the difference in capital cost.

Internal Rate of Return (IRR) is the discount rate at which the base case and current system have the same net present cost. HOMER calculates the IRR by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero. The Return on Investment (ROI) is the yearly cost savings relative to the initial investment. The ROI is the average yearly difference in nominal cash flows over the project lifetime divided by the difference in capital cost. Simple payback is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The

TABLE 8. Comparative Economics of Hybrid System

Metric	Value
Present worth (\$)	80 745
Annual worth (\$/yr)	6 246
ROI (%)	17.9
Internal rate of return (%)	23
Simple payback (yr)	4.07
Discount payback	4.79

TABLE 9. Fuel Consumption for Hybrid System

Description	Value	Units
Total fuel consumed	3 179	l
Average fuel per day	8.71	l/day
Average fuel per hour	0.363	l/hr

TABLE 10. Fuel Consumption for Base Case

Description	Value	Units
Total fuel consumed	9 412	l
Average fuel per day	25.8	l/day
Average fuel per hour	1.07	l/hr

TABLE 11. Emissions from Base case

Description	Value	Units
Carbon dioxide	24 637	kg/yr
Carbon monoxide	155	kg/yr
Unburned hydrocarbons	6.78	kg/yr
Particulate matter	0.941	kg/yr
Sulfur dioxide	60.3	kg/yr
Nitrogen oxides	146	kg/yr

TABLE 12. Emissions from Hybrid System

Description	Value	Units
Carbon dioxide	8 321	kg/yr
Carbon monoxide	52.5	kg/yr
Unburned hydrocarbons	2.29	kg/yr
Particulate matter	0.318	kg/yr
Sulfur dioxide	20.40	kg/yr
Nitrogen oxides	49.3	kg/yr

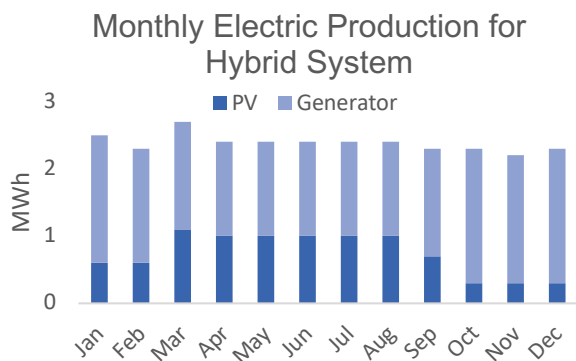


Fig. 6. Monthly electric production for the hybrid system.

payback indicates how long it would take to recover the difference in investment costs between the current system and the base case system.

The present worth is the difference between the net present costs of the base case system and the current system. The sign of the present worth indicates whether the current system compares favorably as an investment option with the base case system: A positive value indicates that the current system saves money over the project lifetime compared to the base case system. The present value is the current equivalent value of a set of future cash flows, taking into account the time value of money. The Annual worth is the present worth multiplied by the capital recovery factor. The total annualized cost is the annualized value of the total net present cost. HOMER calculates the total annualized cost using the following equation:

$$C_{ann,tot} = CFR(i, R_{proj} \cdot C_{NPC,tot}), \quad (3)$$

where $CFR()$ – a function returning the capital recovery factor; $C_{NPC,tot}$ – the total net present cost [\$]; i – the annual real discount rate [%]; R_{proj} – the project lifetime [yr].

Payback is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system. The Simple payback is where the nominal cash flow difference line crosses zero. The Discounted payback is where the discounted cash flow difference line crosses zero.

The total electrical production is the total amount of electrical energy produced by the power system in one year. It is the sum of the electrical energy produced by all components of the system. From the simulation, it is obtained that for a standalone diesel generator, the generation of electricity from the generator is 26 606 kWh/yr. The amount of excess electricity generated is 0.582%, i.e., 155 kWh/yr.

The specific fuel consumption is the average amount of fuel consumed by the generator per kWh of electricity it generates. HOMER calculates the specific fuel consumption using the following equation:

$$F_{spec} = \frac{F_{tot}}{E_{gen}}, \quad (4)$$

where F_{tot} – total annual generator fuel consumption [l/yr, m³/yr, or kg/yr]; E_{gen} – total annual electrical production of the generator [kWh/yr].

Table 9 and Table 10 indicate the fuel consumption data for both the base case and the proposed hybrid system.

HOMER calculates the emission factor (kg of pollutant emitted per unit of fuel consumed) for each pollutant prior to modelling the power system. After the simulation, it multiplies the emission factor by the value of total annual fuel used to determine the pollutant's annual emissions. HOMER employs three principal assumptions to calculate

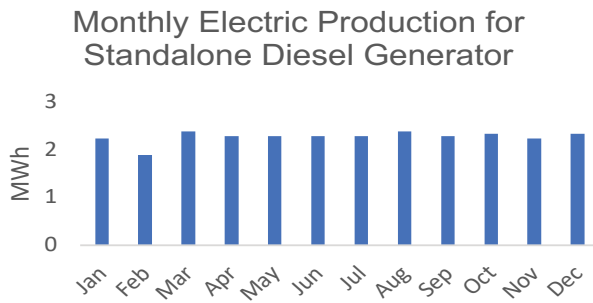


Fig. 7. Monthly electric production for standalone diesel generator.

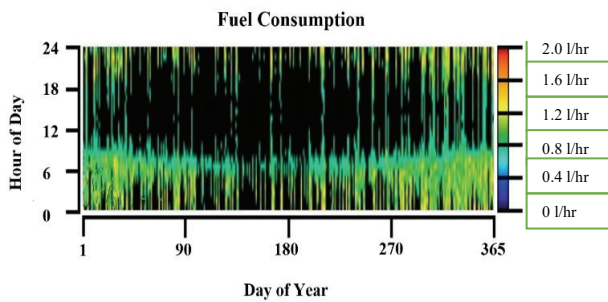


Fig. 8. Fuel consumption for hybrid system.

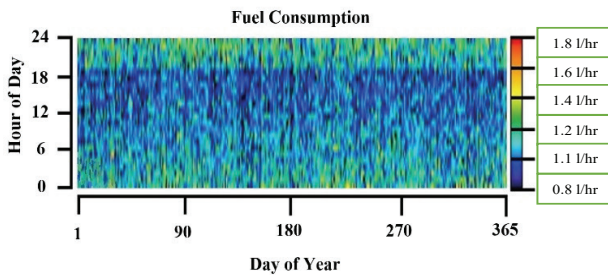


Fig. 9. Fuel consumption for base case.

emission factors of carbon dioxide and sulfur dioxide.

1. Any carbon in the fuel, which is not emitted as carbon monoxide or unburned hydrocarbons, is emitted as carbon dioxide.

2. The carbon fraction of the unburned hydrocarbon emissions is the same as that of the fuel.

3. Any sulfur in the burned fuel, which is not emitted as particulate matter, is emitted as sulfur dioxide.

III. RESULTS AND DISCUSSIONS

A. COE

Table 6 indicates that the O&M cost and the COE for the base case (a diesel generator standalone system) are 27 652\$/yr and 1.05\$/kWh, respectively and those for the proposed hybrid system (a PV/diesel generator system) are \$18 005/yr and \$0.819/kWh, respectively. The scenario where the hybrid system is a combination of PV panels, a battery bank, and a diesel generator delivers the lowest COE, according to the results of the numerous investigated scenarios.

B. Electricity Production

From the simulation of the intended hybrid system, we obtain that electricity generated from the PV is 35.3%, which is 10 681 kWh/yr, and that from the generator is 64.7%, which is 19 592 kWh/yr. The excess electricity generated is 4.35%, which is 1 318 kWh/yr.

From the simulation of a standalone diesel generator, we obtain that electricity produced from the generator is 26 606 kWh/yr. The excess electricity generated is 0.582%, which is 155 kWh/yr.

According to the outcomes of the multiple analyzed scenarios, the hybrid system that combines PV panels, a battery bank, and a diesel generator produces the most electricity.

C. Fuel Consumption

The total fuel consumption for the base case is 9 412 l, and average daily fuel consumption is 25.8 l. The same parameters for the proposed hybrid system are 3 179 l and 8.71 l, respectively, which is 66 % less than the base case.

D. Emissions

As seen in Table 11, emissions of carbon dioxide, carbon monoxide, unburned hydrocarbons, and sulfur dioxide for the standalone diesel generator are 24 637 kg/yr, 155 kg/yr, 6.78 kg/yr, and 60.3 kg/yr, respectively.

According to Table 12, for the proposed hybrid system combining PV panel and diesel generator, the emissions of carbon dioxide, carbon monoxide, unburned hydrocarbons, and sulfur dioxide are 8 321 kg/yr, 52.5 kg/yr, 2.29 kg/yr, and 20.4 kg/yr, respectively.

A comparison of both tables suggests that with the proposed hybrid system, the emissions of carbon dioxide, carbon monoxide, unburned hydrocarbons, and sulfur dioxide are on average 61% less than those of the base case with the standalone diesel generator.

IV. CONCLUSION

This study aims to electrify outlying areas in St. John's, Newfoundland and Labrador, with a hybrid system that combines solar energy with a diesel generator, and a battery bank. Different situations have been examined to determine the best configuration that achieves the lowest cost of electricity production. This study and optimization employed HOMER software. The results obtained suggest that the optimum scenario, which yields the lowest COE, is the one that combines PV panels, a diesel generator, and battery units. The hybrid system's COE is \$0.819/kWh. Because of the low use of diesel fuel, carbon dioxide emissions are regarded as low. Two other situations were also examined. The COE for the standalone diesel generator was \$1.05/kWh. However, implementing such hybrid systems might be more acceptable when taking into account off-grid regions and addressing environmental considerations. In conclusion, the hybrid PV/diesel generator system has a lot of promise for application in electrifying remote off-grid areas. These hybrid renewable

energy systems benefit the environment by using less diesel and emitting less carbon dioxide. Although the analysis in this study was done for a location in St. John's, the findings can be applied to any region with about the same characteristics.

V. NOMENCLATURE

$C_{ann,tot}$ – total annualized cost of the system [\$/yr];
 C_{boiler} – boiler marginal cost [\$/kWh];
 H_{served} – total thermal load served [kWh/yr];
 E_{served} – total electrical load served [kWh/yr];
 $C_{i,ref}$ – nominal annual cash flow for base (reference) system;
 C_i – nominal annual cash flow for current system;
 R_{proj} – project lifetime [yr];
 C_{cap} – capital cost of the current system;
 $C_{cap,ref}$ – capital cost of the base (reference) system;
 $CFR()$ – a function returning the capital recovery factor;
 $C_{NPC,tot}$ – the total net present cost [\$];
 i – the annual real discount rate [%];
 R_{proj} – the project lifetime [yr];
 F_{tot} – total annual generator fuel consumption [l/yr, m³/yr, or kg/yr];
 E_{gen} – total annual electrical production of the generator [kWh/yr].

ACKNOWLEDGMENT

The authors would like to express their deep gratitude to the Almighty Allah for giving them strength and to their beloved parents for providing the mental support to do this research.

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Identification of Promising Research Issues in the Digital Industry Topic by Analyzing Scopus Bibliometric Data for 2018 – 2022

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Abstract — The paper aims to identify promising research issues on the topic of Digital Industry based on the analysis of bibliometric data from Scopus platform for 2018–2022. To this end, the titles and abstracts of highly cited works by authors with high publication activity were considered. Authors' Scopus profiles were used to determine their affiliations, which are important for an in-depth analysis of selected promising Digital Industry strands. Metadata filtering was performed to identify highly cited papers on particular issues by keyword, subject area, affiliation with countries and sponsoring organizations. Additionally, bibliometric metadata were clustered based on the co-occurrence of terms using VOSviewer. Within these clusters, articles of interest were identified for the formulation of promising research issues on the topic of Digital Industry, which will be thoroughly examined in separate papers.

Index Terms: Digital industry, promising research issues, bibliometric metadata, high-cited publications, Scopus, VOSviewer.

I. INTRODUCTION

This paper focuses on a long-term study that utilizes bibliometric data from scholarly publications to analyze the promising areas of digitalization for industry.

The publication aims:

- to provide a brief overview of research into digital industry subjects over the last 5 years, using Scopus data;
- to identify some research issues that require more detailed analysis in the future, e.g., digital manufacturing, Industry 4.0, machine learning in the

oil industry;

- to suggest authors and their articles to start a detailed analysis of the selected issues.

Research Motivation

Identification of promising research issues involves reviewing a broad context of existing works on the topic in question, especially those having achieved international recognition.

Such a possibility, in particular, is provided by databases of abstracts, which allow exporting large amounts of bibliometric metadata for their further analysis. The present paper uses data from Scopus platform, which indexes highly ranked publications and is available to Russian researchers.

Further, open access platforms will be used, including dimensions.ai, lens.org, semanticscholar.org, ieeexplore.ieee.org, and openalex.org, which index a broader range of scholarly publications, such as preprints and academic journals not indexed by Web of Science and Scopus, as well as conference proceedings.

It is worthwhile to remark that tables and graphs based on bibliometric data are mostly self-explanatory, therefore, there is no need to discuss what they show and what they mean. Brief author's notes are more rational and allow the subject-matter expert to decide what information in the tables is of interest. It is useful to give examples of the most cited publications on which the data presented in the tables are based and give information about their authors. The ultimate carriers of knowledge are the authors of publications, which is why it is advisable to focus on researchers involved in promising issues and their affiliations.

More comprehensive high-resolution tables and graphs can be made available to readers, for example by placing them on figshare.com or by making the data available for viewing on specialized services (app.vosviewer.com).

The format of a thematic analysis article is based on research queries to abstract databases and identification of promising themes based on subjective assessments. It is advisable to limit the thematic analysis to a semantic approach, as it is based on analysing the raw texts rather than on identifying their underlying meanings

The Digital Industry theme has the following signs of a

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<http://dx.doi.org/10.25729/esr.2023.02.0002>
Received March 06, 2023. Revised April 13, 2023.
Accepted May 12, 2023. Available online June 10, 2023.

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new in-demand topic:

- The ratio of the number of publications in 2021 to that in 2018 for the query title-abs-key (digital and industry) and pubyear > 2017 (the year 2022 was not over when this paper was submitted for publication and not all publications were indexed) is $7845/3558 = 2.2$. While for more general queries, the increase in the number of publications is less pronounced, over the same time period, it is $125893/88894 = 1.4$. For title-abs-key (industry), and for title-abs-key (economy), the ratio is $48671/31638 = 1.5$.
- New topics are characterized by a higher ratio of document type conference paper/ article in the abstract database; for the topic “digital and industry”, it is $12168/11618 = 1.047$. While for industry it is $129299/298064 = 0.434$. And for economy it is $30347/121501 = 0.25$.
- The publications closest to the content of this paper meet the queries:
- Title-abs-key (digital and industry) and pubyear > 2017 and title (“thematic analysis”) and (limit-to (language, “english”)) for which as of 13-07-2022 there are 4 publications in scopus and only three of them have dois, the fourth is not an article but conference proceedings. Let us analyze only the articles.
- Title-abs-key (digital and industry) and pubyear > 2017 and title (“bibliometric analysis”) and (limit-to (language, “english”)) yield 44 results. Consideration will be given to three most cited publications.

Articles having the terms “thematic analysis” and “bibliometric analysis” in their titles may be similar in content. The difference lies rather in the scope of application – “bibliometric analysis” is more often used as a quantitative analysis of publication metadata and “thematic analysis” as a qualitative analysis of the texts themselves. However, once the texts have been annotated in “thematic analysis,” quantitative methods widely used in “bibliometric analysis,” especially those based on the co-occurrence of terms, can be applied. The clustering of terms or content-related documents, the use of controlled vocabularies (which can be used to annotate texts as well) converge the basic approaches used in both methods of analysis.

Citation is not about “thematic analysis,” it is about selecting data for analysis. The research results depend on the questions we seek to answer using the content of the databases of scientific publication abstracts and on how we choose the filtering criteria and pre-process the data. It is more important to find acceptable answers to the questions posed, which are subjective in nature, than simply to obtain quantitative estimates. For example, when collecting data on a topic of interest, it is more useful to select terms and filters to refine queries than to simply quantify the occurrence of terms. The objective lies beyond the analysis being conducted.

Among the three papers containing the term “thematic

analysis” in their title, the most cited (24) paper [1] deals with the coronavirus pandemic, its relation to the digital industry is very indirect – through the digitalization of big data processing. This is a typical automatic classification problem due to the use of Index keywords.

The paper [2], published in 2022, is the opposite of the first - it is cited twice and its title can be interpreted as the relevant issue of Digital Industry: “Toward digital construction supply chain-based Industry 4.0 solutions: scientometric-thematic analysis.” Supply chain-based Industry 4.0 solutions are an obvious issue, just think of the challenges in logistics during the pandemic and the sanctions; the digitalization of logistics is necessary to quickly adapt solutions in a fast-changing environment.

Another paper, published in 2022 with the term “thematic analysis” in the title [3], looks at Augmented Reality in Design and Construction, and could also serve as a basis for more detailed analysis in the broader context of the digital industry, not just the construction but also the oil and gas industry.

Bibliometric studies are not only more frequent (44 vs. 4) but are also significantly more often cited, which is largely interrelated. The more researchers are involved in a topic, the more likely that a good paper will be cited. For mediocre papers, this statement can hardly be made. The journal of publication has a significant impact on the citation rate. Engineering Applications of Artificial Intelligence published 357 papers in 2021 and is Q1 in the SCImago Journal Rank, Smart and Sustainable Built Environment published 78 papers in 2021 and is also a Q1 journal. More authors publish in the first journal, they read the journal in which they publish and are more likely to cite an article published in that journal.

The most cited work corresponding to the above query for bibliometrics [4] (220 citations) also deals with research on Industry 4.0. This publication is a classic bibliometric work combined with a thematic review and can be useful as a starting point for more detailed research on the individual tasks listed therein.

The paper [5] provides a comprehensive review of BIM-GIS integration for the analysis and practical application of data integration technology, building energy management and urban management. Research trends in the application of BIM-GIS integration are discussed. It is concluded that comprehensive building energy management information should be digitized and quantified for integration and application in urban environment. The value of this paper lies in considering the real digitization challenge of building energy management and urban management.

The authors [6] address the challenge of understanding digital transformation (DT) trends by using a machine learning (ML) approach to thematic modeling and analysis of advanced research and development in the field of DT technologies. A methodology for compiling a systematic review based on the collected literature is developed. Six dominant themes are identified, including

TABLE 1. Top Subject Areas by year, retrieved by inner join lists of Subject Areas terms for each year

SUBJECT AREA	N 2018	N 2019	N 2020	N 2021	N 2022
Engineering	521	840	1098	1444	819
Computer Science	356	607	791	1169	645
Business, Management, and Accounting	300	455	610	882	533
Social Sciences	354	538	636	904	477
Environmental Science	175	222	311	450	239
Energy	111	155	284	411	234
Materials Science	118	169	326	357	173
Mathematics	63	84	148	226	158
Physics and Astronomy	73	99	226	262	135
Decision Sciences	67	86	180	250	134
Economics, Econometrics, and Finance	99	146	183	251	133
Medicine	106	126	144	219	117
Chemical Engineering	95	87	144	209	115
Chemistry	61	88	127	160	88
Agricultural and Biological Sciences	57	94	109	155	87
Biochemistry, Genetics, and Molecular Biology	72	72	118	162	83
Arts and Humanities	96	127	131	174	75
Psychology	24	40	43	94	68
Earth and Planetary Sciences	37	57	113	136	65
Pharmacology, Toxicology, and Pharmaceutics	28	33	65	54	33
Health Professions	7	22	24	30	20
Neuroscience	7	7	5	14	19
Immunology and Microbiology	13	11	19	29	17
Multidisciplinary	13	17	30	52	10
Nursing	9	11	8	13	10
Veterinary	5	10	13	14	10
Dentistry	3	2	5	4	3

smart factory, sustainability and product-service systems, digital transformation in construction, digital infrastructure transformation, technology-driven digital transformation, and business model-driven digital transformation. The authors demonstrate the usefulness of thematic modeling in identifying the promising issues of industry digitalization.

Thus, a brief review of published works shows the relevance of applying thematic analysis of bibliometric data for the analysis of promising issues of digital industry.

II. MATERIALS AND METHODS

The bibliometric data used in this paper were obtained from the Scopus abstract database by querying: TITLE-ABS-KEY (digital AND industry) AND PUBYEAR > 2017 AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")), here j stands for journal article, only publications in English were used, which simplifies textual analysis. The data are up-to-date as of 17 June 2022. A total of 12 452 articles were indexed in Scopus for this query. In comparison, the TITLE-ABS-KEY (digital AND industry) query indexed 59 428 publications in Scopus, of which 22 777 were in the form of journal articles in English.

Using the journal articles metadata alone not only makes the sample more homogeneous but practice also shows that the database fields for such publications are the most populated.

For other purposes, e.g., to determine the growth of

interest in a topic, it is useful to compare the metadata of conference proceedings, articles, and chapters. In conference proceedings, new topics often appear earlier than in articles and book chapters.

Since Scopus allows only 2 000 records to be exported at a time, for 2019–2022, the 2 000 most cited records were exported, and for 2018, all 1 432 records were exported. Thus, a total of 9 432 bibliometric entries were collected for analysis.

Exported data in summary tables, called Scopus_exported_refine_values files, were used to analyze the dynamics of a series of indicators from year to year. The tables in the first part of the Results section were obtained using the SQL Inner Join statement for the annual tables.

We are interested in the common view on publication data for the years 2018–2022, the Inner Join statement was used for this purpose. If there were a different goal, for example, the appearance of new authors or topics, it would be more rational to use the Right Join statement, and the overall picture, accordingly, could be obtained with the Full Join statement.

In the second part of the Results section, the findings obtained by constructing networks based on term co-occurrence (co-authors can also be treated as terms) were used and the data were clustered using the Leiden algorithm of the VOSviewer software [7]. It is most convenient to take data from exported MAP and NET files, which can be handled as tsv tables.

TABLE 2. Top Keywords (Authors and Index) by year, retrieved by inner join lists of Keyword terms for each year

KEYWORD	N 2018	N 2019	N 2020	N 2021	N 2022
Digital Storage	260	302	435	551	310
Industry 4.0	79	199	373	501	324
Digital Transformation	28	88	158	303	172
Human	128	148	187	276	126
Digital Twin	10	44	133	267	126
Article	117	110	172	228	101
Artificial Intelligence	35	61	120	217	123
Humans	82	102	105	181	86
Internet Of Things	63	107	137	179	147
Digital Technologies	33	51	105	179	88
Blockchain	16	50	74	171	89
Machine Learning	22	46	88	156	96
Decision Making	51	58	117	141	89
Construction Industry	32	46	72	135	84
Digitalization	32	62	88	132	108
Sustainability	31	37	67	129	82
Innovation	43	76	83	124	65
Sustainable Development	23	34	71	117	91
Information Management	28	49	61	110	60
Big Data	58	87	83	105	78
Manufacture	38	57	77	104	63
Life Cycle	18	39	59	88	59
Supply Chains	25	25	49	87	50
3D Printers	26	44	64	86	40
Digitization	25	40	63	85	43
Technology	35	37	55	83	47
Automation	31	35	58	82	62
Review	25	42	60	78	33
Industrial Research	23	30	59	78	74
Manufacturing	14	32	48	78	54

TABLE 3. Top Source Titles by year, retrieved by inner join lists of Source Titles for each year

SOURCE TITLE	N 2018	N 2019	N 2020	N 2021	N 2022
Sustainability Switzerland	23	23	62	141	72
IEEE Access	20	32	71	72	26
Applied Sciences Switzerland	5	12	38	70	26
Technological Forecasting and Social Change	8	10	14	41	38
Energies	6	20	24	40	25
Journal of Cleaner Production	11	10	24	28	21
International Journal of Advanced Manufacturing Technology	8	19	13	22	18
Automation in Construction	11	10	15	17	13
Computers in Industry	5	13	12	17	20
International Journal of Production Research	3	4	10	17	19
Materials	3	6	8	15	4
Engineering Construction and Architectural Management	5	6	5	13	8
IEEE Transactions on Industrial Informatics	4	3	10	12	18
International Journal of Computer Integrated Manufacturing	2	6	8	12	5
Plos One	5	3	5	10	4
Advanced Engineering Informatics	3	2	4	10	5
Energy	6	4	7	9	5
Buildings	2	3	3	9	14
Applied Energy	7	13	10	6	6
Multimedia Tools and Applications	3	5	6	6	8
Publishing Research Quarterly	5	8	4	6	4
Computers and Electronics in Agriculture	2	3	7	5	6
International Journal of Advanced Computer Science and Applications	3	3	7	5	3

Table 4. Top Author Affiliations with Countries by year, retrieved by inner join lists of Author Affiliations with Countries for each year

COUNTRY	N 2018	N 2019	N 2020	N 2021	N 2022
United States	319	383	459	599	272
China	128	208	350	529	396
United Kingdom	168	231	293	473	233
India	104	198	232	308	209
Germany	88	134	184	275	144
Italy	59	107	174	241	149
Australia	101	117	152	238	145
Spain	57	70	138	199	88
Russian Federation	42	119	107	152	48
France	39	55	88	147	76
Canada	35	76	88	139	76
Brazil	33	45	73	101	74
Malaysia	38	60	62	94	81
South Korea	51	63	57	93	64
Sweden	27	41	57	87	49
Netherlands	35	41	50	84	43
Portugal	16	26	31	77	44
Poland	12	24	51	73	45
Saudi Arabia	13	14	39	70	57
Turkey	18	15	33	68	45
Switzerland	30	34	43	66	42
Indonesia	12	55	67	61	30
Finland	27	32	31	56	41
Japan	30	29	34	55	24
Pakistan	6	25	27	53	45
Hong Kong	14	14	28	53	41
Austria	16	31	27	53	25
Denmark	15	24	31	52	41
South Africa	16	18	25	52	36
Taiwan	24	25	52	52	31

There is a link to the json format files exported from VOSviewer at the end of the paper, which allows browsing them in detail on the <https://app.vosviewer.com/service>. Presenting such results as pictures in the article is impractical because, unlike the app viewer, they cannot be scaled, and individual connections between terms cannot be examined.

Materials and methods are limited to the main aim of the paper, i.e., “to provide a brief overview of research on digital industry topics.” A more detailed treatment of individual issues on digital industry topics is intended to be given in separate publications.

III. RESEARCH RESULTS

The first part of the analysis of bibliometric data on “Digital Industry” retrieved from Scopus involved producing year-by-year tables for key indicators characterizing publications, such as Subject Areas, Keywords, Source Titles, Author Affiliations with Countries, Author Affiliations with Institutions and Funding Sponsors. These data allow assessing the basic trends in research areas and the resources involved in sustaining these trends. In the second part of this section, the data from the tables are used to identify Digital Industry Issues, which are worth exploring in more detail in separate studies.

Table 1 shows the top Subject Areas for 2018–2022.

Subject Areas including Engineering, Computer Science and Business, Management and Accounting are the expected topics for Digital Industry, whereas Social Sciences are of particular interest for deeper study. For this area, the additional filter in the Scopus query can be given as AND (LIMIT-TO (SUBJAREA, “SOCT”)).

The social aspects of the Digital Industry are presented, for example, in the article [8] cited 503 times in Scopus on 06 July 2022, one of its questions (How do digital platforms affect everyday life?) is not about business but about current life.

A more thorough analysis of the importance of the **social dimension for the Digital Industry** can start with reviewing the profiles of the authors of the publication.

Profiles of the authors of this article are:

Reuver, Mark De; Faculteit Techniek, Bestuur en Management, TU Delft, Delft, Netherlands; Scopus ID 35776955900; <https://orcid.org/0000-0002-6302-7185>; 111 documents by the author; 2 142 citations by 1 876 documents; h-index 23.

Sørensen, Carsten; London School of Economics and Political Science, London, United Kingdom; Scopus ID 7102879062; <https://orcid.org/0000-0002-2002-9383>; 67 documents by the author; 2 833 citations by 2 244

TABLE 5. Top Author Affiliations with Institutions by year, retrieved by inner join lists of Author Affiliations with Institutions for each year

AFFILIATION	N 2018	N 2019	N 2020	N 2021	N 2020
Ministry of Education China	8	9	23	41	14
UNSW Sydney	10	6	19	27	10
CNRS Centre National de la Recherche Scientifique	9	17	18	27	16
University College London	4	9	12	25	9
University of Cambridge	12	12	16	24	17
University of Melbourne	9	9	9	24	17
Imperial College London	8	7	13	23	5
National University of Singapore	6	5	7	22	16
Chinese Academy of Sciences	4	8	22	20	12
Universidade de São Paulo	3	8	10	20	12
Queensland University of Technology	4	9	10	20	16
RMIT University	6	8	9	20	15
University of Nottingham	3	5	14	18	8
Deakin University	5	6	13	18	10
Hong Kong Polytechnic University	4	6	14	17	17
Tsinghua University	4	6	11	17	13
Norges Teknisk-Naturvitenskapelige Universitet	4	10	12	16	16
Technical University of Munich	5	5	11	16	7
Curtin University	9	8	7	16	6
University of Sydney	9	8	15	15	9
King Saud University	5	6	8	15	11
University of Johannesburg	3	5	14	13	20
The University of Manchester	4	11	10	13	12
Monash University	4	12	10	13	11
University of Toronto	4	10	9	13	10
University of Leeds	6	7	8	13	5
Friedrich-Alexander-Universität Erlangen-Nürnberg	4	4	7	13	10
University Kebangsaan Malaysia	3	6	9	12	5
Rheinisch-Westfälische Technische Hochschule Aachen	5	6	8	12	8
University of Technology Sydney	9	7	8	12	8

documents; h-index 21.

Basole, Rahul C.; Accenture, New York, United States; Scopus ID 24329464200; 80 documents by author; 2 437 citations by 1 895 documents; h-index 22.

The importance of human capital in the Digital Industry topic is outlined in [9], cited by 170 documents.

Profiles of the authors of this article are:

Popkova, Elena G.; Moscow State Institute of International Relations (MGIMO), Moscow, Russian Federation; Scopus ID 55671568200; <https://orcid.org/0000-0003-2136-2767>; 202 documents by the author; 3 565 citations by 1 419 documents; h-index 33.

Sergi, Bruno S.; Harvard University, Cambridge, United States; Scopus ID 35369323900; <https://orcid.org/0000-0002-5050-5651>; 170 documents by the author; 1 872 citations by 1 213 documents; h-index 23.

The top keywords (Authors and Index) for 2018-2022 are listed in Table 2.

Most of the keywords in the table are related to the Digital Industry topic. However, it is worth clarifying why publications are so often categorized as Digital Storage by the Scopus platform in all the years under consideration.

Analysis of the metadata of 1 877 publications matching the query TITLE-ABS-KEY (digital AND

industry) AND PUBYEAR > 2017 AND KEY (“Digital Storage”) AND (LIMIT-TO (SRCTYPE, “j”)) AND (LIMIT-TO (LANGUAGE, “English”)) indicates that the term Digital Storage appears only 4 times in the Title, Abstract, and Author keywords, more specifically, only in the Abstract and in phrases such as ...using digital storage oscilloscope...; in Indexed Keywords, the term Digital Storage is found in all records. Therefore, the term Digital Storage is strictly a Scopus Index Keywords term and reflects the classification of records in the system, not the occurrence of the term in publication metadata.

The topic referred to by Scopus as best for “Digital Storage” is reflected in the title of the article [10], “**Digital twin-driven product design, manufacturing and service with big data,**” which describes the issue fitting well a separate study.

The profiles of the authors of this article are used below and listed after Table 8.

The top Source Titles for 2018–2022 are listed in Table 3.

The top three journals in the Table (Sustainability Switzerland, IEEE Access, and Applied Sciences Switzerland) published 14 051, 12 850, and 11 975 open access articles respectively in 2021. This makes these

TABLE 6. Top Funding Sponsors by year, retrieved by inner join lists
of Funding Sponsors for each year

FUNDING SPONSOR	N 2018	N 2019	N 2020	N 2021	N 2022
National Natural Science Foundation of China	56	86	163	193	122
European Commission	30	52	85	114	71
Horizon 2020 Framework Programme	18	36	68	69	26
National Key Research and Development Program of China	6	6	38	63	32
European Regional Development Fund	12	15	39	51	17
Engineering and Physical Sciences Research Council	29	39	45	50	18
National Science Foundation	22	26	37	42	16
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	7	16	21	40	26
Fundamental Research Funds for the Central Universities	9	23	24	35	15
Australian Research Council	13	16	22	35	12
Conselho Nacional de Desenvolvimento Científico e Tecnológico	8	18	30	34	27
National Research Foundation of Korea	16	17	23	34	19
U.S. Department of Energy	12	15	23	32	11
Fundação para a Ciência e a Tecnologia	4	12	13	32	18
UK Research and Innovation	19	21	33	28	19
Ministry of Science and Technology of the People's Republic of China	6	15	25	25	17
Natural Sciences and Engineering Research Council of Canada	5	7	19	25	13
Ministry of Education of the People's Republic of China	11	21	24	23	14
Horizon 2020	6	10	20	23	17
Bundesministerium für Bildung und Forschung	9	8	15	22	11
Russian Foundation for Basic Research	5	16	12	21	4
Ministry of Education	9	8	11	20	3
Deutsche Forschungsgemeinschaft	4	9	15	19	12
Government of Canada	2	14	13	18	8
Ministerio de Economía y Competitividad	7	14	8	18	5
China Postdoctoral Science Foundation	5	7	8	15	9
European Social Fund	2	2	4	15	11
Ministry of Science and Technology, Taiwan	7	7	17	14	8
National Institutes of Health	11	12	7	14	9
Ministry of Finance	4	12	11	12	6

TABLE 7. Top Author ID in cluster #1 by Average normalized citation, occurrence (the number of publications by author), and average publication year

Author ID	Cluster	Occurrences	Average publication year	Average Normalized citations
57192100009	1	3	2019.3333	23.0898
57193673728	1	6	2019	22.5854
12141248300	1	11	2019.6364	15.7347
57195245075	1	6	2020.1667	14.2821
37102014400	1	6	2020.5	12.2811
24921483100	1	3	2020	11.006
57203151995	1	3	2020	11.006
56173081300	1	6	2019.6667	9.1559
57207454205	1	8	2020	7.1859
7801563868	1	3	2020.6667	7.0217
55080150600	1	7	2020.2857	6.8247
57188970257	1	3	2021	5.2968
57219656467	1	4	2020	5.2332
54895137000	1	3	2020.6667	5.044
55101071200	1	3	2021.3333	3.8914
44261803600	1	6	2020.1667	3.7732
36141576300	1	14	2020.8571	3.4892
56948414800	1	3	2021.3333	3.3327
56996337400	1	3	2021.3333	3.3327
57191981777	1	3	2021.3333	3.3327

TABLE 8. Examples of the most cited publications of Author with ID=57192100009 and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Tao F., Cheng J., Qi Q., Zhang M., Zhang H., Sui F.	12141248300, 57192081753, 57193673728, 57192100009, 57190839107, 57189511188	Digital twin-driven product design, manufacturing and service with big data. [10]	1 059
Tao F., Sui F., Liu A., Qi Q., Zhang M., Song B., Guo Z., Lu S.C.-Y., Nee A.Y.C.	12141248300, 57189511188, 37102014400, 57193673728, 57192100009, 57201022514, 57201033062, 25933160000, 57195245075	Digital twin-driven product design framework. [14]	322

TABLE 9. Examples of the most cited publications of Author with ID=57193673728 and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Tao F., Cheng J., Qi Q., Zhang M., Zhang H., Sui F.	12141248300, 57192081753, 57193673728, 57192100009, 57190839107, 57189511188	Digital Twin-Driven Product Design, Manufacturing and Service with Big Data. [10]	1 059
Qi Q., Tao F.	57193673728, 12141248300	Digital Twin and Big Data towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. [15]	550
Tao F., Sui F., Liu A., Qi Q., Zhang M., Song B., Guo Z., Lu S.C.-Y., Nee A.Y.C.	12141248300, 57189511188, 37102014400, 57193673728, 57192100009, 57201022514, 57201033062, 25933160000 57195245075,	Digital Twin-Driven Product Design Framework. [14]	322
Tao F., Qi Q., Wang L., Nee A.Y.C.	12141248300, 57193673728, 55080150600, 57195245075	Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. [16]	271

journals attractive for collecting material on the topic of the Digital Industry. IEEE Access is indexed on the open platform IEEE Xplore, and Sustainability Switzerland and Applied Sciences Switzerland are indexed on the platform of MDPI Publisher, which has its own effective search engine.

The top Author Affiliations with Countries for 2018–2022 are listed in Table 4.

The USA was the leading publication destination until 2021, but in 2022, China took the lead. It is also noteworthy that publications from India increase.

The top Author Affiliations with Institutions for 2018–2022 are listed in Table 5.

The affiliation to the institutions of the authors of the publications agrees well with the affiliation by country. In the abstract databases, the fields “Affiliation” and “Foundation” are the least correctly filled in. It is not very useful to analyze the statistics on them. It is interesting however to use the list of affiliated institutions to identify their involvement in specific digital industry tasks.

For example, the article [11] cited 41 times in Scopus, has the following record in the affiliation field “School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, 150001, China; Key Laboratory of Fluid and Power Machinery (Xihua University), Ministry of Education, Sichuan, Chengdu, 610039, China; State Key Laboratory of Hydro-Power Equipment, Harbin Institute of Large Electrical Machinery, Harbin, 150040, China.”

The author affiliated with the Chinese Ministry of

Education has the following Scopus profile:

Li, Zhenggui; Xihua University, Chengdu, China; Scopus ID 54894723200; 70 documents by the author; 368 citations by 255 documents; h-index 10. The Scopus profiles of authors of highly cited publications are usually carefully reviewed, making their use practical.

The metadata of this article are indicative in the context of bibliometric analysis. For example, let us compare the lists of Author and Index Keywords in the record of this publication.

Author Keywords are Bispectrum; Dean Vortex; Frequency characteristic; Pump-turbine; Pumped storage power plant.

Index Keywords are Computational fluid dynamics; Digital storage; Frequency domain analysis; Pumped storage power plants; Shear stress; Turbulence models; Vortex flow; Bispectrum; Dean vortex; Energy storage technologies; Frequency characteristic; Performance characteristics; Pump-turbines; Time- and frequency-domain analysis; Unsteady numerical simulations; Hydraulic turbines; Amplitude; Energy storage; Frequency analysis; Numerical method; Performance assessment; Pump; Turbine; Turbulence.

The lists above show that Index Keywords significantly expand the set of terms, which, according to Scopus, describe the topic of a publication. However, the result is far from being consistent, what is the relevance of the term Digital Storage mentioned earlier to the topic of the article?

Another problem with the direct use of keywords to

TABLE 10. Top Author ID in cluster #2 by Average normalized citation, occurrence (the number of publications by the author), and average publication year.

Author ID	Cluster	Occurrences	Average publication year	Average normalized citations
55599784700	2	5	2019.6	18.5453
54790849500	2	7	2020	13.7009
15757819200	2	4	2020.25	11.0723
54977014200	2	4	2020.5	7.8203
36864045000	2	8	2020	7.772
8417810000	2	3	2019.6667	7.712
9279823400	2	3	2020.6667	7.3767
26429368200	2	3	2020	7.3301
56238759300	2	10	2020.2	6.6938
57192378881	2	3	2021	6.2634
55757488200	2	10	2020.5	6.0734
24831905500	2	3	2019.6667	5.9432
57201069320	2	3	2020.6667	5.4164
55851943244	2	9	2021.1111	4.9571
56370773200	2	3	2019.6667	4.3227
42262603800	2	4	2021.25	3.3407
55735821600	2	4	2020.5	3.1253
57191022246	2	8	2021	3.1245
57193437808	2	3	2021.6667	3.1008
14833520200	2	3	2020.3333	3.053

identify relevant research issues is the fact that it is difficult to conclude from the lists of terms given why a particular publication is of interest to the Digital Industry topic. However, if we address the title of the article, “Mechanism of high amplitude low frequency fluctuations in a pump-turbine in pump mode,” the phrase “Mechanism of high amplitude low frequency fluctuations in a pump” describes well the problem under study. The snippets from the abstract, ... “Pumped storage technology has become the most important energy storage technology in industry today. The instabilities of pump-turbines as key parts of pumped storage power plants have become critical issues in the development of pump storage technology.” ... explain the “critical issues” and how “unsteady numerical simulations have been carried out,” which can be effectively addressed by digitizing the process, from initial information gathering to system simulation.

It is more appropriate to use publication titles to identify topical issues in the digital industry and, if they are not clear enough, to look for explanations in the abstracts. The meaning of the keywords themselves is more relevant in the first stage of research, when querying abstract databases to collect publication metadata.

The article cited in Scopus 12 times [12] illustrates how the title of the paper “Identifying soil management zones in a sugarcane field using proximal sensed electromagnetic induction and gamma-ray spectrometry data” can be reformulated for similar research, since the problem of “Identifying soil management zones” can be solved by other technical approaches.

The top Funding Sponsors for 2018–2022 are listed in Table 6.

The data in Table 6 can be used to search for projects funded by these donors. For example, Horizon 2020 funds various projects, searches GOOLE for projects related to the Digital Industry. Look at ... “the DAIS project will research and deliver Distributed Artificial Intelligent Systems” ... with the section “Digital Industry” and find the issue “**Energy management based on a fog computing approach.**” From personal experience, it is more appropriate to formulate objectives within a topic rather than the topics themselves in order to collect publications in abstract databases. Thus, there are no publications in Scopus that match the TITLE-ABS-KEY (DAIS AND “digital industry”), but there are 611 documents that match the TITLE-ABS-KEY (energy AND management AND fog AND computing). One of the papers matching the above request [13] and published in 2017 has 2 235 citations. The authors’ affiliation is also of interest: Hong Kong University of Science and Technology and Hamad Bin Khalifa University, Doha, Qatar.

The following conclusion can be made from the analysis of the tables in this section. The summarized data presented in the tables are of limited interest for identifying current issues for the Digital Industry, but are useful filters for querying abstract databases.

The second part of the study concerns the identification of the authors of highly cited articles and finds out how relevant research issues can be formulated based on the wording of the titles of these articles.

TABLE 11. Examples of the most cited publications of Author with ID=55599784700 and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Dalenogare L.S., Benitez G.B., Ayala N.F., Frank A.G.	57203842897, 57197831648, 55599784700 , 54790849500	The expected contribution of Industry 4.0 technologies for industrial performance. [	568
Frank A.G., Dalenogare L.S., Ayala N.F.	54790849500, 57203842897, 55599784700	Industry 4.0 technologies: Implementation patterns in manufacturing companies. [18]	707

TABLE 12. Examples of the most cited publications by Author with ID=54790849500 and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Frank A.G., Mendes G.H.S., Ayala N.F., Ghezzi A.	54790849500 , 56785594200, 55599784700, 24831905500	Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. [19]	271
Benitez G.B., Ayala N.F., Frank A.G.	57197831648, 55599784700, 54790849500	Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. [20]	112

TABLE 13. Examples of the most cited publications by Author with ID 56238759300 and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Kamble S.S., Gunasekaran A, Gawankar S.A.	36864045000, 56238759300, 55846962200	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. [21]	464
Kamble S.S., Gunasekaran A, Sharma R.	36864045000, 56238759300, 57196545771	Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. [22]	229

TABLE 14. Top Author ID in cluster #3 by Average normalized citation, Occurrence (the number of publications by author), and Average publication year

Author ID	Cluster	Occurrences	Average publication year	Average normalized citations
56687825200	3	3	2020.3333	4.8081
56349650400	3	3	2020	4.7602
57195542948	3	3	2020.3333	4.7487
57021768700	3	3	2021.3333	4.6685
35239818900	3	7	2021.1429	4.6676
6508058214	3	3	2021.3333	4.5874
55348625200	3	4	2020	4.3028
35310169200	3	4	2021	4.2821
21743792400	3	6	2019.5	4.2438
35427952100	3	3	2020	3.9212
55808097300	3	3	2021.6667	3.8566
14037119900	3	4	2019.5	3.8353
57194166860	3	6	2019.6667	3.7957
50262828700	3	4	2021.5	3.7849
26422351200	3	3	2020	3.7542
15726654000	3	4	2020.25	3.7464
56595145400	3	4	2020.25	3.7464
57224222999	3	4	2020.5	3.6195
55911169300	3	6	2021.1667	3.5298
55960201200	3	4	2020.5	3.0689

Table 15. Examples of the most cited publications by Author with ID 56687825200 and their co-authors, Authors ID, Title, DOI, and Citation

Authors	Author(s) ID	Title. DOI	Cited by
Rosa P., Sassanelli C., Urbinati A., Chiaroni D., Terzi S.	56687825200 , 56595145400, 57194166860, 14037119900, 15726654000	Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. [23]	162
Rocca R., Rosa P., Sassanelli C., Fumagalli L., Terzi S.	57192381259, 56687825200 , 56595145400, 55348625200, 15726654000	Integrating virtual reality and digital twin in circular economy practices: A laboratory application case. [24]	47

TABLE 16. Examples of the most cited publications by Author with ID 56349650400 and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Cimino C., Negri E., Fumagalli L.	57210824444, 56349650400 , 55348625200	Review of digital twin applications in manufacturing. [25]	174
Negri E., Berardi S., Fumagalli L., Macchi M.	56349650400 , 57216900878, 55348625200, 7004929933	MES-integrated digital twin frameworks. [26]	37

TABLE 17. Examples of the most cited publications by Author with ID 35239818900 and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Ali O., Ally M., Clutterbuck, Dwivedi Y.	56498722200, 8925161400, 57218221904, 35239818900	The state of play of blockchain technology in the financial services sector: A systematic literature review. [27]	65
Bag S., Pretorius J.H.C., Gupta S., Dwivedi Y.K.	55757488200, 8417810000, 55851943244, 35239818900	Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities. [28]	109

TABLE 18. Top countries by number of publications (occurrences) in cluster #1

Country	Cluster	Occurrences	Average publication year	Average normalized citations
India	1	767	2020.2073	1.1072
France	1	334	2020.3174	1.9847
Canada	1	334	2020.2425	1.2743
Russian Federation	1	292	2019.7877	0.7267
Malaysia	1	264	2020.2765	0.8247
Saudi Arabia	1	160	2020.725	1.2119
Turkey	1	139	2020.4964	1.3329
United Arab Emirates	1	98	2020.3571	1.4716
Egypt	1	55	2020.4364	1.1889
Kazakhstan	1	37	2020.4595	0.4417

There can be diverse approaches to solving this problem. This paper considers only the use of co-occurrence of Authors and Index Keywords in articles and their clustering with the Leiden algorithm built into the free program VOSviewer [7].

Clustering enables the creation of groups of coauthors or keywords based on their co-occurrence in metadata.

There are many other methods for forming groups based on the proximity of their elements, but this goes far beyond the scope of one article. You can use clustering of documents by comparing their metadata or using algorithms like Apriori.

Since identifying authors by their last name and first name can be ambiguous, especially in the case of Chinese authors, it is appropriate to use the Author ID.

IV. AUTHORS ID CO-OCCURRENCE

To maintain the general approach of using VOSviewer to cluster key terms, at this point, the Author(s) ID field was renamed to Index Keywords, the data were analyzed and exported, and the field was again renamed to Author(s) ID. Additionally, the following fields were used: Authors, Title, Year, Cited by, and DOI. At the second step, the Index Keywords field itself was used.

Average normalized citation was used to select the authors, and then the most cited publications for these authors were selected. Promising issues for a further, more detailed analysis were formulated according to the publication titles (optionally the abstracts). Brief data on the author's profile from Scopus system were given to understand the author's affiliation and indicators of his/her publication activity. Both factors are important when gathering information on an issue. Such a choice always carries elements of subjectivity – if not, there will be many choices.

VOSviewer program parameters are total values of Author(s) ID – 32008, occurring more than three times – 787, the minimum number of Author(s) ID in a cluster – 20. Three clusters were obtained with these values, which are discussed below.

Cluster 1

Table 7 shows the 20 Author IDs from the first cluster, sorted by Average normalized citation. The first three Author IDs given in bold in the Table will be used below.

To get a list of the author's publications by their ID, a query to the general table of publications was used in the form: Select ... from ... where Author(s) ID is

TABLE 19. Examples of the most cited publications by Authors from India and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Kamble S.S., Gunasekaran A., Gawankar S.A.	36864045000, 56238759300, 55846962200	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. [21]	464
Kamble S.S., Gunasekaran A., Sharma R.	36864045000, 56238759300, 57196545771	Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. [22]	229

TABLE 20. Top countries by the number of publications (occurrences) in cluster #2

Country	Cluster	Occurrences	Average publication year	Average normalized citations
Italy	2	599	2020.3389	1.29
Portugal	2	156	2020.4487	1.1906
Poland	2	150	2020.42	0.8464
Taiwan	2	145	2020.131	1.0742
Austria	2	130	2020.1769	1.6275
Iran	2	129	2020.3798	1.2064
Pakistan	2	129	2020.6357	1.2364
Indonesia	2	128	2019.9219	0.5852
Hungary	2	76	2020.2763	1.0597
Romania	2	76	2020.0132	0.7591

TABLE 21. Examples of the most cited publications by authors from Italy and their co-authors, Authors ID, Title and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Bressanelli G., Adrodegari F., Perona M., Saccani N.	57194720467, 55932417100, 7003407947, 15849430200	Exploring how usage-focused business models enable circular economy through digital technologies. [29]	210
Chiarello F., Trivelli L., Bonaccorsi A., Fantoni G.	57215031142, 57202071072, 7005502691, 8515018000	Extracting and mapping industry 4.0 technologies using Wikipedia. [30]	101

‘%57192100009%’.

Author Profile from Scopus: Zhang, Meng; Tsinghua University, Beijing, China; Scopus ID 57192100009; 23 documents by the author; 3 244 citations by 2 130 documents; h-index 16.

Next, the most cited articles of the author were taken from the obtained selection.

Table 8 shows the titles and citations of two works by this author. The titles of the articles reflect their subject. The high citation rate, numerous publications, and affiliation with one of the leading universities in the PRC guarantee the promising nature of the issue under study and the possibility of further gathering of publications for a more detailed analysis.

From the title of the articles, it is clear that “**Product design based on a digital twin**” is a hot topic.

Comparable data for the author with ID 57193673728 are presented in Table 9. The first and third most cited articles of this author are the same as those given above in Table 8 and will not be considered.

Author Profile from Scopus: Qi, Qinglin; Beihang University, Beijing, China; Scopus ID: 57193673728; <https://orcid.org/0000-0002-3247-0440>; 29 documents by the author; 4 617 citations by 3 083 documents; h-index 18.

Digital Twin, Big Data, Cyber-Physical Systems, and Smart Manufacturing are other wordings of a promising

topic.

Fei Tao is the first author of all the above articles, therefore, it is reasonable to cite his profile in Scopus (Beihang University, Beijing, China; Scopus ID: 12141248300; <https://orcid.org/0000-0002-9020-0633>; 280 documents by the author; 17 177 citations by 8 534 documents; h-index 64) and use his ID to collect publications.

The promising topic of the first cluster can be summarized as “Digital Twin for Manufacturing.”

Cluster 2

A similar procedure is performed for the second cluster, where the IDs of the most cited authors are presented in Table 10. Here, as an example, we select two authors with the highest Average normalized citation and one with the largest number of publications (10) and Average normalized citation equal to 6.6938.

The titles of articles by the author with ID 55599784700 are available in Table 11.

Author Profile from Scopus: Ayala, Néstor Fabián; Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil; Scopus ID 55599784700; <https://orcid.org/0000-0001-8888-9227>; 26 documents by the author; 1 943 citations by 1 447 documents; h-index 11.

The promising topic following these titles can be summed up as follows: **Industry 4.0 technologies for**

TABLE 22. Top Countries by number of publications (occurrences) in cluster #3

Country	Cluster	Occurrences	Average publication year	Average normalized citations
China	3	1 274	2020.4733	1.309
United kingdom	3	1 167	2020.1602	1.4262
Germany	3	672	2020.1771	1.3402
Australia	3	631	2020.1775	1.1918
South Korea	3	271	2020.0443	1.0527
Sweden	3	214	2020.1963	1.2387
Netherlands	3	207	2020.0918	1.2115
Switzerland	3	178	2020.118	1.3937
Norway	3	157	2020.5159	1.2094
Finland	3	155	2020.129	1.8575

TABLE 23. Examples of the most cited publications by Authors from China and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
Tao F., Cheng J., Qi Q., Zhang M., Zhang H., Sui F.	12141248300, 57192081753, 57193673728, 57192100009, 57190839107, 57189511188	Digital twin-driven product design, manufacturing and service with big data. [10]	1059 China
De Reuver M., Sørensen C., Basole R.C.	35776955900, 7102879062, 24329464200	The digital platform: A research agenda. [8]	500 United Kingdom

TABLE 24. Top Countries by the number of publications (occurrences) in cluster #4

Country	Cluster	Occurrences	Average publication year	Average normalized citations
United States	4	1632	2019.894	1.1957
Spain	4	444	2020.2297	0.8859
Brazil	4	253	2020.2925	1.5445
Denmark	4	140	2020.4357	1.1693
Japan	4	134	2019.9179	1.2473
South Africa	4	109	2020.4037	1.9153
Mexico	4	64	2020.1094	0.7644
Thailand	4	54	2019.9074	0.5506
Vietnam	4	51	2020.6275	1.6194
Nigeria	4	48	2020.5	1.4158

industrial performance.

Frank A.G. (ID 54790849500) co-authored the articles presented in Table 11. Table 12 gives his next two most-cited articles.

Author Profile from Scopus: Frank, Alejandro Germán; Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil; Scopus ID 54790849500; <https://orcid.org/0000-0001-5041-6467>; 63 documents by the author; 2 955 citations by 2 228 documents; h-index 23.

The promising topic from these titles can be summed up as follows: Industry 4.0 and innovations.

The author with ID 56238759300 has one of the biggest number of publications, but a medium Average normalized citation. His profile in Scopus: Gunasekaran, Angappa; California State University, Los Angeles, United States; Scopus ID 56238759300; 571 documents by the author; 33 042 citations by 22 767 documents; h-index 96.

His large total number of 571 papers and his affiliation with a strong laboratory at a prominent university are worth noting. Two of his papers are presented in Table 13.

The promising topic from these titles is Sustainable Industry 4.0.

The promising topic for Cluster 2 is Sustainable, Innovative, Technology-efficient Industry 4.0.

Cluster 3

The Average normalized citation of the publications by the authors whose list is presented in Table 14 is lower than in the first two clusters. Understanding the underlying reasons for the lower citation rate is also crucial for choosing a promising research topic.

Two authors with the highest Average normalized citation and one with 7 publications are selected from this Table.

Author (56687825200) Profile from Scopus is Rosa, Paolo; Politecnico di Milano, Milan, Italy; Scopus ID 56687825200; <https://orcid.org/0000-0003-3957-707X>; 54 documents by the author; 2 046 citations by 1 651 documents; h-index 23.

Both articles of the author in Table 15 are of a reviewing nature.

The promising topic: **Circular Economy and Industry 4.0**. The Circular Economy is a separate topic for analysis. A more targeted issue is the use of the capabilities of Industry 4.0 to improve the efficiency of Circular Economy.

TABLE 25. Examples of the most cited publications by U.S. Authors and their co-authors, Authors ID, Title, and DOI

Authors	Author(s) ID	Title. DOI	Cited by
De Reuver M., Sørensen C., Basole R.C.	35776955900, 7102879062, 24329464200	The digital platform: A research agenda. [8]	500
Kamble S.S., Gunasekaran A., Gawankar S.A.	36864045000, 56238759300, 55846962200	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. [21]	464
Li L.	55760654300	China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0". [31]	378

TABLE 26. Top Index Keywords by the number of publications in whose metadata they appear (occurrences) in cluster #1

Index Keywords	Cluster	Occurrences	Average publication year	Average normalized citations
Human	1	685	2019.9781	0.9672
Humans	1	449	2019.9889	1.0826
Procedures	1	203	2019.4877	1.2717
Priority journal	1	169	2019.1124	1.7594
Adult	1	157	2019.8089	0.7131
Female	1	149	2019.8322	0.6319
Controlled study	1	142	2019.9366	0.5804
Male	1	135	2019.8148	0.6388
Internet	1	133	2019.6617	1.743
Health care	1	124	2020.0806	1.1681
Betacoronavirus	1	10	2020.2	6.7188
Pneumonia, viral	1	11	2020.1818	6.6295
Virus pneumonia	1	11	2020.1818	6.6295
Coronavirus infection	1	13	2020.1538	5.6288
Coronavirus infections	1	13	2020.1538	5.6288

for example, by adding the terms “product design” or “manufacturing.”

Data for the last fourth cluster are given in Table 24.

Cluster 4

In this cluster, the United States leads by a considerable margin, which is why attention is focused on publications related to it (Table 25). An interesting observation is that South Africa has the highest Average normalization citations. Some reasons for this are that only the best papers from developing countries are funded for publication in ranked journals or that a small number of authors from such countries reveal their expertise, which is of interest but rarely represented in publications by authors from developed countries.

The first paper in this Table was already considered in cluster 3, therefore, the other two will be discussed.

Author profiles in Scopus of the second paper are:

Gunasekaran, Angappa; California State University, Los Angeles, United States; Scopus ID 56238759300; 571 documents by the author; 33 121 citations by 22 815 documents; h-index 96.

Kamble, Sachin S.; EDHEC Business School, Roubaix, France; Scopus ID 36864045000; <https://orcid.org/0000-0003-4922-8172>; 98 documents by the author; 3 335 citations by 2 705 documents; h-index 25.

Gawankar, Shradha Ashok; National Institute of Industrial Engineering, Mumbai, India; Scopus ID

55846962200; 10 documents by the author; 800 citations by 769 documents; h-index 7.

The article [21] was written by a team of international professionals. Note that Gunasekaran, Angappa is of Indian descent. Involving compatriots in collaborative research is a significant potential for emerging economies.

Author profiles in Scopus of the last paper are:

Li, Ling; Old Dominion University, Norfolk, United States; Scopus ID 55760654300; 127 documents by the author; 6 111 citations by 5 009 documents; h-index 39.

This article provides a comparison of the digital industry goals and achievements of China, Germany, and the United States.

The objectives put forward for in-depth analysis after reading this article are challenges, strategic plans, and implementations for the development of Digital Industry.

VI. INDEX KEYWORDS

To use Index Keywords for direct choice of research topics is not rational. This issue was previously discussed on the example of the Data Storage Index Keyword. Our objective, however, is different; we select authors who have numerous publications and high-citation rate, and whose articles are assigned to a certain category, in this case determined by the co-occurrence of the Index Keywords. Index Keywords are in fact Elsevier's controlled vocabulary, which, together with their large number for

TABLE 27. Examples of the most cited publications with the Index Keyword “human” in their metadata and their Authors, Authors ID, Title, and Index Keywords list

Authors	Authors ID	Title	Citation	Index Keywords
Kamble S.S., Gunasekaran A., Gawankar S.A.	36864045000, 56238759300, 55846962200	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives	464	Accident prevention; Augmented reality; Big data; Flow control; Internet of things; Sustainable development; Automated manufacturing environments; Human machine interaction; Organizational performance; Process safety; Research and development; Smart manufacturing; Sustainable industries; Systematic literature review; Industry 4.0
Li L.	55760654300	China’s manufacturing locus in 2025: With a comparison of “Made-in-China 2025” and “Industry 4.0”	378	Embedded systems; Industrial research; Industry 4.0; Internet of things; Investments; Collaborative robots; Cyber-Physical System (CPS); Emerging economies; Human capitals; Internet of Things (IOT); Made in China; Manufacturing capability; Industrial economics; algorithm; automation; comparative study; human capital; manufacturing; research and development; robotics; China; Germany
Tseng M.-L., Tan R.R., Chiu A.S.F., Chien C.-F., Kuo T.C.	44261803600, 56962727300, 57215070441, 57219656467, 7401533845	Circular economy meets industry 4.0: Can big data drive industrial symbiosis?	203	Big data; Digital storage; Supply chains; Circular economy; Data-driven analysis; Economic perspective; Industrial 4.0; Industrial networks; Industrial symbiosis; Multiple supplies; Optimization solution; Industrial economics; automation; economic analysis; industrial production; model test; optimization; sustainability; economic aspect; human ; symbiosis
Özdemir V., Hekim N.	57203613602, 57555263500	Birth of Industry 5.0: Making sense of big data with artificial intelligence, “the Internet of Things” and next-generation technology policy	138	Article; artificial intelligence; big data; biomedicine; human ; industry; information; Internet; medicine; nonhuman; policy; priority journal; technology; legislation and jurisprudence; procedures; trends; Artificial Intelligence; Big Data; Humans ; Internet; Technology

Two papers by the author (56349650400) with profile from Scopus (Negri, Elisa; Politecnico di Milano, Milan, Italy; Scopus ID 56349650400; <https://orcid.org/0000-0002-0006-7497>; 40 documents by the author; 1 521 citations by 1 197 documents; h-index 18) are given in Table 16.

The promising topic Digital twin applications in manufacturing overlaps with the topic of cluster 1. The clustering is based on co-authorship, not proximity of the texts of publications, therefore, the result is affected by the affiliation of the authors. The authors with ID 56349650400 and ID 56687825200 are both from Milan, Italy.

Two papers by the author (35239818900) with profile from Scopus (Dwivedi, Yogesh K.; Swansea University, Swansea, United Kingdom; Scopus ID 35239818900; <https://orcid.org/0000-0002-5547-9990>; 528 documents by the author; 20 159 citations by 12 107 documents; h-index 76) are given in Table 17.

The Circular Economy topic brings the publications in Tables 15 and 17 into closer alignment. Whereas the publications in the first Table focus on more general issues of Industry 4.0, the publications in the second one address more specific areas (blockchain technology, big data, artificial intelligence, and sustainable manufacturing practices).

Remark. Clustering based on co-authorship strongly

depends on the authors’ affiliation. Thus, the first cluster may be related to China, the second to Brazil, and the third to Europe. It is very important to understand which terms prevail in the publications of a particular region/state, as this makes it easier to collect literature revealing the research and economic priorities of a particular region. The meaning of the content of articles is best reflected in their titles and abstracts; keywords are more needed when making queries to abstract databases.

When formulating promising research areas, it is advisable to use two or three key terms, rather than one, for example, Circular Economy is a very broad topic, while big data analytics + manufacturing practices + Circular Economy define a particular issue for which one can search for examples of implementations and projects, and this is of most interest to specialized professionals.

V. COUNTRIES CO-OCCURRENCE

Clustering based on co-occurrence of affiliations with countries for co-authors of publications helps to understand with which countries cooperation is developed and with which it is weak, but there is potential to increase it.

The scope of publications by country varies greatly, and the citation rate can be strongly influenced by publication activity in the native language. Therefore, at this stage of the analysis, we sort simply by the number of publications.

TABLE 28. Top Index Keywords by the number of publications in whose metadata they appear (occurrences) in cluster #2

Index Keywords	Cluster	Occurrences	Average publication year	Average normalized citations
Industry 4.0	2	610	2020.4967	2.4021
Internet of things	2	430	2020.307	2.2515
Decision making	2	391	2020.243	1.3097
Artificial intelligence	2	316	2020.4589	1.5163
Digital transformation	2	298	2020.6141	1.7262
Manufacture	2	297	2020.2054	2.1907
Construction industry	2	292	2020.411	1.2523
Digital technologies	2	272	2020.4669	1.3183
Digital twin	2	269	2020.5019	2.8927
Information management	2	250	2020.308	1.5127
Flow control	2	58	2020.2931	5.3381
Enabling technologies	2	53	2020.2642	4.4097
Manufacturing enterprise	2	21	2020.4286	4.1141
Smart manufacturing	2	111	2020.5946	3.7056
Fog	2	22	2019.8636	3.6695
Predictive maintenance	2	24	2020.625	3.4382
Fog computing	2	30	2020.2	3.2768

Table 18 shows the list of countries with the highest number of publications in the first cluster, formed on the basis of affiliations co-occurrence of co-authors by country.

Cluster 1

Despite the low level of normalized citations, both Russia and Kazakhstan have good publication activity in English, despite the fact that authors from these countries actively publish in Russian.

Multiple sampling options out of numerous bibliometric data can be justified. In this paper, the emphasis is placed on identifying the authors most relevant to a particular topic, regardless of the type of clustering: by country, index keywords, or co-authorship.

This paper underscores that the authors of publications are the final holders of knowledge and expertise. It is difficult to use an organization as a provider of knowledge; even the Scopus system itself warns that determining affiliation is challenging, since authors may write the names of their institutions differently. It is more realistic to identify the organizations involved in topics through profiles of highly cited authors.

The two most cited publications that have Indian co-authors are given in Table 19.

Profiles of Indian co-authors: Gawankar, Shradha Ashok; National Institute of Industrial Engineering, Mumbai, India; Scopus ID 55846962200; 10 Documents by the author; 793 Citations by 762 documents; h-index 7.

Sharma, Rohit; National Institute of Industrial Engineering, Mumbai, India; Scopus ID 57196545771; <https://orcid.org/0000-0001-7160-4862>; 19 documents by the author; 830 citations by 776 documents; h-index 8.

Profiles of co-authors from other countries: Gunasekaran, Angappa; California State University, Los Angeles, United States; Scopus ID 56238759300; 571 documents by the author; 33 055 citations by 22 776

documents; h-index 96.

Kamble, Sachin S.; EDHEC Business School, Roubaix, France; Scopus ID 36864045000; <https://orcid.org/0000-0003-4922-8172>; 97 documents by the author; 3 305 citations by 2 688 documents; h-index 25.

The data show that non-Indian co-authors have higher citation rates, which may affect the citation of the articles in the Table.

It seems worthwhile to conduct a separate study of the reasons why India's research performance is high in the area of "Digitalization of Industry." Advancing research topics is important for both attracting funding and gaining additional scientific knowledge through broader collaboration.

In addition to the term Industry 4.0, the titles of the cited publications include Supply Chain Disruptions, therefore, a possible theme for a more detailed study could be Supply Chain Disruptions and Industry 4.0.

Russia, within this cluster, has the greatest cooperation with India, Malaysia, Saudi Arabia, and Turkey.

Similar results, but for the second cluster, are presented in Table 20.

Here, publications with authors from Italy dominate. From the total table of publications, two articles satisfying the query "... with Affiliations to institutions in '%Italy%'" are presented in Table 21.

The first publication is more specific and has twice the number of citations, making it more appropriate for identifying issues worthy of more detailed research.

Profiles of co-authors are:

Bressanelli, Gianmarco; Università degli Studi di Brescia, Brescia, Italy; Scopus ID 57194720467; <https://orcid.org/0000-0003-2255-9983>; 18 documents by the author; 568 citations by 487 documents; h-index 8.

Adrodegari, Federico; Università degli Studi di Brescia, Brescia, Italy; Scopus ID 55932417100; <https://orcid.org/0000-0003-2255-9983>

TABLE 29. Examples of the most cited publications with the Index Keyword “**Fog computing**” in their metadata and their Authors, Authors ID, Title, and Index Keywords list

Authors	Authors ID	Title	Citations	Index Keywords
Naha R.K., Garg S., Georgakopoulos D., Jayaraman P.P., Gao L., Xiang Y., Ranjan R.	56841650300, 55365934100, 7003391364, 24824284200, 36133254500, 7201978796, 57197711780	Fog computing: Survey of trends, architectures, requirements, and research directions	221	Architecture; Big data; Computer architecture; Digital storage; Fault tolerance; Fog; Internet of things; Multitasking; Resource allocation; Surveys; Taxonomies; Allocation and scheduling; Computing architecture; Computing environments; Future research directions; Internet of thing (IOT); Internet of Things (IOT); IOT applications; Microservices; Fog computing
Kumari A., Tanwar S., Tyagi S., Kumar N.	57203787564, 56576145100, 55549655700, 57206866080	Fog computing for Healthcare 4.0 environment: Opportunities and challenges	213	Biomedical equipment; Data handling; Digital storage; Fog; Hospitals; Information services; Internet of things; Investments; Patient treatment; Capital investment; Context aware services; Future applications; Healthcare industry; Medical Devices; Real time data collections; Storage facilities; Technological advancement; Fog computing
Mellado J., Núñez F.	57221293455, 15072084200	Design of an IoT-PLC: A containerized programmable logical controller for the industry 4.0	5	Containers; Control systems; Controllers; Digital storage; Fog computing ; Industry 4.0; Automation technology; Feedback control loops; Industrial control systems; Laboratory experiments; Programmable logical controller; Programmable logical controller (PLC); Virtual device models; Wireless interfaces; Internet of things

org/0000-0001-7939-4150; 33 documents by the author; 771 citations by 658 documents; h-index 13.

Perona, Marco; Università degli Studi di Brescia, Brescia, Italy; Scopus ID 7003407947; <https://orcid.org/0000-0002-9082-2950>; 57 documents by the author; 1 901 citations by 1 677 documents; h-index 22.

Saccani, Nicola; Università degli Studi di Brescia, Brescia, Italy; Scopus ID 15849430200; <https://orcid.org/0000-0002-4603-5060>; 76 documents by the author; 2 607 citations by 1 963 documents; h-index 25.

The authors are from the same university, which contrasts with the case for Indian authors discussed above.

The goal of a prospective study may be development of the circular economy through digital technology.

The countries in the third cluster have significantly more publications than those in the first two clusters. The results are presented in Table 22.

Cluster 3

China and Great Britain have similar figures. Here are examples of highly cited papers for each country in Table 23.

A large number of co-authors is typical of Chinese publications. This can increase the citation rate of a publication, since each author may have a non-overlapping set of colleagues who could be interested in such a work.

The publication [10] was previously considered in the context of clustering based on co-authorship and the topic “Digital twin-driven product design and manufacturing” was treated as reasonable for a more detailed analysis, therefore the focus will be on the English publication and

its co-authors.

Authors Profiles in Scopus are:

Sørensen, Carsten; London School of Economics and Political Science, London, United Kingdom; Scopus ID 7102879062; <https://orcid.org/0000-0002-2002-9383>; 67 documents by the author; 2 833 citations by 2 243 documents; h-index 21.

Reuver, Mark De; Faculteit Techniek, Bestuur en Management, TU Delft, Delft, Netherlands; Scopus ID 35776955900; <https://orcid.org/0000-0002-6302-7185>; 111 documents by the author; 2 135 citations by 1 869 documents; h-index 23.

Basole, Rahul C.; Accenture, New York, United States; Scopus ID 24329464200; 80 documents by the author; 2 434 citations by 1 893 documents; h-index 22.

There is only one author from England in this article. Northern Europe and North America are characterized by publications with international co-authors. In conjunction with the large number of publishers of scientific papers in these countries, articles by such authors, along with their quality, are well cited, meaning that their topics are highly branded, which is an important factor for attracting resources for the ongoing research.

Accenture is a global professional services company with leading capabilities in digital solutions, cloud, and security, and its authors’ participation underlines the importance of the publication for the industry.

The topic “Digital Platform” is very broad. The term “digital platform” appears 591 times in the metadata used in the analysis. The area can be made more specific,

TABLE 30. Top Index Keywords by the number of publications in whose metadata they appear (occurrences) in cluster #3

Index Keywords	Cluster	Occurrences	Average publication year	Average normalized citations
Digital storage	3	1508	2020.057	1.0618
Sustainable development	3	260	2020.6231	2.016
Commerce	3	177	2020.0395	1.0148
Innovation	3	166	2020.2651	1.3495
China	3	149	2020.3624	1.7787
Sustainability	3	148	2020.4122	1.6075
Costs	3	146	2020.0685	0.9817
Energy efficiency	3	144	2019.9444	1.4081
Energy utilization	3	144	2020.2083	1.0587
Carbon dioxide	3	129	2020.0388	0.8684
Environmental economics	3	26	2020.4231	4.9271
Sustainable development goal	3	18	2021.4444	4.5386
Environmental policy	3	16	2020.5625	4.0994
Pollution control	3	19	2019.8947	3.7117
Environmental protection	3	35	2020.4857	3.1108

each publication, yields a few stable clusters. Stability can be tested by changing the clustering parameters within small limits. In this case, we have four clusters.

Various parameters can be used to select keywords for identifying promising publications. In this case (Table 26), the 10 most frequent Index Keywords and the 5 with the maximum Average normalized citations were used.

SQL like “human” operator was used to select articles from the full metadata table. The two most cited ones are given in Table 27.

The dominant theme is Industry 4.0 in its usual context: artificial intelligence, big data, industry, information, Internet, data-driven analysis, economic outlook, augmented reality, and Internet of Things (IoT) combined with the keyword “human.” These results are expected. Interesting is the emergence of the Industry 5.0 theme presented in the article [32].

The term “Industry 5.0” appears 128 times in the collected metadata. It is possible to trace the emergence of the term in more detail over the past years, but this is beyond the scope of this article and can be addressed in a special publication revealing the specific aspects of Industry 5.0 digitalization that distinguish it from Industry 4.0.

Authors profiles in Scopus are:

Özdemir, Vural; OMICS: A Journal of Integrative Biology, New Rochelle, United States; Scopus ID 57203613602; 186 documents by the author; 3 374 citations by 2 562 documents; h-index 29. This author publishes articles on medicine and genetics; therefore, his opinion on Industry 5.0 in the life science context is of interest.

Hekim, Nezihi; Biruni Üniversitesi, Istanbul, Turkey; Scopus ID 57555263500; 22 documents by the author; 323 citations by 310 documents; h-index 7. This author also publishes medical articles.

The interest in the Society-5.0-and-Industry -5.0 topic is exemplified by the 2022 paper [33], already cited three

times in Scopus.

Although betacoronavirus is the most cited topic in this cluster according to “Average normalized citations,” it is too broad and overrides the purpose of this article, i.e., Digital Industry.

While humanities challenges of Industry 4.0 dominate the previous cluster, the engineering issues prevail in the second cluster (Table 28).

The selection of the topic “fog computing” is strictly subjective. Query TITLE-ABS-KEY («fog computing») in Scopus matches 7 713 papers, and the specialized abstract database OnePetro yielded only 2 peer-reviewed publications as of July 30, 2022.

Therefore, it is reasonable to determine in which periodicals other than the Society of Petroleum Engineers the results of research on the implementation of fog computing in the oil and gas sector are published. By analyzing the proceedings of non-peer-reviewed conferences, for example, one can find out the current problems of fog computing for petroleum engineering and then discover their solutions in the publications indexed in Scopus.

Table 29 shows three papers that contain the term “fog computing” not only in the Index Keywords but also in the titles.

The first article in the Table is a review article, while the second one, on the contrary, focuses on a specific industry – Healthcare 4.0. Case-specific articles reveal potential problems related to the implementation of Fog computing better than review publications. Therefore, we consider the profiles of the authors of the second publication.

Authors profiles in Scopus are:

Kumari, Aparna; Nirma University, Institute of Technology, Ahmedabad, India; Scopus ID 57203787564; <https://orcid.org/0000-0001-5991-6193>; 32 documents by the author; 891 citations by 662 documents; h-index 14.

Tanwar, Sudeep; Nirma University, Institute of

TABLE 31. Examples of the most cited publications with the Index Keyword “Digital storage” in their metadata and their Authors, Authors ID, Title, and Index Keywords list

Authors	Authors ID	Title	Citation	Index Keywords
Tao F., Cheng J., Qi Q., Zhang M., Zhang H., Sui F.	12141248300, 57192081753, 57193673728, 57192100009, 57190839107, 57189511188	Digital twin-driven product design, manufacturing and service with big data	1 059	Big data; Design; Digital storage ; Industrial research; Manufacture; Product design; Cyber and physical convergence; Digital twin; Future applications; Manufacturing enterprise; Product life cycle management; Product lifecycle data; Product-life-cycle; Service; Life cycle
Naha R.K., Garg S., Georgakopoulos D., Jayaraman P.P., Gao L., Xiang Y., Ranjan R.	56841650300, 55365934100, 7003391364, 24824284200, 36133254500, 7201978796, 57197711780	Fog computing: Survey of trends, architectures, requirements, and research directions	221	Architecture; Big data; Computer architecture; Digital storage ; Fault tolerance; Fog; Internet of things; Multitasking; Resource allocation; Surveys; Taxonomies; Allocation and scheduling; Computing architecture; Computing environments; Future research directions; Internet of thing (IOT); Internet of Things (IOT); IOT applications; Microservices; Fog computing
Dong F., Yu B., Hadachin T., Dai Y., Wang Y., Zhang S., Long R.	45661148900, 57193681442, 57196344975, 57158064800, 55733813600, 57196348422, 8396729800	Drivers of carbon emission intensity change in China	182	Digital storage ; Emission control; Energy efficiency; Regression analysis; Carbon emission intensities; China; Energy conservation and emission reductions; Industrial sector; Product structure; Quantile regression; Structural decomposition analysis (SDA); Technical progress; Industrial emissions; carbon emission; energy conservation; energy efficiency; environmental economics ; Gross Domestic Product; regression analysis; urbanization; agriculture; Article; carbon footprint; China; coal power; economic development; energy conservation; industrialization; industry; urbanization; China
Ma M., Cai W.	57192905542, 57043939900	What drives the carbon mitigation in Chinese commercial building sector? Evidence from decomposing an extended Kaya identity	99	Carbon; Climate models; Decomposition; Digital storage ; Energy efficiency; Energy utilization; Office buildings; Quality control; Building energy consumption; Carbon mitigation; Commercial building; Decomposition analysis; Kaya identity; Energy conservation; carbon; building; carbon emission; decomposition analysis; emission control; energy efficiency; environmental assessment ; environmental economics; analytic method; Article; building industry; carbon footprint; climate change; decomposition; energy conservation; energy resource; feasibility study; priority journal; quality control; China; Torreya nucifera

Technology, Ahmedabad, India; Scopus ID 56576145100; <https://orcid.org/0000-0002-1776-4651>; 304 documents by the author; 5 115 citations by 2 854 documents; h-index 41.

Tyagi, Sudhanshu; Thapar Institute of Engineering & Technology, Patiala, India; Scopus ID 55549655700; <https://orcid.org/0000-0002-2989-3098>; 94 documents by the author; 3 194 citations by 1 933 documents; h-index 31.

Kumar, N.; Thapar Institute of Engineering & Technology, Patiala, India; Scopus ID 57206866080; <https://orcid.org/0000-0002-8923-2208>; 791 documents by the author; 20 779 citations by 13 029 documents; h-index 77.

All the authors work in India but at different institutes. They have a lot of publications and high citations, which makes it reasonable to analyze other publications on the subject affiliated with Nirma University, Institute of Technology, and Thapar Institute of Engineering & Technology and determine if they are working on a single program or project.

Table 30 again indicates the case of the dominance of

the Index Keyword Digital Storage, which seldom appears in the titles and abstracts of the publications in question but is frequent in the Index Keywords.

Although Scopus labels the largest number of published papers by Digital Storage, the most cited articles in this cluster refer to Environmental Economics and the Sustainable Development Goals. Both Index keywords “Digital Storage” and “Environmental Economics” are found in the last two articles in Table 31.

The first paper has already been mentioned in Cluster 1 about the co-authors, and the second one when considering Fog computing, the term Digital storage is not found in these papers. It is purely the result of assigning the label Digital storage to these publications by the publishing system, hence we will not consider them in this section.

Note. The list of Index keywords can be very large compared to the list of Author keywords. In the bibliometric data collected from Scopus, the total number of (non-unique) Author Keywords is 48 324 or 5.68 per article, and Index Keywords are 113 305 or 17.9 per entry.

TABLE 32. Top Index Keywords by the number of publications in whose metadata they appear (occurrences) in cluster #4

Index Keywords	Cluster	Occurrences	Average publication year	Average normalized citations
3D printers	4	234	2020.2137	1.696
Machine learning	4	207	2020.6087	1.3437
Quality control	4	150	2020	1.4176
Deep learning	4	141	2020.6383	1.5361
Forecasting	4	129	2020.4806	1.2191
Additives	4	121	2020.3471	1.3959
Gas industry	4	121	2020.1901	0.8425
Image analysis	4	115	2019.9391	0.6595
Algorithm	4	101	2020.0396	1.198
Petroleum industry	4	93	2019.957	0.6246
Deep neural networks	4	24	2021	4.1635
Food industries	4	19	2020.8421	4.0852
Support vector machine	4	18	2020.0556	2.5202
Measurement accuracy	4	17	2020.2941	2.3512

TABLE 33. Examples of the most cited publications with the Index Keyword “3D printers” in their metadata and their Authors, Authors ID, Title, and Index Keywords list

Authors	Authors ID	Title	Citations	Index Keywords
Delgado Camacho D., Clayton P., O'Brien W.J., Seepersad C., Juenger M., Ferron R., Salamone S.	57196234223, 39360892000, 36485213300, 6508183775, 6701841561, 16241303300, 35574901800	Applications of additive manufacturing in the construction industry – A forward-looking review	147	Accident prevention; Compensation (personnel); Construction industry; Copying; Disaster prevention; Manufacture; Printing; Productivity; Quality assurance; Wages; 3-D printing ; Construction workforces; Conventional constructions; Experimental application; High performance material; Infrastructure construction; Interdisciplinary research; Non-structural elements; 3D printers
García de Soto B., Agustí-Juan I., Hunheviz J., Joss S., Graser K., Habert G., Adey B.T.	57219474603, 56204634800, 57217925661, 57201885481, 57193861254, 8391064400, 6602448661	Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall	144	3D printers; Automation; Concretes; Construction industry; Cost benefit analysis; Costs; Economic and social effects; Productivity; Robotics; Walls (structural partitions); 3-D printing ; Construction automation; Digital fabrication; Industrialized construction; Labor productivity; Robot system; Robotic construction; Fabrication

Index Keywords are available for clustering, but the topic is better determined from the original texts, and the most concise summary of the content is the title of the article.

A promising research issue could be the Drivers of carbon mitigation [34] in the context of the Digital Industry. As the last publication in the Table is a more specific case, the authors' information will be examined in more detail.

Authors profile in Scopus are:

Ma, Minda; Tsinghua University, Beijing, China; Scopus ID 57192905542; <https://orcid.org/0000-0002-5533-656X>; 34 documents by the author; 1 628 citations by 945 documents; h-index 22.

Cai, Weiguang; Chongqing University, Chongqing, China; Scopus ID 57043939900; 69 documents by the author; 2 064 citations by 1 333 documents; h-index 27.

Cai, Weiguang; Chongqing University, Chongqing, China; Scopus ID 57043939900; 72 documents by the author; 2 192 citations by 1 406 documents; h-index 27.

Energy efficiency in the building sector (and thus carbon mitigation) is especially important for large data centers, where projects to recover the heat dissipated when cooling servers are in demand.

The last cluster of Index keywords, shown in Table 32, can be attributed to manufacturing based on 3D printing optimized by using AI.

The 3D printer is perhaps the most in-demand technology in digital manufacturing and main areas of its application are gas, petroleum, and food sectors, as listed in Table 32.

The fact that “deep neural networks” are a highly cited topic is a quite expected result. Support vector machine is inevitably found in machine learning topics. However, it is worth noting that derived metrics like Average normalized citations should be used with caution, for example, the most cited publication for the Index keyword “deep neural networks” was published in 2019 and has only 24 citations [35].

The 3D printing is a very broad topic. It is important to almost every industry. Table 33 shows two highly cited articles related to the construction industry.

The first article is an overview, and we look at the data on the authors of the second article [36]. There are many co-authors, so we present data on the three with the highest h-index.

Table 34. Examples of the most cited publications with the Index Keyword “deep neural networks” in their metadata and their Authors, Authors ID, Title, and Index Keywords list

Authors	Authors ID	Title	Citations	Index Keywords
Moreno-García C.F., Elyan E., Jayne C.	56332688500, 35226184300, 36608214500	New trends on digitization of complex engineering drawings	22	Classification (of information); Complex networks; Computer vision; Deep learning; Deep neural networks ; Feature extraction; Image analysis; Image segmentation; Neural networks; Processing; Contextualization; Convolutional neural network; Digitization; Engineering drawing; Recognition; Engineering education

Authors profile in Scopus are:

Habert, Guillaume; ETH Zürich, Zurich ZH, Switzerland; Scopus ID 8391064400; <https://orcid.org/0000-0003-3533-7896>; 166 documents by the author; 6 047 citations by 4 510 documents; h-index 40.

Adey, Bryan Tyrone; ETH Zürich, Zurich ZH, Switzerland; Scopus ID 6602448661; 141 documents by the author; 1 357 citations by 1 060 documents; h-index 19.

García de Soto, Borja; NYU Abu Dhabi, Abu Dhabi, United Arab Emirates; Scopus ID 57219474603; <https://orcid.org/0000-0002-9613-8105>; 63 documents by the author; 568 citations by 478 documents; h-index 11.

“Productivity of digital fabrication in construction” AND “3-D printing” is a request that deserves an in-depth analysis.

Table 34 presents the data of the article that has high Average normalized citations (4.1635) and contains “deep neural networks” in the Index Keywords.

Authors profile in Scopus is:

Moreno-García, Carlos Francisco; Robert Gordon University, Aberdeen, United Kingdom; Scopus ID 56332688500; <https://orcid.org/0000-0001-7218-9023>; 44 documents by the author; 216 citations by 145 documents; h-index 9.

Elyan, Eyad; Robert Gordon University, Aberdeen, United Kingdom; Scopus ID 35226184300; <https://orcid.org/0000-0002-8342-9026>; 59 documents by the author; 1 051 citations by 912 documents; h-index 16.

Jayne, Chrisina; Teesside University, Middlesbrough, United Kingdom; Scopus ID 36608214500; <https://orcid.org/0000-0001-7292-2109>; 68 documents by the author; 759 citations by 686 documents; h-index 15.

Topic “Digitization of complex engineering drawings.” This topic is not perceived as a hyped one, but as the authors of the article note, “Digitizing engineering drawings is becoming increasingly important mainly due to the legacy of drawings and documents that may provide rich source of information for industries.”

VII. CONCLUSIONS

The study has identified the prospective research issues on the topic of Digital Industry based on the analysis of Scopus bibliometric data for 2018–2022. The final formulation of the problems is telling, for example, in the text of the article, one can find the following formulations: “Industry 4.0 technologies for industrial performance,”

“Industry 4.0 and innovations,” “Sustainable, Innovative, Technology-efficient Industry 4.0.” They suggest using the query “Industry 4.0 technologies AND (performance OR innovations OR efficient)” for a thorough analysis. In any case, such queries are nothing more than a starting point for further research of promising issues and will be refined according to the results of queries to abstract databases. It is not necessary to perform a comprehensive analysis of bibliometric data to identify the topics of new studies. These data however suggest a sufficient number of high-cited papers, their authors, and the authoritative organizations with which the authors are affiliated.

The promising research issues on the topic of Digital Industry, which have been chosen for a more detailed study in later works (here AND and OR are operators), are:

- (Social dimension) AND (Digital Industry);
- (Digital twin-driven) AND (Product design OR Manufacturing OR Service);
- (Energy management) AND (Fog computing OR Edge computing);
- (Industry 4.0 technologies) AND (Performance OR Innovations OR Efficient);
- (Circular Economy) AND Industry 4.0;
- Digital twin applications in manufacturing;
- India AND (Digitalization of Industry);
- (Supply Chain Disruptions) AND Industry 4.0;
- Industry 5.0 vs Industry 4.0 digitalization;
- (Carbon mitigation) AND (Digital Industry.)

Note: Fuller tables than those presented in the text of this paper, some JSON files that can be used to view co-occurrence graphs using the app.vosviewer.com service, and the main summary graphs provided by Scopus for the metadata used are available by direct link: https://figshare.com/articles/dataset/Identification_of_promising_research_issues_in_the_Digital_Industry_topic_by_analyzing_Scopus_bibliometric_data_for_2018_2022/20431071.

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Ensuring the Reliability of Energy Systems with a New Method for Reducing Seasonal Variations in Ground Resistance

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Abstract—The paper shows the possibility of improving the reliability of a grounding system. The moisture dependence of soil resistivity is analyzed. Based on the analysis, the soil composition was proposed to normalize (reduce seasonality) its electrical resistivity. Several full-scale experiments are carried out to measure the resistance of grounding devices of experimental circuits, after backfilling the places of laying the circuit components with soil of various compositions and using other types of soils and minerals.

Index Terms: Resistance, grounding circuit, hydrogel, graphite, deep-driven electrode, near-electrode space, seasonality coefficient.

I. INTRODUCTION

The uninterrupted operation of electrical plants requires reliable grounding, which can reduce the risk of electric shock to maintenance personnel and protect equipment. It is well known that the electrical resistance of the grounding circuit is determined by many factors, such as soil porosity, soil moisture, freezing depth, and mineral salt content [2]. These parameters change throughout the year, which is why the so-called seasonal coefficient is introduced to calculate the grounding circuit.

This study aims to develop a method to reduce the effect of seasonality on the resistance of grounding devices.

II. WAYS TO REDUCE THE SEASONAL COEFFICIENT

The spreading resistance of a grounding device depends on the types of soil (sand, clay, limestone), particle size and density, moisture and temperature, as well as the chemical composition of soil, i.e., the presence of acids,

salts, and alkalis in it [1, 2]. The determining parameters for seasonal effects on soil resistivity, in turn, are moisture and temperature [3, 4]. It can be concluded that an increase in the ability of the soil to retain water with minerals and salts dissolved in it in the near-electrode space improves the properties of the grounding device.

An analysis of the previously studied moisture dependences of soil resistance, which are described, in particular, in [9], indicates their good agreement with the results obtained by the authors and presented in Fig. 1. The analysis shows that stabilization of soil moisture occurs at 12–16 mass percent and it is optimal, since further increase in moisture no longer leads to any significant decrease in resistance (Fig. 1).

One of the well-known ways to reduce the effect of change in annual temperature on the grounding device resistance is the use of deep-driven electrodes. The disadvantages of this method include the high metal intensity of work.

Another way to reduce seasonal fluctuations in resistance is to use electrolytic electrodes. Electrolytic grounding is a tubular electrode with a diameter of 50–110 mm, 3 m long, which is made of stainless steel with perforations on the walls. The electrodes are filled with an electrolyte based on mineral salts [6, 7]. Known mineral activators produced in the CIS are a mixture of an ion-exchange salt modified with a halide activator and a surfactant. The disadvantage of such grounding electrodes is the use of corrosion-resistant steel or non-ferrous metals as an electrode material [5]. In addition, this method contributes to soil salinization and an increase in the rate of destruction of metal structures located in close proximity to the grounding device.

III. EXPERIMENTAL STUDIES

The research presented in this paper involved developing a soil-substituting mixture based on hydrogel, bentonite clays, and graphite.

The use of hydrogel is due to its ability to bind water in the near-electrode space, which helps to maintain a stable moisture level. Maintaining the same soil moisture throughout the year allows stabilizing the quantity of mineral salts dissolved in the soil, which has a positive

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<http://dx.doi.org/10.25729/esr.2023.02.0003>

Received March 05, 2023. Revised April 17, 2023.

Accepted May 11, 2023. Available online June 10, 2023.

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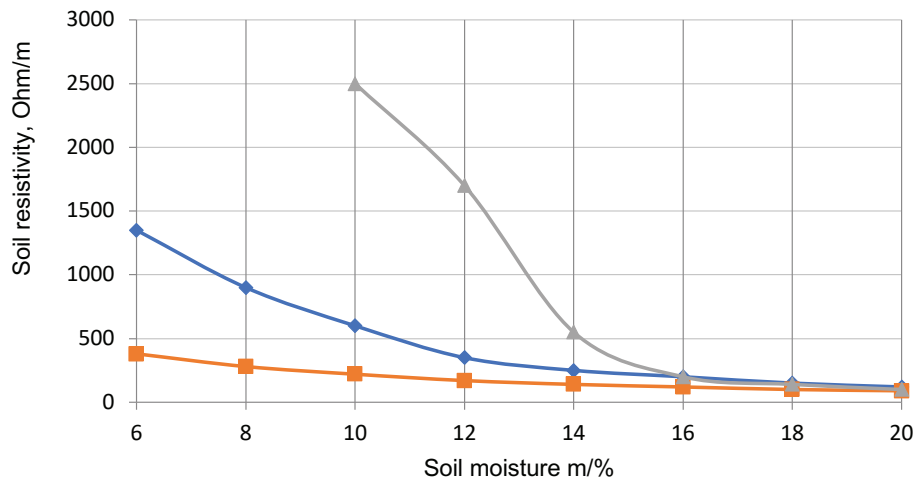


Fig. 1. Relationship between spreading resistance of various soils and moisture, expressed in mass percent.

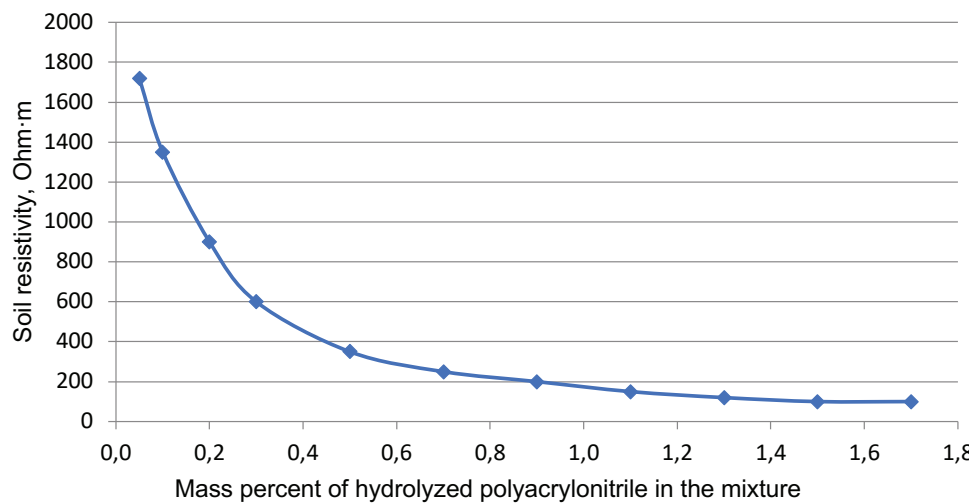


Fig. 2. Relationship between soil resistivity and percentage of injected gel based on hydrolyzed polyacrylonitrile.

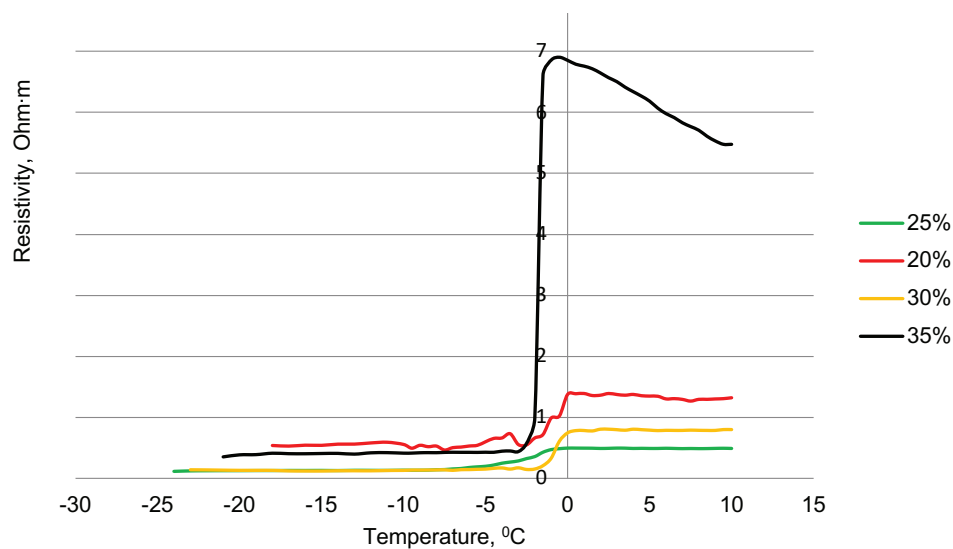


Fig. 3. Temperature versus resistivity for the mixture at varying moisture.

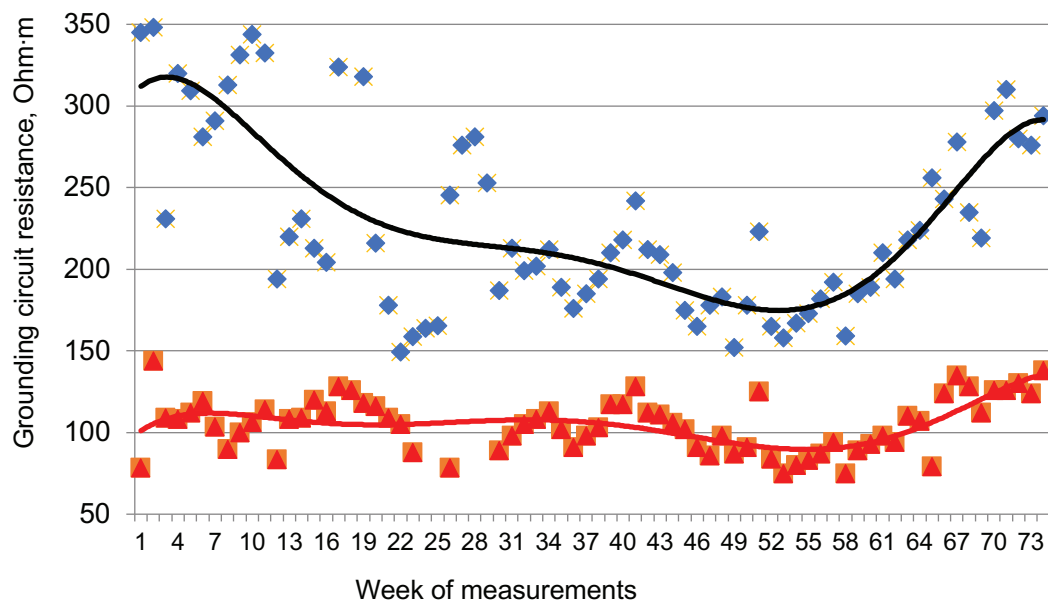


Fig.4. Values of spreading resistance for the control circuit (blue markers and line) and experimental circuit (red markers and line), measured every 10 days, starting in September.

effect on the spreading resistance in the soil.

Figure 2 shows the results of the resistivity measurements for a mixture of soil with hydrolyzed polyacrylonitrile in various proportions.

As seen in the graph presented in Fig. 2, with hydrogels obtained by swelling hydrolyzed polyacrylonitrile with a dry weight of more than 1.3–1.5% of the soil mass, moisture gets stabilized, and a further increase in concentration does not lead to a decrease in soil resistivity, which indirectly indicates that the optimal soil moisture is obtained.

The use of graphite in this mixture is necessary to compensate for the decline in conductivity in mixtures when the crystallization temperature of water is reached. Conducted experimental and field studies revealed that the use of graphite powder allows keeping the resistance of the mixture at a low level even at sub-zero temperatures (Fig. 3).

Field experiments involved the installation of grounding devices consisting of two vertical electrodes made of ordinary black steel with a diameter of 12 mm and a length of 2 m. These vertical electrodes were connected by a 4×40 mm horizontal strip, 4 m long. During the installation, the soil in the near-electrode volume of soil of the experimental circuit was replaced with a mixture. Systematic measurements of the control and experimental grounding devices were carried out using a four-wire method with an IS-10 measurement device, according to the method proposed by the manufacturer.

The results of experimental studies on the resistance of the control and experimental circuits are shown in Fig. 4. The data obtained enable us to conclude that the lowest resistance value is characteristic of the grounding device whose near-electrode space is treated with an experimental

mixture to reduce the spreading resistance of the grounding device. The findings suggest that the resistance of the grounding circuit changes slightly, which is also an evidence of the decrease in the influence of the seasonal coefficient. It is worth noting that there is an overall decline in the resistance of such a circuit with regard to the control one.

As seen in the graph, the use of hydrogel reduces not only fluctuations in the spreading resistance of the grounding device but also the resistance of the grounding device in comparison with the control circuit. The use of the proposed additive also decreases the freezing point of the soil by 4–6°C, which makes it possible to use higher average long-term low temperatures when determining the climatic zone of the site for the electrical equipment to be designed, and to reduce the seasonality coefficients when interpreting field measurements. The conducted studies show that the effect on the reduction in the electrical resistance can be divided into 2 factors: a change in the seasonality coefficient and a decline in the soil resistivity in the near-electrode space, which allows adjusting the calculations of the ground electrode resistance when using mixtures during the installation of the grounding device. It is obvious that the larger the difference in resistivity between the soil and the mixture, and the greater the amount of soil replaced in the near-electrode space, the higher the efficiency of such a replacement. However, the previous studies [6] indicate that there is a relatively small optimal volume (~10 cm in a radius around the electrodes) when such a replacement is as efficient as possible and a further increase in the volume of soil to be replaced loses its efficiency according to an exponential law.

This will ensure the longest possible prevention of soil

freezing in the autumn-winter period, which is one of the factors for the high-quality operation of the grounding device.

IV. CONCLUSION

The use of a soil-substituting mixture reduces the influence of seasonal temperature fluctuations, thereby providing stable performance of the grounding circuit functions, which has a positive effect on the stability and reliability of energy systems. Reduction in the influence of external factors on the resistance of the grounding device will enable a more rational approach to the consumption of materials and a reduction in labor costs, and will improve the reliability of grounding and electrical plants in general. The method developed to reduce the seasonality coefficient by using a soil-substituting mixture in the near-electrode space allows the use of ordinary black steel [5].

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Application of FACTS Devices for Damping of Low-Frequency Oscillations in Azerbaijan's Power System

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Abstract — The structure of Azerbaijan's power system is characterized by its substantial heterogeneity, i.e., unevenly loaded transmission lines in a large number of power flows, limited possibility of wheeling through backbone tie-lines due to the bypass power grid operation. The use of Flexible AC Transmission System (FACTS) devices makes it possible to impart active properties to a passive electrical network and thus provide flexible control over the operation of the power system. FACTS devices increase the transfer capability of the electrical network. It is known that a system of automatic control of damping can be used to augment the stability of power systems. Damping may be achieved using other devices installed with the express purpose of stability augmentation. Disruption of stability of the power system is the result of loss of synchronism of the generator rotor because of insufficient damping torque of low-frequency oscillations (usually 0.1–1.0 Hz) and local oscillations (1–3 Hz). We propose improving the damping of low-frequency oscillations by placing a unified power flow controller in the power system. The efficiency of the application is demonstrated through a case study of a 220 kV – 330 kV – 500 kV network.

Index Terms : power system, FACTS devices, unified power flow controller, damping of low-frequency oscillations, static synchronous compensator.

I. INTRODUCTION

FACTS devices have mainly been used to address various tasks of power system steady-state operation, such as voltage regulation, power flow management, and transfer capability enhancement.

As a rule, the installation of FACTS devices for the sole purpose of augmenting power system stability is economically unfeasible.

This study examines reactive power distribution using different types of FACTS with electronic devices. We analyze the problem of stabilizing the power system by using a static synchronous compensator (STATCOM) to increase the damping of electromechanical oscillations of the power system and control the system voltage. The proposed combined control by STATCOM and Unified Power Flow Controllers (UPFC) through online coordinated control to dampen oscillations improves stability of the power system. These devices must be supplemented with an auxiliary controller for damping low-frequency oscillations.

The structure of Azerbaijan's power grid is characterized by its pronounced heterogeneity, due to which for a large number of power flows there is an uneven load of transmission lines observed, in connection with which the operating conditions of the bypass power grid can limit the capabilities of wheeling along the backbone links.

The use of FACTS devices makes it possible to impart active properties to the passive power grid and thereby implement flexible control over power system operating conditions [1–4].

II. APPLICATION OF FACTS DEVICES FOR DAMPING OF LOW-FREQUENCY OSCILLATIONS IN POWER SYSTEMS

The main advantage of the STATCOM and Unified Power Flow Controller (UPFC) is their speed. The time of transition from the maximum reactive power generation to the maximum consumption is less than 0.01 s.

The stability of power systems depends on complex interrelationships, and it is the main challenge facing the power system.

The power system may cease to provide adequate damping for cross-zone oscillations and variation of voltage profile. The use of FACTS devices can contribute to effective damping of low-frequency oscillations and improve bus voltage levels.

The unified power flow controller is the most promising device in the FACTS concept. It has the ability to adjust three control parameters, i.e., busbar voltage, transmission

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<http://dx.doi.org/10.25729/esr.2023.02.0004>

Received March 13, 2023. Revised April 21, 2023.

Accepted May 13, 2023. Available online June 10, 2023.

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line reactance, and phase angle between two busbars simultaneously or independently. The UPFC does this by controlling the in-phase voltage, quadrature voltage, and shunt compensation [3, 4].

The UPFC can control the three control parameters either individually or in appropriate combinations on its series-connected output, thereby maintaining reactive power support on its parallel input.

It is generally recognized that adding an additional controller to the UPFC can significantly improve the damping of the power system. Therefore, several control configurations have been proposed to address the task of oscillation damping.

Huang et al. attempted to use a UPFC placed on the transmission line of a two-zone system to damp the oscillation between sections [5].

A PI controller with multiple inputs and multiple outputs was proposed. The study shows that if more than one UPFC controller, such as a power flow controller, AC voltage controller, and DC voltage controller, are designed separately, the dynamic interaction between different control channels can disturb the stability of the system.

Mishra et al. developed various intelligent damping controllers for the UPFC to damp both local and cross-zone oscillations for a multi-machine system. The efficiency of such controllers was demonstrated and described in a fairly successful way [6].

FACTS devices allow solving a wide range of problems: from voltage regulation at the buses of a power grid and the redistribution of active and reactive power flows between networks of different voltage classes, to an increase in the degree of utilization of the transfer capability of the power grid [1–4].

The use of the STATCOM and UPFC for the sole purpose of damping frequency oscillations of the power system may prove economically unfeasible. At the same time, the steady state control produces a large economic effect.

III. CONTROLLED AND UNCONTROLLED SERIES COMPENSATION DEVICES (SCD).

The use of SCDs makes it possible to increase the transfer capability of power lines and controlled cutsets, to redistribute active power flows across power lines, including those of different voltage classes, and to damp low-frequency power oscillations (if the SCD has a controlled part).

The use of phase-shifting devices (PSDs) enables voltage regulation at the installation site with respect to both the magnitude and the phase, while changing both active and reactive power on the corresponding power grid component.

Wide-area damping control (WADC) is a class of automatic control systems used to augment the stability of modern electric power systems known as smart grids. The controller is actuated by modulation of active or reactive

power devices throughout the grid. Such actuators are most often pre-existing power system devices such as static VAR compensators (SVCs), which serve primary purposes, which are not directly related to the WADC application. However, damping may be achieved with the other devices installed with the express purpose of stability augmentation. The instability of a large power grid not equipped with WADC results from the loss of synchronism of the generator rotor and is usually treated as a generator (or a group of generators) oscillating along an undamped exponential trajectory because of inadequate damping torque.

A combination of the STATCOM and UPFC added to the dual-zone system significantly increases oscillation damping and augments power system stability.

This involves coordination between the STATCOM controller and UPFC and is taken into account to enhance system stability during transients and to regulate the system voltage.

The static synchronous series compensator (SSSC) is a flexible AC transmission system which consists of a voltage source inverter coupled with a transformer connected in series with a transmission line. This device can inject an almost sinusoidal voltage in series with the line. The injected voltage can be considered as an inductive or capacitive reactance connected in series with the transmission line. This feature can provide controlled voltage compensation. In addition, SSSC can reverse the power flow by injecting a sufficiently large series reactive compensating voltage [3], [4].

The UPFC uses solid-state devices that provide functional flexibility normally unattainable with a conventional thyristor-controlled system. The UPFC is a combination of a static synchronous compensator and a static synchronous series compensator that are coupled via a common DC voltage link.

IV. FACTS DEVICES BASED ON STATCOM AND UNIVERSAL POWER FLOW CONTROLLER

Power system stability is the ability of an electric power system under given initial operating conditions to restore the state of operating equilibrium after exposure to a physical disturbance, with most system variables constrained so that virtually the entire system remains intact.

The power system stabilizer (PSS) is generator control equipment that is used in feedback to amplify the damping of rotor oscillations caused by small signal disturbances. These disturbances can be caused by even a small change in the automatic excitation control (AEC) reference voltage, which results in a constant increase in rotor oscillations.

This is achieved by modulating the AEC so that the electric torque components develop in phase with the rotor speed deviations. Thus, the PSS contributes to the stability augmentation of power systems under weak signal conditions.

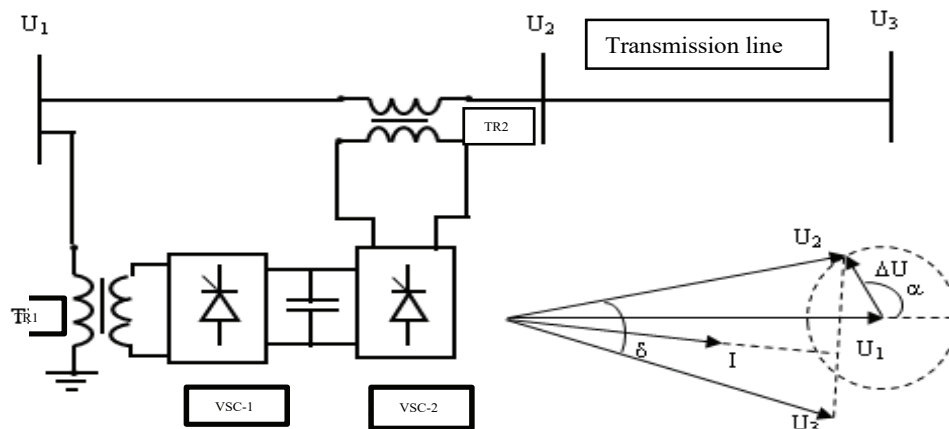


Fig. 1. The model of the UPFC system for damping of power system oscillations. TR1 – Transformer 1; TR2 – Transformer 2; VSC-1 – Voltage Source Converter-1; VSC-2 – Voltage Source Converter-2.

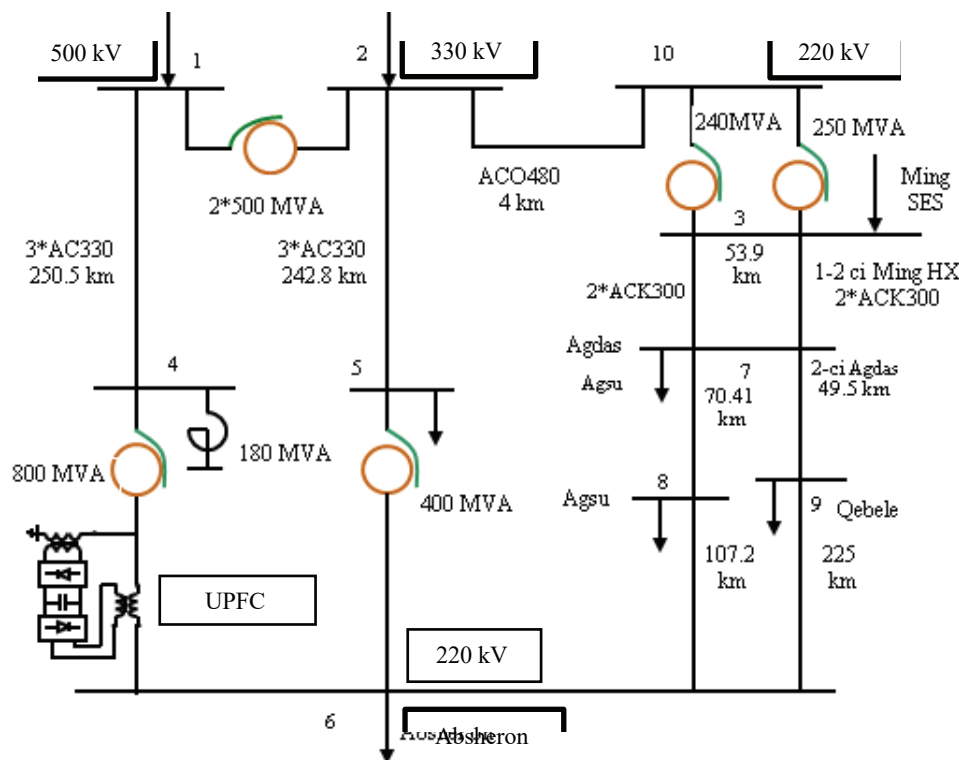


Fig. 2. Equivalent circuit of the 220-330-500 kV section.

TABLE. Calculation Results for Power Flows with and without the UPFC

Branch 4–6	Active power flows in overhead line, MW				Active power loss in overhead line, MW			δ_6 , degree
	P_{500}	P_{330}	P_{220}	ΔP_{sum}	ΔP_{500}	ΔP_{330}	ΔP_{220}	
With UPFC	971.4	403.1	433.0	57.81	30.7	12.3	14.4	-21.09
Without UPFC	888.3	449.0	482.0	69.27	30.5	17.6	21.2	-25.95

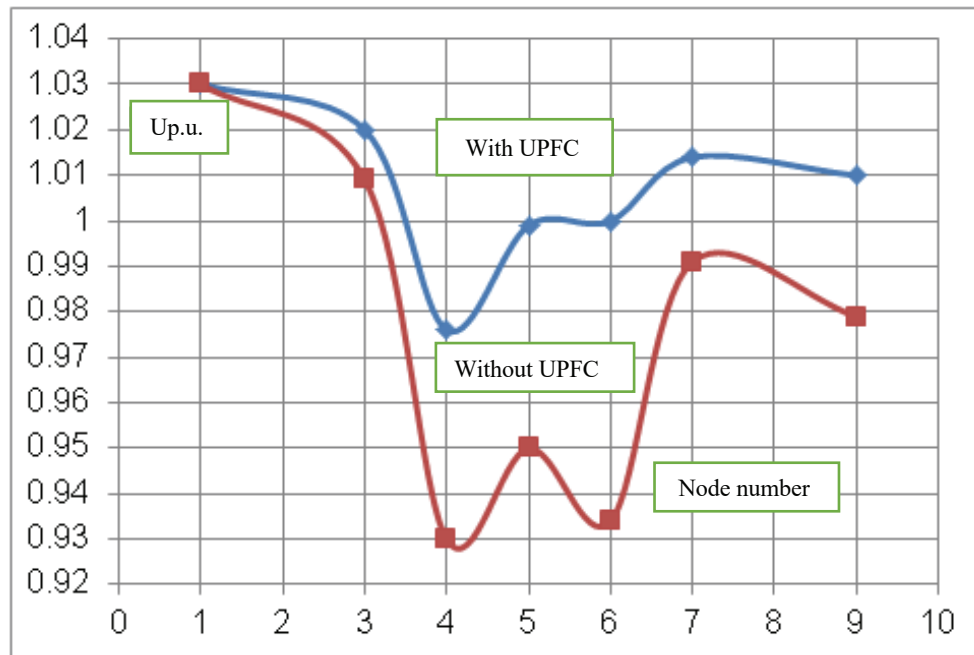


Fig. 3. Voltage profile by node.

Interconnected power systems are prone to generator rotor instability, especially when disparate groups of machines are connected to the system through power lines with UHV overhead lines. Oscillations between zone sections pose the greatest threat to widespread accidents leading to significant power outages.

The rotor instability phenomena can be studied by considering two different types of disturbances: weak-signal and transient ones.

The study of stability with a weak signal disturbance considers the electrical network to be under “normal” operating conditions, whereas the study on stability during transients examines the ability of the system to remain stable under large disturbances (e.g., transmission line failures). While many different features of the electrical network affect rotor stability (e.g., transmission line overloading, power system stabilizer (PSS) settings, etc.), the WADC architecture introduces sufficient torque to suppress the negative effects of resonant systems.

The static VAR compensator (SVC) is one of the FACTS shunting devices that augments network stability by limiting low-frequency oscillations, and others. The PSS also effective in damping of oscillations.

The STATCOM has an output feedback controller, and the PSS has a PI controller. These STATCOM and PSS devices are used together to improve the damping of power system oscillation.

V. POWER SYSTEM STABILIZERS (PSS)

Excitation systems with a high gain factor and short response time greatly augment transient stability but can also reduce the stability of small signals (damping torque). Power system stabilizer control contributes to

stability augmentation by damping generator rotor angle oscillations, which are in a wide range of frequencies in the power system. These vary from low-frequency cross-grid (usually 0.1–1.0 Hz), to local (usually 1–2 Hz) and in-plant (about 2–3 Hz) ones.

Weak links in line operations and large system loads can lead to poorly damped power flows between individual buses. PSS control can usually provide significant improvements in power flow damping between individual buses by applying stabilizers to most of the units that participate in power flows with power swings.

The PSS provides an excitation voltage modulation that dampens power and speed oscillations by means of conventional automatic voltage regulation (AVR) control. A study of its settings determines the optimal PSS settings based on the specific generator, automatic excitation control (AEC) settings, and system characteristics.

PSS is usually tested when the plant is put into operation. The testing condition for a PSS is that the output power has to be equal to the plants’s base load or a value close to it. The testing of modern excitation systems is facilitated by the use of internal data logging and test signals.

Modern FACTS devices require state-of-the-art testing and validation approaches. These compensators can also be used to reduce voltage oscillations.

The problem of FACTS device placement is usually solved using heuristic optimization methods, which are diverse and constantly improving.

Short-term problems with voltage stability are usually due to the rapid response of voltage regulators (AVR of generators) and power electronic converters, such as those found in flexible AC transmission systems. In the case of voltage regulators, voltage instability is usually due to

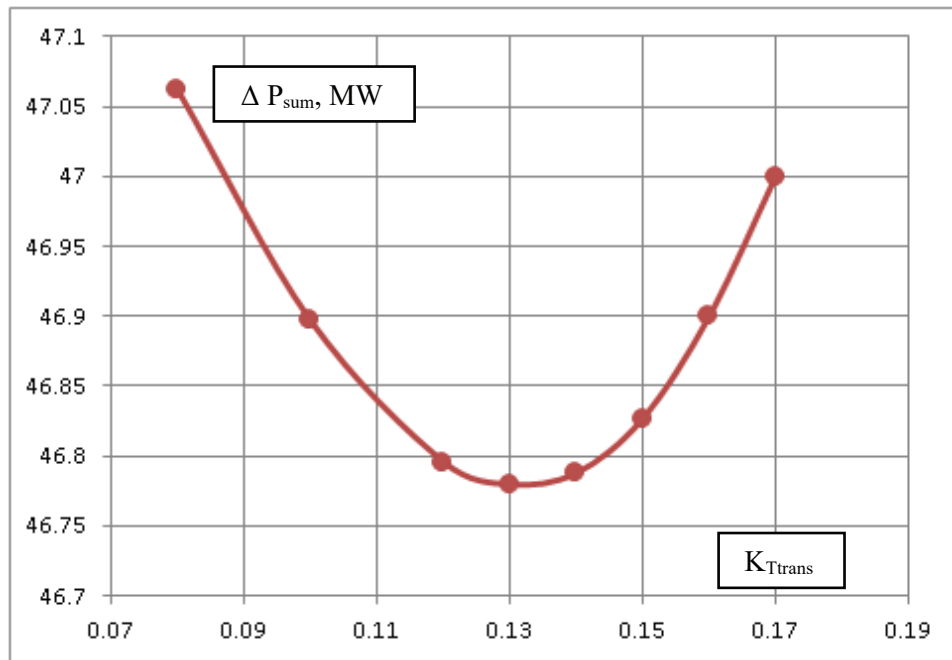


Fig. 4. Relationship between active power loss and the transverse component of the complex transformation ratio.

incorrect parametrization of the system controllers.

The equivalent circuit of the 220-330-500 kV section of Azerbaijan's power system combining two zones is shown in Fig. 2.

We consider the installation of a STATCOM (on the 220 kV buses of the Absheron substation with 220 kV, 330 kV, and 500 kV incoming transmission lines) and a UPFC (on the 500 kV line). The generation from power plants in the northwestern zone of Azerbaijan's power system is about 3 400 MW, that in the Absheron zone is about 3 000 MW.

VI. COMPARATIVE RESULTS

The STATCOM and UPFC are installed at the end of the 500 kV overhead line on the side of ATr 800 MVA (500/220 kV), 220 kV Absheron substation.

We considered the active power consumption in the Absheron zone (at node 6), 1 600 MW, with active power consumption at 220 kV substations (Agdas, Agsu, Qebele) equal to 50 MW each (see Table).

The calculations were carried out using a software package developed by the Azerbaijan Scientific-Research Design-Prospecting Institute of Power Engineering. Modeling power flows relied on the appropriate mathematical models of FACTS.

Transfer capability of a transmission system is limited due to a variety of factors such as steady state stability limit, thermal limitation, transient stability limit, and system damping. The heterogeneity in the network circuit (Fig. 2) leads to overloading of 220 kV overhead lines and an increase in active power loss.

The active power flows at the 500 kV overhead line increase from 888.3 MW to 971.4 MW, and at 220 kV overhead lines, they decrease from 482 MW to 433 MW.

The voltage at the nodes of the circuit with and without the UPFC is shown in Fig. 3.

The use of UPFC reduces power losses by 11.46 MW.

According to calculation results, the installation of a STATCOM on 220 kV buses in the Absheron power system (node 6), under normal operating conditions, reduces active power loss by more than 10 MW.

A STATCOM and a UPFC when installed simultaneously at node 6, under steady-state conditions, reduce loss of active power by more than 12 MW [12–15].

Active power loss as a function of the transverse component of the complex transformation ratio is shown in Fig. 4

In the case of power transmission of 1600 MW, the required reactive power generation from the Absheron power system is 320 MVar.

The effect is achieved primarily due to the installation of a UPFC at node 6.

VII. CONCLUSION

1. The paper proposes augmenting the stability of Azerbaijan's power system by improving the damping of low-frequency oscillations with a unified power flow controller to be placed in the power system.
2. The findings suggest that the rational placement of UPFC:
 - enhances the technical and economic performance

of Azerbaijan's power system under all operating conditions;

- enables redistribution of active power flows over overhead lines in a heterogeneous 220 kV-330 kV-500 kV network: loading of 500 kV overhead lines by more than 100 MW and unloading of 220 kV overhead lines;
- reduces active power loss by more than 12 MW;
- improves voltage levels by up to 10% at power system nodes.

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Improving the Reliability of the Central Asia Power System in the Context of the Energy Transition

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Abstract — This paper provides an analysis of the issues concerning the improvement of the reliability of the Central Asia Power System in the contexts of its operation and the energy transition. The study considers the integration of renewable energy sources in the power system, given their prospective capacity additions to be made before 2030.

Index Terms: Power system, renewable energy, system failure, reliability, redundancy, stability.

I. MAIN OBJECTIVES OF THE CENTRAL ASIA POWER SYSTEM

The Integrated Power System (IPS) of Central Asia and South Kazakhstan (Central Asia Power System, CAPS) has been the backbone of the electric power industry of the four Central Asia republics and the adjacent regions of South Kazakhstan since 1960. The benefits of the interconnection of the power systems are known and related to the degree of their integration. Under the conditions that occurred in 1991, the strategically justified intent of independent states to achieve self-sufficiency in terms of energy balances led to the loss of the integration benefits and until recently, only power exchanges under intergovernmental agreements (IGAs) remained preserved. The new context has changed the principles for the joint operation of power systems in the CAPS, functions of coordinating bodies and the Joint Supervisory Control Office (JSCO). It was impossible to preserve all the advantages of parallel operation of power systems that had existed under rigid supervisory control, because each power system had its own criteria. The intention of each power system to maximize profits neglecting the interests

of its partners results in the deterioration in terms of the criterion of the respective system [1].

The main objectives of the IPS remain to provide the redundancy of power systems under normal and emergency operating conditions, implement contractual cross-border exchanges of electric power under IGAs, and rationally consume energy resources. The power systems of individual states must meet the needs for baseload, peak, and reserve power; sources of reactive power, and develop expansion planning projects of the electric power industry with respect to the IPS as a whole. Such a plan should consider alternative options for the commissioning of generation capacity, the construction of new power plants with the efficient use of various energy resources, and promotion of renewable energy sources (RES) and energy-saving technologies.

II. INTEGRATION OF RES INTO THE CAPS

According to the Vision Statement of Energy Sector Development, Uzbekistan is planning to introduce RES with the total capacity of 4,000 MW (including photovoltaic power plants – 2 400 MW and wind farms – 1 600 MW) by 2024 and to increase RES capacity to 9 000 MW by 2030 [3].

To better understand this scale, it is worth noting that the installed capacity of the Uzbek power system is just over 16 GW. Whereas the impact of RES variability can be coped with by maintaining hot reserves at power units and with the help of storage units, the problem of intermittency inherent in PV plants has its features for Uzbekistan. Even such a gas-rich country as Uzbekistan cannot solve this problem by using mobile gas power plants, for example, gas turbines or gas-fired reciprocating engine plants. The problem with replacing the PV power that becomes increasingly unavailable as the sun goes down is not because of a lack of generation capacity in the power system but because the power ramp rate at gas-fired plants is limited due to existing constraints in the country's gas transmission system (GTS).

The ramp rate problem at the plants can be solved by [4–6]:

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<http://dx.doi.org/10.25729/esr.2023.02.0005>

Received March 15, 2023. Revised April 19, 2023.

Accepted May 21, 2023. Available online June 10, 2023.

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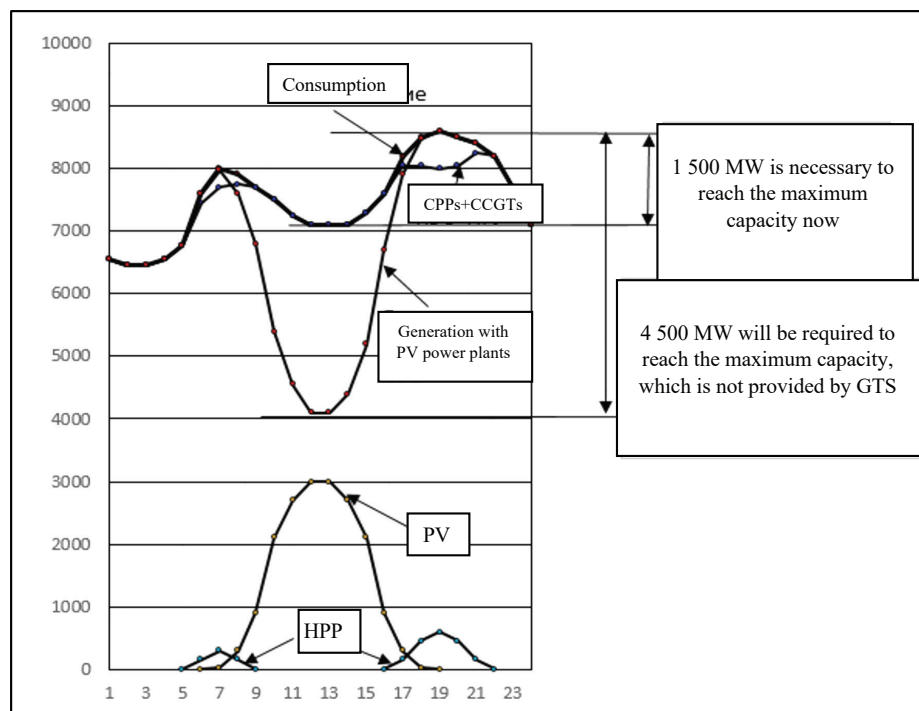


Fig. 1. Changes in daily generation from TPPs and HPPs in the Uzbek power system before and after commissioning the 3 000 MW PV power plants.

- restructuring the operation of the gas transporters so that they operate according to a flexible daily load profile of power plants, rather than a practically flat load profile as is today, which is a very costly measure in terms of financial outlays and time;
- installing, where possible, gas storage tanks at the plants to accumulate gas during off-peak hours and release it during peak hours (control over daily gas offtake at the plant itself). There has been no experience of this kind in the country yet;
- switching to the daily combustion of fuel oil in the hours of evening peak load pickup, when there are restrictions on the load pickup due to a gas shortage. This would require maintaining the working condition of some of the existing conventional power units that can run on both gas and fuel oil. However, this is a very expensive measure: fuel oil is currently burned only under extreme circumstances in the wintertime and the transition to year-round daily burning of fuel oil is unlikely;
- placing energy storage units at PV power plants and/or in the power system, which is also a costly measure, which countries adopting renewable energy on a large scale are forced to take.

If the above-mentioned problem is not solved, the situation with large uncompensated power surges on Kazakhstan's North-South transmission line, which is loaded to its limit, and, consequently, on the interface between the UPS of Kazakhstan and the UES of Russia will be created almost on a daily basis.

Currently, the permissible power surge is 500 MW

in the direction of Russia, and 300 MW from Russia to the CAPS. Given the latter factor and the need to prevent stability loss in the power system of Uzbekistan, devices for automatic tripping of power units with a capacity of over 300 MW were introduced. For example, in case of shutdown of the 800 MW unit at the Talimarjan TPP, the special automatic load shedding system (SALSS) responds and sheds $800-300=500$ MW, thereby monitoring the preceding power flow (PPFM), which determines the required size of load to be shed, depending on the load of the unit undergoing emergency shutdown.

As of today, there are not enough capacity reserves in the CAPS. For example, the Kyrgyz power system has reserves of about 150-200 MW, and after the connection of the Tajik power system, the reserves will reach about 700-1,000 MW. Mobile reserves can be increased through the joint construction of new HPPs by the countries of the region in water-abundant Tajikistan and Kyrgyzstan. With the view to creating peak capacity, compensating for the impact of RES, and taking into account the reduction in water resources, the focus should be on the use of pumped-storage power plants (PSPP) and the existing daily and weekly storage reservoirs [7, 8]. These measures will help reduce imbalances due to RES, but this is a very long-term process.

Note that the problem is not just a shortage of power reserves. The existing load surges in the direction of the UES of Russia are because of the currently operating centralized system of frequency control, which does not allow regulators in the national power systems of the CAPS to respond to disturbances earlier than the primary

and secondary control units in Russia. Large imbalances leading to stability loss occur infrequently at present, mainly during emergency shutdowns, in which, compensating actions of the automatic emergency control system are inadequate for one reason or another. The introduction of RES, as will be shown below, will cause such imbalances in the CAPS to occur every day, which calls into question the possibility of fully ensuring the stability of parallel operation of power systems.

III. THE STABILITY OF THE CAPS WITH THE INTRODUCTION OF RES

Given the high rate of RES penetration into the CAPS and the duration or costliness of measures to overcome the problems related, we should expect that power imbalances due to RES will take place daily and the probability of accidents in the CAPS will increase accordingly, as evidenced by system blackouts in the power systems of the CAPS in 2020–2022. In addition, the transfer capability of the North-South transmission line of the UPS of Kazakhstan is utilized to its maximum load capacity and, therefore, it will be necessary to daily disconnect consumers in the CAPS from the automatic emergency control system to maintain the stability of parallel operation.

Let us demonstrate this with the example of commissioning a power plant with a total capacity of 3 000 MW. Under the current operating conditions in the Uzbek power system, to cover the load during evening peak hours, the output at thermal power plants should be increased by about 1 500 MW, which the existing GTS can hardly cope with, especially in winter (Fig. 1).

With the commissioning of PV power plants in Uzbekistan, which will conclude take-or-pay contracts upon agreement between the parties, the power system will be forced to additionally unload up to 3 000 MW at TPPs during the day and, consequently, to increase output by already 4 500 MW in the evening, given the replacement of increasingly unavailable power at PV power plants. Since operating conditions of JSC Uztransgas do not allow changing gas consumption at thermal power plants by more than 250–300 thousand m³ per hour, which is equivalent to 1 000 MW/hour, it is clear that problems in the GTS will occur both during daytime unloading and during evening load pickups at thermal power plants, which will lead to power imbalances.

The danger of large uncompensated power imbalances was demonstrated by the events in the CAPS that took place on January 25, 2022 and resulted in the complete blackout of the power system interconnection.

The Commission of the CAPS under the leadership of the Coordination and Supervisory Control Center (CSCC) “Energiya” conducted an investigation with the involvement of independent experts, including SO UES, identified the causes of the accident, and developed a set of measures to prevent similar accidents in the future.

The investigation of the accident revealed that at the

Syrdarya TPP (STPP), there was prolonged arcing between fixed and mobile contacts of the incoming suspended-type disconnector of the 500 kV line L-502 (STPP - Tashkent SS), which, due to air ionization, turned into an inter-phase short circuit with L-502 tripping from fast-acting protections (phase-differential protection) on both ends with successful three-phase automatic reclosing.

At the same time, the second 500 kV bus bar at STPP was disconnected due to excessive action of the main and redundant sets of differential protection of the second 500 kV bus bar. Two minutes later, as a result of a repeated two-phase short circuit, L-502 again disconnected from the phase-differential protection on both ends. The short circuit occurred for the same reason. The first 500 kV bus bar at STPP was tripped due to excessive action of the main and redundant sets of differential protection of the first 500 kV bus bar.

A local accident with the outage of 500 kV bus bars at STPP, the loss of generation there, and separation of the power system resulted in an imbalance of more than 2 000 MW, which was seven times greater than the design value of imbalance and had to be offset by Kazakhstan’s North-South transmission line, which caused a dynamic stability loss on that transmission line loaded almost to its limit.

The partition of the transmission line almost doubled the power imbalance in the CAPS, which led to the development of an emergency with a frequency drop to 47.1 Hz, the operation of under-frequency islanding system at some plants in South Kazakhstan, the shutdown of two CCGTs in the Uzbek power system and, eventually, a frequency avalanche.

The Commission has developed a set of measures to prevent the recurrence of such accidents and the cases of uncompensated power surges in the future. However, these measures seem to be insufficient to avoid such system-wide accidents in the event that the plans to build RES in the CAPS are implemented.

The accelerated introduction of RES in Uzbekistan and Kazakhstan can lead to:

- a dramatic exacerbation of the problem of controlling imbalances and the power reserves required for that during all hours of the day, not just during peak hours;
- the urgent need to solve the problem of surplus gas during daytime hours, when PV plants operate at full capacity and thermal power plants are at their minimum safe output;
- the ramp rate problem at thermal power plants.

Given the previously noted shortage of power reserves in the CAPS, we can conclude that with a large-scale introduction of RES, power surges will be inevitable for Kazakhstan’s North-South transmission line, and daily stability loss on this transmission line will be the key problem, which may become the main obstacle to the RES integration. As experience shows, the increase in the transfer capability of Kazakhstan’s North-South transmission line to maintain stability during power surges

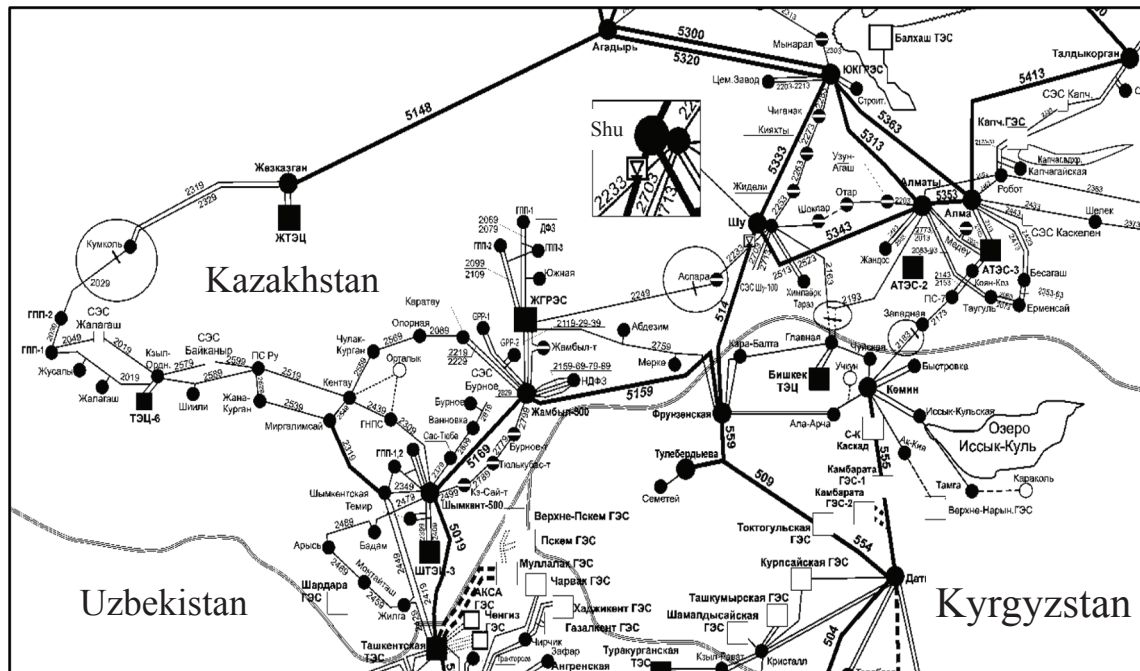


Fig. 2. Proposed DC link.

is an expensive and, at the same time, temporary measure, which reaches its limits quickly.

The idea of using a DC link in a problem area of the CAPS is proposed in [2] to ensure the stability of parallel operation of power systems of Central Asia with the UPS of Kazakhstan and the UES of Russia (Fig. 2).

As noted above, in the accident on January 25, 2022, the disconnection of Kazakhstan's North-South transmission line virtually doubled the power imbalance and the propagation of the accident.

If the injection of power supplied through this transmission line to the southern regions of Kazakhstan was maintained in the event of emergency, it would contribute to the operation of the CAPS with a smaller shortage and, accordingly, with lower costs for its normalization. We propose separating the CAPS and the southern regions of Kazakhstan from the UPS of Kazakhstan by installing a DC link in the L-514 (Shu - Frunze) break, and by switching the bypass 220 kV overhead lines to dead-end modes. The capacity of the DC link should be selected to be sufficient to supply Shymkent and Dzhambyl regions from the UPS of Kazakhstan, which is estimated at about 1 000 MW. The analysis shows that if such a link had been installed in the CAPS, then in the January 25th accident, after the bus bar outage at the Syrdarya TPP, the frequency would have been reduced only to 48.5 Hz and there would have been no development of the emergency followed by the operation of under-frequency islanding system at the plants and frequency avalanche in the power system. This approach will enable us to get rid of several current problems:

- with the frequency controlled in a centralized way by Russian plants, all power imbalances in the CAPS are offset by the cross-border tie lines directed to the UES of

Russia and overload them, however, with the operation through the DC link, the imbalances will remain within the CAPS itself;

- with the power supplied through the DC link and the frequency effect of the load considered, the frequency control will be much easier than in the case of parallel operation with the UES of Russia and the UPS of Kazakhstan;

- the structure of the automatic load frequency control (ALFC), which is planned to be developed and implemented in the CAPS, will be simplified, because there will be no need to control deviations of the net power flows at the CAPS border with the UPS of Kazakhstan, and the ALFC will focus on the control of frequency and power flows within the power interconnection.

IV. CONCLUSION

1. Analysis of the January 25th accident in the CAPS highlights the power balancing problems when the stability of Kazakhstan's North-South transmission line is disturbed.
2. The large-scale introduction of variable and intermittent RES combined with existing and anticipated problems in Uzbekistan gas transmission system multiply the probability of uncompensated surges in Kazakhstan's North-South transmission line. The program for the introduction of RES should be linked to a large-scale redevelopment of the gas transmission system and the creation of interaction between the operators of electric and gas networks in the region to ensure the GTS operation aligned with the load profile of the power system.
3. In order to use water efficiently and create peak capacity

to compensate for the impact of RES, we propose intensifying the efforts in the region to jointly build HPPs and PSPPs, using the existing daily and weekly balancing storage reservoirs for this purpose.

4. The probability of the power imbalances due to RES in Kazakhstan's North-South transmission line increases several times. To prevent power surges and preserve this transmission line, we propose switching to the joint operation of the IPS of Central Asia and South Kazakhstan with the UPS of Kazakhstan and the UES of Russia through a DC link.

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Mongolian and Russian Coals On the International Market – Is the Competition Real?

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Abstract — The coal industries in Russia and Mongolia tend to increase coal supplies for export. The competition between Russian and Mongolian coal so far concerns only the Chinese coal market. In the future, however, there can be competition in the international coal market of the countries in the Asia-Pacific Region (APAC). Mongolia exports mainly premium (coking) coal. Russia exports coking and steam coal, with a predominance of steam coal. An analysis of the factors influencing the development of Mongolian and Russian coal export to the APAC countries indicates that the increase in export supplies is limited mainly by the capabilities of the transport infrastructure and geopolitical conditions. Mongolia has additional restrictions due to its geographical position, since the country does not have access to sea trade routes, which creates the need for cooperation with Russia and China to enable access to the sea coast. The Russian coal industry depends on the coal supply for export to a lesser extent than the Mongolian coal industry. At present, almost all Mongolian coal exports go to China, while the share of exports to China in the volume of Russian coal exports to the Asia-Pacific countries is no more than 30%. An analysis of the development indices for the coal industry in Mongolia and Russian regions exporting coal to the Asia-Pacific countries has not shown a significant influence of the Mongolian factor on the volume of Russian coal exports.

Index Terms: production, Mongolia, Russian regions, coal, coal industry, export.

I. INTRODUCTION

Trends in the development of the coal industry in Mongolia and Russian regions that supply coal to the Asia-Pacific market are associated with an increase in the export coal supplies [1, 2]. Only Australia and Indonesia are ahead of Russia in terms of coal export volumes. Since 2016, Mongolia has become one of the top ten coal exporters [3] competing with Russia, Australia and Indonesia in the Asia-Pacific coal market [1]. Analysis of the retrospective development of export supplies of Russian and Mongolian coal and the factors affecting the export of these coals to the Asia-Pacific countries answers the question of how significant such competition is. Russian coal is exported to the Asia-Pacific countries including China, Japan and South Korea, which are the largest coal importers, and to other countries in the region. Mongolia exports coal mainly to China. Coal from the Far Eastern and Siberian federal districts of Russia is exported to the Asia-Pacific countries. In the future, Mongolia can compete with Russia on the Asia-Pacific market. The most important components of such competition are the availability of balance reserves of coal suitable for export, the possibility of boosting coal production and the possibility of increasing supplies to a wide international market. The course towards the decarbonization of the economy taken by many countries of the world, including the countries importing Russian and Mongolian coal, has become an important direction in recent years [4]. Geopolitical conditions also have a significant impact on the export of Russian coal.

Given the available big coal reserves of export quality in Mongolia and Russia, the study on the prospects for the development of coal export and factors affecting the export volumes and directions, in terms of competition, is relevant.

II. RUSSIA AND MONGOLIA ON THE INTERNATIONAL COAL MARKET OF THE APAC COUNTRIES

Currently, competition between Mongolian and Russian coal exists only on the Chinese market. The main competitors to Russian and Mongolian coal on the Chinese coal market are Australia and Indonesia (Table 1).

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<http://dx.doi.org/10.25729/esr.2023.02.0006>

Received April 06, 2023. Revised April 21, 2023.

Accepted May 03, 2023. Available online June 10, 2023.

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TABLE 1. Characteristics of the main coal importers on China's coal market

Exporting country	Share of exporting countries in coal import to China, %*			Coal reserves-to-production ratio, years	Export volume in 2020, EJ		Share of coal exports to China in 2020, %*
	2018	2019	2020		Total	including to China	
Russia	11.7	12.8	15.1	407	5.66	1.00	17.7%
Mongolia	15.9	16.0	11.9	58	0.79	0.79	100%
Australia	35.4	32.3	31.8	315	9.25	2.10	22.7%
Indonesia	31.3	34.2	35.4	62	8.51	2.34	27.5%
Other	6	5	6				

Source: [1],

Note: * Calculated based on the data [3, 5, 6]

TABLE 2. Characteristics of the coal industry in Mongolia and Russian regions supplying coal to the Asia-Pacific countries, million tons

Index	Year					
	2015	2016	2017	2018	2019	2020
Mongolia						
Mining	24.2	35.5	48.1	51.4	55.8	43.8
Processing	2.6	3.0	8.0	9.1	9.0	8.5
Supplies	23.8	35.7	46.0	51.0	51.8	42.8
Export	13.3	24.1	29.0	32.0	32.3	25.2
Share of export supplies	56%	68%	63%	63%	62%	59%
Regions of Russia (Western Siberia and the Far East)						
Mining	352.5	371.2	395.1	425.3	426.9	385.7
Processing	155.7	165.8	182.3	187.8	197.1	193.0
Supplies, of which	310.6	319.7	344.5	364.1	362.9	348.9
Export supplies, including	149.4	160.5	183.9	190.1	190.3	192.8
Export supplies to Asia-Pacific countries, of which	55.0	63.3	72.9	72.8	77.0	85.6
to China	11.8	15.2	21.0	21.4	23.1	25.3
Share of export supplies, total	48%	50%	53%	52%	52%	55%
to Asia-Pacific countries in total exports	37%	39%	40%	38%	40%	44%
to China in exports to Asia-Pacific countries	21%	24%	29%	29%	30%	30%
to China in total exports	8%	9%	11%	11%	12%	13%

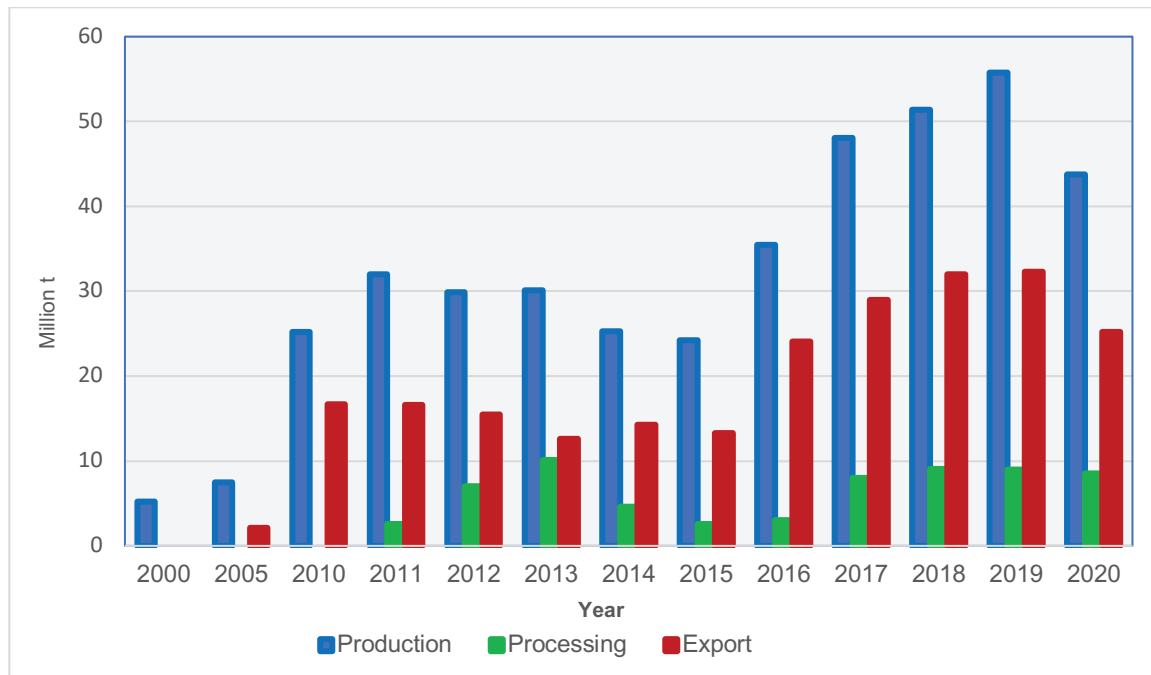
Source: [1, 2] and author's calculations based on the data [1, 2]

According to international statistics [3], Mongolia's coal accounts for 1.24% of the world's reserves, which corresponds to the 24th place of the country in terms of reserves. Russian coal reserves account for 15.10% of the world's reserves and are second only to those of the United States. Mongolian coal is in demand on the world coal market because of their high quality. The share of Mongolian high-quality coal (anthracite and bituminous, mainly coking) in the world proven coal reserves is 0.16%, which corresponds to the 15th place in terms of high-quality coal reserves. The reserves of Russian high-quality coal account for 9.52% of the world's reserves, following only those of the USA, China, India, and Australia. The extent to which the coal reserves of Mongolia are investigated is low. With an increase in the exploration work, Mongolia's position in terms of coal reserves can significantly improve.

In terms of available coal reserves, Russia leads among the countries exporting coal to China. The availability of coal reserves is calculated as the reserves-to-production ratio according to 2020 data [1]. According to the official data of Mongolian statistics [7], the proven coal reserves of Mongolia are significantly higher than those presented

in international statistics. Comparing Russian and international data on Russian proven coal reserves, one can assume that international statistics take into account only reserves of categories A + B + C1, while the Mongolian statistics indicates the reserves of categories A + B + C1 + C2. According to international statistics, Mongolian proven coal reserves are 2.52 billion tons. According to Mongolian statistics, the total proven geological reserves of coal in Mongolia are 32.6 billion tons, and the reserves that can be further explored are 150 billion tons. This indicates that coal reserves-to-production ratio of Mongolia can be more than 58 years.

Russian coal is exported to the APAC countries from Western Siberia and the eastern regions of Russia (the Far East and Eastern Siberia). The rise in coal production in these regions of Russia and in Mongolia is due to the growth of coal exports (Table 2). Table 2 presents data from the official site of Mongolian statistics [3], according to which the share of export supplies ranges from 56 to 68%. According to another official source [8, 9], the share of exports in coal sales ranges from 65 to 80%. This indicates the dependence of the coal industry development



**Fig. 1. Development indices of the Mongolian coal industry. Source: [2]
Mongolian Statistical Information Service www.1212.mn**

TABLE 3. Mongolian coal trade movements, million tons

Index	Year		
	2018	2019	2020
Supplies	45,7	47,0	41,0
Domestic market, brown coal	9,1	10,2	9,8
Exports, including:	36,7	36,8	31,2
Coking coal concentrate	5,5	6,8	5,0
Raw coking coal	26,1	25,5	23,6
Steam coal	5,1	4,5	2,6
Share of steam coal in exports	14%	12%	8%
Share of coking coal concentrate in exports	15%	18%	16%

Source: [8, 11, 12]

in Mongolia on coal exports.

The Russian coal export depends on export to the Asia-Pacific countries (in particular, on export to China) to a lesser extent than that of Mongolian coal. The share of coal exports to the Asia-Pacific countries in the period at issue ranged from 37 to 44% of the total exports and the share of coal exports to China was of 8 to 13% of the total exports. In recent years, there has been an upward trend in the share of coal exports from Russia to the Asia-Pacific countries. The share of China in the Russian coal export to the Asia-Pacific countries is not dominant and in retrospect, it ranged from 21 to 30%.

Comparison of coal processing and export volumes shows that Mongolia supplies mainly run-of-mine coal, while Russia exports washed coal. This is an undoubted advantage of Mongolian coal over Russian one.

III. COAL EXPORT FROM MONGOLIA

The export of goods, including mineral resources, is

of great importance for the economy of Mongolia [2, 7]. In recent years, the export of coal has developed at the fastest pace and has surpassed the export of other mineral resources. The significant resources of high-quality coal available [2, 9] and the growing demand for Mongolian coal in the international market creates the prospects for increasing coal exports from Mongolia [10].

From 2005 to 2019, coal production in Mongolia increased more than 7 times from up to 7.5 million tons to 55.8 million tons, while coal exports rose more than 16 times from 2.1 million tons to 32.3 million tons (Fig. 1). The main increase in production is due to the growth in demand for export supplies. In 2020, production and export volumes decreased, but this year is not indicative due to pandemic-related supply restrictions.

The analysis of coal supplies (Table 3) shows the dominant role of export supplies, which makes the development of the Mongolian coal industry dependent on the demand for coal on the international market, limited

TABLE 4. Quality characteristics of coal suitable for export

Type of coal		Total moisture	Ash content	Volatiles	Sulfur	Calorific value
		TM	Adb	Vdaf	St,db	Qnet,ar
		%				Kcal/kg
al	Coking	2.1–4.6	12.6–18.6	26.9–28.0	0.67–0.98	6 755–7 256
	Coking (low-caking)	2.6–4.3	7.2–17.2	30.6–42.0	0.77–1.22	6 158–7 200
	Steam	3.2–5.3	15.4–22.0	28.6–45.4	0.88–1.19	5 598–5 963
i	Coking	9.0	9.1	25.6	0.66	6 809

TABLE 5. Indices of the development of coal deposits in Mongolia, million tons

Index	Year					
	2015	2016	2017	2018	2019	2020
Overburden volume, million m ³	93.0	102.4	197.2	244.9	292.2	209.4
Stripping ratio, m ³ /t	3.9	2.9	4.0	4.5	5.1	4.9

Source: [8, 9]

Table 6. Development indices for the coal industry in Western Siberia, million tons

Index	Year						2020–2015
	2015	2016	2017	2018	2019	2020	
Production	221.3	234.3	252.3	270.1	264.9	232.1	10.8
Processing	116.0	124.2	134.9	140.4	148.1	142.9	26.9
Deliveries	190.8	198.4	215.7	226.2	221.2	210.4	19.6
Exports, including	118.6	126.3	145.5	148.1	143.1	139.4	20.8
to APAC countries, of which	29.4	35.1	41.1	40.3	37.0	41.2	11.8
to China	6.8	7.2	9.8	12.1	11.7	11.3	4.5
coking coal exports to APAC countries, of which	7.2	5.0	5.3	5.0	4.5	6.0	–1.2
coking coal exports to China	2.1	0.3	0.1	0.3	0.8	0.9	–1.2
Share of exports							
in supplies, total	62%	64%	67%	65%	65%	66%	0.04
to APAC countries of export volume	25%	28%	28%	27%	26%	30%	0.05
to China of export volume to APAC countries	23%	21%	24%	30%	32%	27%	0.04

Source: [2, 3] and author's calculation based on the data [2, 3]

Table 7. The development indices for the coal industry in the eastern regions of Russia, million tons

Index	Year						2020–2015
	2015	2016	2017	2018	2019	2020	
Production	131.2	136.9	142.8	155.2	162	153.6	22.4
Processing	39.7	41.6	47.4	47.4	49	50.1	10.4
Supplies	119.8	121.3	128.8	137.9	141.7	138.5	18.7
Exports, of which	30.8	34.2	38.4	42	47.2	53.4	22.6
to APAC countries	25.6	28.3	31.7	32.4	40.0	44.4	18.8
to China	5	8	11.2	9.3	11.4	14	9
coking coal to APAC countries	3.5	4.2	4.6	4.4	5.1	4.7	1.2
coking coal to China	2.5	4.0	3.1	1.0	1.3	2.0	–0.5
Share of export supplies in deliveries, total	26%	28%	30%	30%	33%	39%	13%
to APAC countries in export volumes	83%	83%	83%	77%	85%	83%	0.0%
to China in export volumes to APAC countries	20%	28%	35%	29%	29%	32%	12%

Source: [1] and author's calculations based on the data [1]

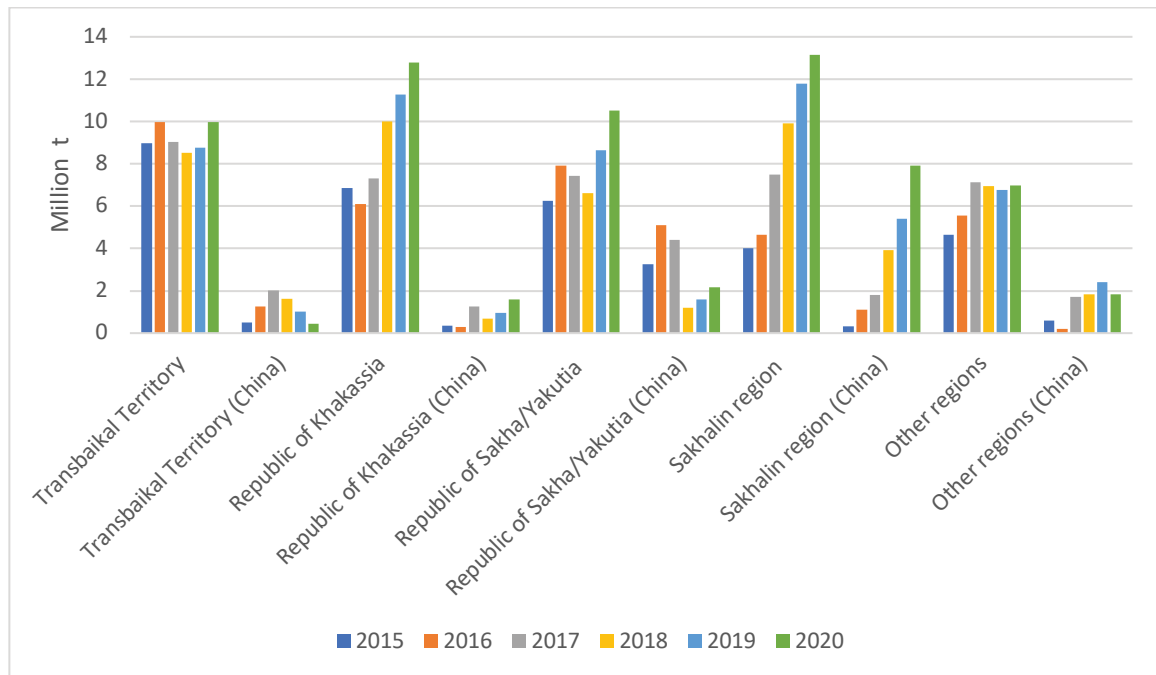


Fig. 2. Coal exports to the APAC countries. Source: [1]

Table 8. Share of exports to China in the exports from the eastern regions of Russia

Region	Year					
	2015	2016	2017	2018	2019	2020
Exports, total	16%	23%	29%	22%	24%	26%
Transbaikal Territory	5%	13%	23%	19%	12%	4%
Republic of Khakassia	5%	5%	17%	7%	8%	13%
Republic of Sakha (Yakutia)	52%	65%	59%	18%	18%	21%
Sakhalin region	8%	24%	24%	40%	46%	60%
Other regions	13%	4%	24%	26%	36%	26%

Source: Calculated using the data [1]

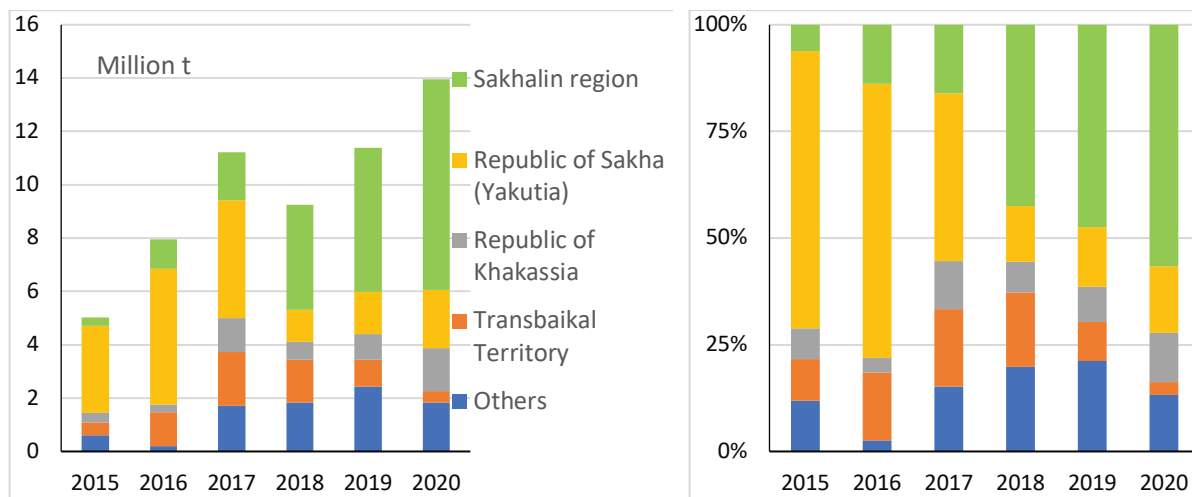


Fig. 3. Coal exports to China from the eastern regions of Russia: a) in physical terms; b) shares of regions in total exports to China. Source: [1] and the author's calculations based on the data [1]

only by China.

Only lignite (brown coal) is supplied to domestic market [7–9]. Exports consist of almost 90% of coking coal, of which only about 15% is coking coal concentrate, the rest is ordinary coking coal, i.e., coal that has not been processed at the washing plant. The quality indices of Mongolian coal correspond to the premium class and allow it to be supplied to the international market in an unprocessed form (Table 4).

Projects for expanding the capacities of existing enterprises and building new ones focus on the increase in coal exports. To increase export supplies, projects for the development of coking coal production are considered [13]. The most significant of them are the development of the Tavan Tolgoi deposit in the south of Mongolia and Shivee-Ovoo deposit in the northeast. The total volume of coal production in general for these projects can be more than 90 million tons per year, including up to 62.5–67.5 million tons per year in the southern regions of Mongolia [14].

Mining and geological conditions are favorable. The coal deposits in Mongolia are developed by an open method. To assess the feasibility of open pit coal mining, the stripping ratio is used. The stripping ratio is the ratio of the amount of waste rock to the amount of minerals. For the coal industry, the limiting (or the maximum allowable in terms of economic feasibility of mining) stripping ratio is 15–20 m³/t. The dynamics of changes in the stripping ratio (Table 5) show a slight, but quite acceptable, deterioration in the development conditions for the coal deposits.

Difficulties in the development of promising deposits are associated with the need to create social and transport infrastructure, including energy infrastructure and water supply. The shortage of water resources is typical of many areas in Mongolia, especially those of the deposits located in the Gobi desert.

IV. EXPORT OF RUSSIAN COAL TO APAC COUNTRIES

Russian coal from Western Siberia (Table 6) and the eastern regions of Russia (Far East and Eastern Siberia) is exported to the Asia-Pacific countries (Table 7). There is a stable upward trend in export deliveries, especially for the eastern regions.

The share of export supplies from Western Siberia is more than 60%, which makes the coal industry of Western Siberia dependent on them. At the same time, in 2020, only 30% of export volumes go to the eastern direction, where competition with Mongolian coal is possible. With stable growth in coal export from Western Siberia, including that to the Asia-Pacific countries and to China in particular, coking coal deliveries to China decreased. Thus, Mongolian coking coal squeezed out coking coal from Western Siberia from the Chinese market, which did not affect the trend of increasing coal export to the Asia-Pacific countries. The growth in supplies to the Asia-Pacific countries from 2015 to 2020 amounted to 11.5 million tons, including 4.5

million tons to China.

Coal from the eastern regions is mainly exported to the APAC countries, and in small volumes to other countries. In 2015–2020, the eastern regions, as well as Western Siberia, increased export deliveries, and their share in total deliveries rose from 26% to 39%. Almost all coal-mining eastern regions export coal to the Asia-Pacific countries, including China (Fig. 2). With a significant increase in exports from the eastern regions in 2015–2020, export to China more than doubled, and its share in export volumes rose from 16% to 26%.

The Sakhalin Region provided the largest increase in coal exports to the Asia-Pacific countries, including those to China. In 2020, the share of coal supplies to China in export deliveries to the APAC countries from the Sakhalin region was 60%, while this share in export deliveries from other regions ranged from 4% to 26% (Table 8). Other regions include the Republic of Tyva, Irkutsk Region, Primorsky Territory, Khabarovsk Territory, and Chukotka Autonomous Area. The coal of the eastern regions competes on the Chinese market only with coking coal from Mongolia. Coking coal was supplied from the Republic of Sakha (Yakutia). The reduction in the coking coal supplies to China did not affect the total coal export from Yakutia (Fig. 2). The export of steam coal to China decreased only for the Transbaikal Territory, which also did not affect the total export volumes.

The total volume of exports to China increased, mainly due to the steam coal supplies from the Sakhalin Region (Fig. 3).

V. FACTORS AFFECTING EXPORT SUPPLIES OF MONGOLIAN COAL

The main factors hindering the increase in the export of Mongolian coal are the state of Mongolia's transport infrastructure and continental geographical position of the country with no access to sea trade routes [15].

Access to the international market can only be ensured by transit to seaports through the territory of China or Russia. Potential transportation corridors, including those to the border through the territory of Mongolia and further to sea coal terminals through the territory of Russia, are of 3213 km to 5300 km long, and on the territory of China – of 1622 km to 2633 km [10]. Thus, the possibility for Mongolia to enter an international market depends on the ability to conclude mutually beneficial agreements with Russia and China on the terms of coal transit, which also involves the availability of sufficient transit and throughput railway capacity, and the capacity of sea coal terminals.

Significant restrictions on domestic transport infrastructure also hinder the coal export from Mongolia. Coal is transported across the territory of Mongolia to border crossings mainly by road.

The internal transportation infrastructure of Mongolia significantly limits the possibilities of transporting other goods either. The main transportation artery of Mongolia is

the Ulaanbaatar Railway (UBR), which provides domestic and transit transportation. UBR needs to be reconstructed and cannot fully meet the demand for cargo transportation [15]. The operational length of Mongolian railways is a little over 2215 km. The throughput capacity of UBR is 14 pairs of trains per day, and the carrying capacity is 25 million tons per year, while the plan is - 50 million tons. UBR consists mainly of single-track sections (76 sections), with a predominance of diesel traction. A Russian-Mongolian project for the creation of a new railway infrastructure and the expansion of the JSC "UBR" has been developed and is being implemented. The project involves the modernization of the existing network of the JSC "UBR" and the construction of new railway lines.

The most promising deposits of coal suitable for export are located in the south of Mongolia. Coal mines and border crossings on the border with China are connected by paved roads of 45 to 310 km in length.

A plan was developed to construct railway lines connecting coal deposits with border crossings, and/or UBR. The total length of the lines is 2.2 thousand km [8], including 8 lines with a length of 13 to 770 km. The lines of the highest priority are those connecting the Tavan Tolgoi deposit and the UBR (458 km) and the Tavan Tolgoi deposit and the Gashuun Sukhait border crossing on the border with China (267 km). The construction of the line to the UBR will enable coal transportation both to the Russian border and to China. Currently, new railway lines are under construction, the lines of top priority will be built first.

The transit transportations through the territories of Russia and China to seaports require appropriate agreements to be concluded if there are conditions for such transportations. According to the research [14], the transportation costs for the countries that do not have access to maritime trade routes are about 50% higher than for those with access to the sea [16].

In addition, there are restrictions on the throughput and carrying capacity of both Russian and Chinese railways, where priority is given to the domestic cargo. The capacity of coal terminals in China is several times higher than the capacity of coal terminals in Russia [16]. Although China has several coal terminals, Mongolia has authorized access only to one, Tianjin terminal. Some agreements with Russia on the use of the Russian transport infrastructure for the Mongolian coal delivery to the international market were also reached [17].

Despite the agreements reached, coal exports from Mongolia have so far been shipped only to China. According to the data of 2021, coal production in Mongolia decreased to 26.7 million tons, and exports went down to 15.9 million tons [18].

From the perspective of logistics, the coal transportation to the Asia-Pacific markets through China is the most feasible. The only question is whether the carrying and handling capacity of China's railways allows transporting Mongolian coal and how profitable it is for China.

The option of transporting coal through Russian territory also has its limitations and not only because of the limited capacity of the Eastern Polygon railway, which does not allow even Russian coal mining companies to transport the demanded volumes of coal. Coal terminals in the east of Russia are largely controlled by coal companies that supply coal to the Asia-Pacific countries, and the total capacity of the terminals is almost 7 times less than the capacity of Chinese terminals [19].

VI. FACTORS AFFECTING THE RUSSIAN COAL SUPPLIES TO THE APAC MARKET

Eastern regions of Russia and Western Siberia have sufficient capacities of existing coal mining companies to increase coal export. There are also projects for the construction of new coal mines and processing plants, which can contribute to the coal export development. Given the demand for Russian coal in the Asia-Pacific countries, the main factors that constrained and will constrain export of Russian coal in the future are:

- capabilities of transportation infrastructure (carriage and throughput capacity of the Eastern Polygon railway, which includes the Krasnoyarsk, East Siberian, Transbaikal and Far Eastern railways);
- shortage of capacities in the Far Eastern coal terminals;
- lack of demand for low-grade coal processing products on the domestic market.

Coal (slightly less than 90% of production volumes) is transported to coal consumers, to border crossings, and to sea coal terminals mainly by rail (Table 9) [20–22]. The share of coal in the cargo transported by rail is of 25 to 27%. From sea coal terminals, coal is delivered to Russia's regions, where it is impossible to deliver goods by land transport, and for export.

The capacity of the Eastern Polygon of Russian railways and the lack of capacities of the Far Eastern coal terminals limit the export supplies of the required amount of coal [23].

The growing need for cargo transportation is ahead of the increasing possibilities offered by the ongoing modernization of Russian railways. Due to infrastructural restrictions that limit the development of Russian coal supplies to the Asia-Pacific countries, about 6% of exports to these countries are transported through European Russian ports [24].

The Comprehensive Plan, approved by order of the Government of the Russian Federation on September 30, 2018, involved the project "Development of the railway infrastructure of the Eastern Polygon" [25], but the measures taken to date do not meet the growing need to increase the volume of cargo transportation, including transportation of coal.

Coal companies also look for their solutions to transport coal, despite the limitations on the capacity of the railway infrastructure. The transported coal volume was increased partially by implementing a project that involved creating

TABLE 9. Characteristics of production, export, and transportation of Russian coal, million t

Index	Year						2015–2020
	2015	2016	2017	2018	2019	2020	
Coal mining	374	386.9	414.1	441.6	442.7	401.6	27.6
Loading coal on railway transport	323	329	359	375	372	353	30.0
Coal exports, total, including	156	171	190	210	218	212	56.0
Coal exports from the Eastern regions and Western Siberia, of which	149.4	160.5	183.9	190.1	190.3	192.8	43.4
Coal exports to Asia-Pacific countries	55	63.4	72.8	72.7	77	85.6	30.6
Transshipment in seaports, total, including	123	136	155	161	176	189	66.0
in Far Eastern ports	n.d.	81.8	86.2	91.1	98.8	107.6	25.8*

*Over 2016–2020

Source: [1, 20–22].

innovative next generation railcars, which can transport up to 77 tons of coal. The project was developed and implemented by the Production and Transport Department of JSC SUEK-Kuzbass in cooperation with JSC Russian Railways.

They also developed a technology to increase the weight of cargo in standard wagons up to 65–71 tons [26].

The Russian investment company A-Property LLC, which is the owner of Elgaugol LLC and the Ogodzhinsky open pit in the Amur Region, suspended production at the Ogodzhinsky deposit in 2021 to ensure coal export from the priority Elginsky open pit [27].

Coal exports include mainly coking and steam coal concentrates. In addition to concentrates, which are in demand on the world market, the coal beneficiation plants also produce middling, i.e., fuel of lower quality, suitable for use at energy facilities. The lack of demand for middling on the domestic market may also hold back the growth of coal export.

In 2022, two more factors were added to the listed factors limiting coal export:

- geopolitical conditions [28], and
- tariff policy of the JSC Russian Railways.

Sanction restrictions on the coal export to the EU countries, the United States and Canada affected the Republic of Khakassia, the Kemerovo and Novosibirsk regions. About 1.8–2 million tons of coal have been exported from Khakassia to Poland and the UK in recent years, which is 14–17% of the export volumes from these regions [1]. To a greater extent, these restrictions affected the Kemerovo and Novosibirsk regions, the volume of exports from which to the countries that supported the sanctions amounted to about 60% for the Kemerovo region and about 30% for the Novosibirsk region in previous years. The largest coal importers, China and some Asia-Pacific countries, have not yet joined the direct sanctions, which theoretically makes it possible to redirect export supplies eastward. Everything is only limited by the carriage and throughput capacities of the Eastern Polygon of railways and the changed tariff policy of Russian Railways. Until recently, coal was a priority cargo and belonged to the preferential first tariff class [29]. According to the Decree of the Government of the Russian Federation of March

6, 2022 no. 304 “On the suspension of the Decree of the Government of the Russian Federation of November 25, 2003 no. 710” [30], the tariff class for coal was changed to the second. The change in the tariff makes coal deliveries unprofitable, since the transportation distance for most companies is quite long. The longest distance is for the companies of the Kemerovo region, about 5.5 thousand km. Quotas for the coal volume to be transported (categories of shipments to be decided by President Vladimir Putin) are 76 million tons, of which 18 million tons are for the eastern regions of Russia. Quotas affected the coal supplies from Kuzbass, Buryatia and Khakassia. Other regions may lose the opportunity to supply coal for export.

VII. CONCLUSIONS

Coal exports from the Russian Federation and Mongolia currently overlap only in China’s market. The competition between Mongolian and Russian coal only affected the coal supplies for export to China from the Republic of Sakha (Yakutia) and the Transbaikal Territory. At the same time, the total coal deliveries from all regions increased, regardless of the Mongolian coal supplies to China.

More significant changes in the volumes of Russian coal deliveries to the Asia-Pacific countries are made by geopolitical conditions related to sanctions, the capabilities of transport infrastructure, and the policy of JSC Russian Railways.

An obstacle to the supply of Mongolian coal through the territory of Russia to the sea coast is not only the limited capacity of the railways of the Eastern Polygon but also the fact that the Far Eastern sea coal terminals are mostly owned by Russian coal companies supplying coal for export. A positive aspect of the sanctions for the Mongolian coal export is the refusal of Japan and South Korea, the world’s largest coal importers, to renew signed contracts on the import of Russian coal. The contracts were valid until August 10, 2022 [31].

Foreign companies take part in the development of export-promising coal deposits in Mongolia and Russia. The stability of the interests shown and the degree of participation of these companies in the projects are important for the development of coal mining at such deposits.

The main limitation for the increase in export supplies of Mongolian and Russian coal is the state of the transportation infrastructure. This limitation is especially relevant for Mongolia, which has no access to maritime trade routes.

The prospects for the development of Russian and Mongolian coal export depend on the following factors:

- State of the transportation infrastructure and implementation of projects for its development;
- Potential for the expansion of internal and external coal markets;
- Geopolitical conditions limiting coal consumption and the conditions associated with sanctions;
- Opportunities to increase the volume of exploration work;
- Contribution of foreign companies to the implementation of projects for the development of export-quality coal deposits.

In the future, depending on the dynamics of changes in these factors, Mongolian and Russian coal may compete on the international market. Moreover, for Mongolia, it is essential to build and develop international transportation corridors for the entry of Mongolian coal to the APAC market.

In the considered period, the growth in the Mongolian coal export supplies did not have a significant impact on the export of Russian coal. If sanctions are eased or lifted, there is little chance of significant competition between Mongolian and Russian coal.

ACKNOWLEDGMENT

The study was carried out within the framework of the scientific project XI.174.2 of the program of fundamental research of the Siberian Branch of the Russian Academy of Sciences, reg. no. AAAA-A21-121012090010-7.

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The Influence of Electric Vehicle Charging Stations on the Quality of Power Supply to the Consumer in Novosibirsk 10/0.4 KV Electrical Networks

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Abstract — Currently, there is a massive use of electric vehicles in the world. This is due to the ever-increasing importance and severity of the environmental safety issue. Now, there is no more convenient, affordable, popular and at the same time less harmful alternative to road transport. The annual global emissions are more than 25 million tons of pollutants of various origins, which are extremely dangerous for nature in general. On average, they increase by 3% every year. The transport sector accounts for 23% of all greenhouse gas emissions in the world. Electric vehicles can contribute enormously to the reduction in greenhouse gas emissions. In 2025, sales of electric vehicles are expected to increase to 100 000 units. By 2030, the number of electric vehicles will reach 1.5 million units. However, widespread adoption of electric vehicles will cause an increase in electricity consumption. In addition, an appropriate charging infrastructure is required to power electric vehicles. It is worth noting that the market for electric vehicles and charging stations is developing dynamically with an annual growth rate up to 80%. The main barriers to the development of electric vehicles in Russia are their high cost and underdeveloped network of charging stations. The relevance of the problem is confirmed by an order signed by Prime Minister Mikhail Mishustin in March 2022 to allocate about 1.37 billion rubles for the creation of charging infrastructure for electric vehicles in Russia. As for incentives, there are many of them. This is the need to solve the environmental problem in large cities, achieve the goal of reducing CO₂ emissions and pursue industrial policy, including the policy of

innovative development of the country. Another way of increasing the payback of charging stations is the employment of smart services, which can reduce the cost of technological connection through dynamic power distribution between the main facility and the charging station. There are other, more advanced solutions, which are currently being piloted, such as optimization of investment in network infrastructure, including an operator of a regional public charging infrastructure. This study focuses on the development of a power supply system to connect an electric vehicle charging station to a substation in Novosibirsk. The connected electric vehicle charger, being a non-linear load, can not only increase the load on the power grid infrastructure, but also cause a deterioration in the power quality due to the generation of harmonic distortions. Therefore, special attention is paid to the analysis of the power supply quality during the operation of the charging station by using the model developed in the MATLAB Simulink software for the analysis of harmonics.

Index Terms: Charging station, electric vehicles, mathematical modeling, non-linear load, harmonics.

I INTRODUCTION

One of the effective tools to prevent climate warming on Earth is the large-scale introduction of an electric vehicle (EV), especially in metropolises. Over the past few years, the demand for electric vehicles has grown. For comparison, the number of electric vehicles in China has exceeded one million units and there are already more than 167 000 charging stations, whereas in Russia, there are about 1 000 electric vehicles and approximately 150 public charging stations. The number of individual (home) charging stations is unknown. Electric vehicles release half as much CO₂ emissions as internal combustion engine vehicles on average. In addition, an important incentive for the introduction of electric transport is support for industrial policy, including the policy of innovative development of the country.

According to [1], 2021 saw a sharp increase in the

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<http://dx.doi.org/10.25729/esr.2023.02.0007>

Received March 06, 2023. Revised April 13, 2023.

Accepted May 12, 2023. Available online June 10, 2023.

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share of electric vehicles sold globally. That year marked a turning point for the entire electric vehicle industry as sales more than doubled compared to 2020 and made up 9% of the global car sales, which is a serious bid for the future dominance of “green” transport.

The large-scale adoption of electric vehicles, however, will increase electricity consumption. It is also necessary to establish an appropriate charging infrastructure to power electric vehicles. All this will require commissioning the additional power capacities and changing the electric load curve. It is worth noting that the market for electric vehicles and charging stations is developing dynamically with an annual growth rate of up to 80%.

The main barriers to the development of electric vehicles in Russia are their high cost and a poorly developed network of charging stations. The urgency of the problem is confirmed by an order signed by Prime Minister Mikhail Mishustin in March 2022 to allocate about 1.37 billion rubles to create the charging infrastructure for electric vehicles in Russia.

Smart services could increase the payback of charging stations, primarily by reducing the cost of technological connection through dynamic power distribution between the main facility and the charging station. There are other, more advanced solutions, such as optimizing investment in network infrastructure, for example, for the operator of a regional public charging infrastructure.

Vehicle-to-Grid (V2G) technology seems promising (it allows connecting a car to a common power grid for timely recharging it or returning excess electricity back).

Today private charging infrastructure prevails in the world, when the owner of an electric car buys a charging station, installs it in their private house, underground parking, or near the house. The same trend is observed in Russia. It is also clear that with an increase in the number of budget proposals for electric vehicles, it is necessary to competitively develop public charging infrastructure near shopping and business centers and residential complexes.

Modern trends in transport infrastructure are reflected in a growing number of vehicles that switch to electric traction motors. Instead of an internal combustion engine, such cars are equipped with an electric motor (EM), which receives energy from batteries. These batteries can be charged from the mains or from other electrical energy sources (for example, from an induction transformer located under the roadbed). The main automakers have begun to actively introduce a new generation of electric vehicles with the improved battery technology (lithium-titanate batteries), increased energy intensity, and lower production costs. It has led to the demand for modern electrical equipment that provides both fast battery charging and conversion of electrical energy stored in the battery for the needs of the final electrical equipment. New electronic components emerge as electronics develops and new opportunities appear for creating power electrical equipment with improved characteristics.

Battery life is a defining factor to be given special attention to, as the energy efficiency of a vehicle depends on it. Today, the world’s infrastructure of charging stations operating from the electrical network is developing at a fairly high pace. The study on the enhancement of battery life and economic efficiency is relevant today because it aims to improve consumer properties and the availability of electric vehicles for the end consumer [2–4].

This paper aims to design a power supply system for a charging station considered as a load of the power grid and analyze its impact on the quality of electricity in the grid on the example of the Teatralnaya substation in Novosibirsk.

This can be achieved by:

- Analyzing the operational principles of the charging stations and battery swapping stations for electric vehicles;
- Analyzing the main types of charging stations, namely charging stations for trucks, electric buses, cars; and their location for megacities (on long highways outside the city), for private use (own), in terms of maximizing the life and improving the performance of the vehicle;
- Designing a power supply scheme for connecting EV charging stations;
- Analyzing the harmonics during the charging station operation in the MATLAB Simulink software for the quality of power supply.

II IMPLEMENTATION OF ELECTRIC VEHICLE CHARGING STATIONS

According to the Federal Law of November 23, 2009, No. 261-FL “On Energy conservation, energy efficiency enhancement, and amendment to some legislative acts of the Russian Federation,” the development of electric vehicles is a significant direction, which requires state regulation and support.

Now, the model range of the automotive manufacturer of electric cars consists of four cars that are different not only in their appearance but also in their functions and purposes: TeslaModelS hatchback, TeslaModel X crossover, TeslaModel3 budget electric car, and new off-road vehicle TeslaCyberTruck [5–7].

Electric vehicles however have disadvantages, the main of which are the battery capacity for their long-term operation and the operating temperature range, which is especially significant for Russia. Although electric buses that can withstand temperatures down to -40°C for 12 hours have recently appeared in Moscow, St. Petersburg and Volgograd, they encounter temporary difficulties, including an underdeveloped infrastructure of charging stations inside the megacities, which is the subject of this paper.

A charging station is an electrical device equipped with connectors necessary to plug in electric vehicles, which charges electric vehicles in various conditions [8–10]. Figure 1 shows grid connection options for the charging stations [11].

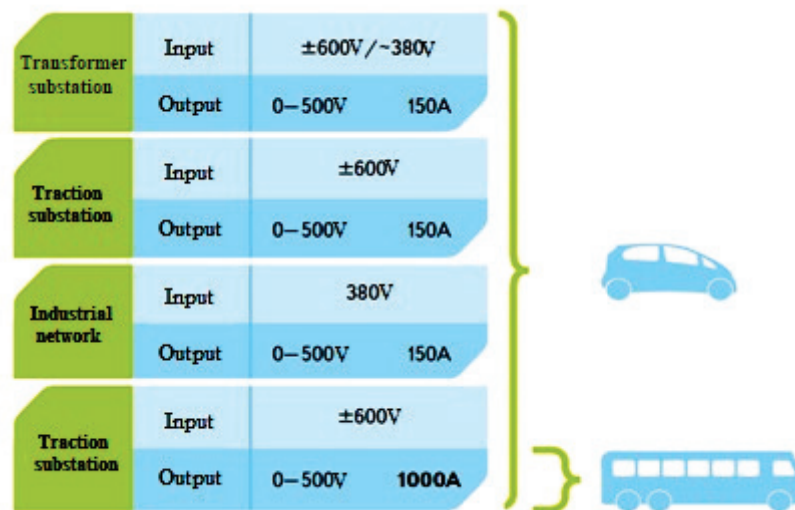


Fig. 1. Options for the connection of charging stations to the grid.

TABLE 1. Comparison of Charging Station Concepts

Charging stations powered from the buses of DC traction substation	Charging stations powered from the buses of AC 10 kV traction substation	Remarks and explanations
Installed capacity of traction substation does not change	Installed capacity of traction substation should be changed	New technical conditions for power connection
No additional 10 kV switchgear, MV transformer (100 kVA), the ATS system are required	It is necessary to install a 10 kV switchgear, a MV transformer (100 kVA), an ATS system	Additional 3 chambers with high-voltage circuit breaker and at least 1 chamber with AT + ATS on the 10 kV side are required
Charger cost is lower, no rectifier is required	Charger cost is higher because of converter cost	A rectifier is used in the option of power supply from AC bus bars
Charger dimensions are smaller	Charger dimensions are larger	Because no rectifier, switchgear 10, ATS system, 10 kV transformer are required
No power corrector for the charging station is required	Power corrector is required for the charging station	If charging stations are considered separately
There is no need to obtain new specifications for connection	New specifications for connection are required	

A wide range of developed charging stations provides fast charging from the traction substation network, industrial network and by currents up to 1000 A for charging electric buses.

Design of charging stations should factor in the requirements of State Standards (GOSTs), for example, such as EN-61851-1, IEC 62196. Permissible charging modes are described in section 1 of the IEC 62196 standard, which defines the main options.

To date, there has been a developed infrastructure of charging stations for electric vehicles in large cities of Russia (Moscow, St. Petersburg, Samara, Kazan, etc.). In the context of growing fleet of electrical vehicles, the design and establishment of power supply systems for charging stations in megacities becomes a relevant issue for Russia.

Table 1 indicates possible options for charging stations, including those for megacities, remote routes, individual use; for electric buses, cars, and trucks.

Some countries are developing and testing the so-called

“smart road” or induction road. In the future, Russia may follow this experience, when electric vehicles gain popularity in the Russian market.

The mass use of electric vehicles will:

- significantly enhance the efficiency of application and design of electrical distribution networks due to controlled distributed load;
 - increase the useful supply to the network by the inverter mode;
 - level the night-time valley of the load in the power system;
 - consider electric vehicles as distributed energy storage devices to cover the peak loads of the power system when introducing the latest technologies (Vehicle-To-Grid (V2G));
 - significantly boost the efficiency of the electrical distribution networks and increase productive supply;
 - reduce emissions of harmful substances, which will improve the environmental situation in the world.
- Moreover, since the main generating sources of energy

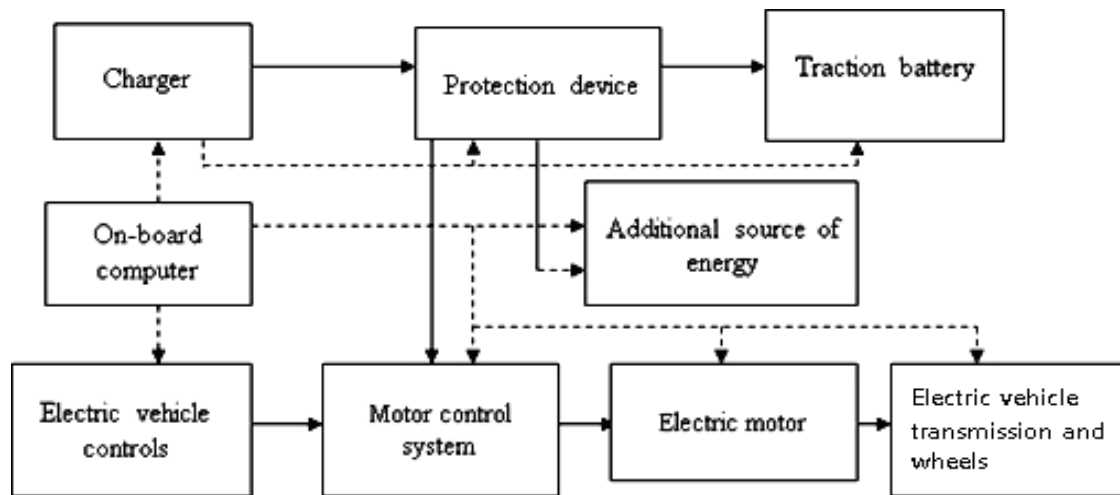


Fig. 2. Block diagram of an electric vehicle.

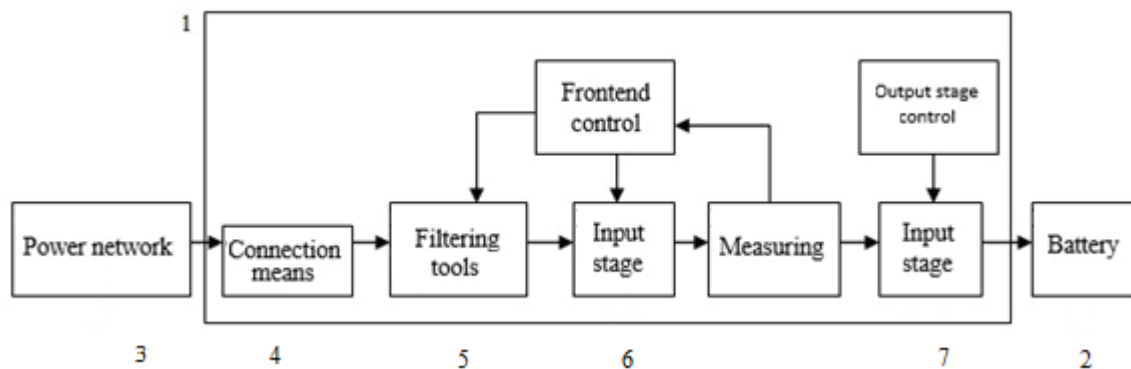


Fig. 3. Diagram of an electric vehicle battery charger.

and other industries are located within the boundaries of large metropolitan areas, the most relevant direction for the development of charging stations are megacities.

A Description of the electric vehicle layout

Unlike a car with an internal combustion engine, an electric car has a simpler design, including a minimum number of moving parts, and is therefore more reliable [14–17]. The block diagram of the electric vehicle is shown in Fig. 2.

Charger converts the AC voltage of the external network to DC to charge the traction and auxiliary batteries. *Protection device* (relay and fuse box) consists of switches, relays, and fuses. When a fault occurs, the AC circuit and batteries are disconnected. *Traction battery* provides energy to the motor of an electric vehicle. *On-board computer* monitors the condition of the main functional components and on-board systems of the electric vehicle, and initiates protective measures if necessary. *Additional power source* (usually a 12 V auxiliary battery) ensures the operation of lighting devices, instrument panel, power windows, wipers, etc. *Electronic motor controller* forms the required type of supply voltage and controls the number of revolutions and

the traction moment on the shaft by the driver's commands or automatically. Electric motor drives the wheels of an electric vehicle directly or through a transmission.

The main battery is charged from a charger located either on board the electric vehicle or outside it. It aims to provide the required current in the shortest period of time in compliance with the battery charging algorithm recommended by the manufacturer.

Features of electric vehicle engines. The electric motor includes a stator and a rotor. The rotating magnetic field in the stator acts on the rotor winding and induces an induction current in it, a torque occurs that sets the rotor in motion. The electrical energy supplied to the motor windings is converted into mechanical rotational energy.

AC electric motors are divided into groups. The two types of electric motors most often used in the modern production cars with electric traction [18–20] are asynchronous, where the rotation speed of the stator magnetic field is higher than the rotor speed, and synchronous, for which the rotation speed of the stator and rotor magnetic field are the same.

Structural diagrams of chargers. One of the main weaknesses of electric vehicles is their low availability for work. In practice, when the battery is depleted, the electric

TABLE 2. Calculation of the Charging Station Loads.

Group	$\cos \varphi$	$\operatorname{tg} \varphi$	P_P , kW	Q_P , kvar	S_P , kVA
Charging station (CS) TeslaSuperCharger	0.89	0.51	250.00	127.5	280.6
Power supply to Business center	0.87	0.56	282.70	158.31	324.94
Business center auxiliaries	0.90	0.50	42.65	21.25	47.65
Total			575.35	307.06	653.19

vehicle remains inoperable and if a complete discharge of the battery occurs far from the charging station, it will lead to difficulties in getting to the charger.

It is known that in order to reduce the battery recharge time, it is necessary to increase the charging power by boosting the current consumed from the network. It is also proposed to draw this current from a three-phase network, and not from a single-phase one. In the case of a three-phase power supply network, the charging power is increased.

Thus, the charger is completely built into the car and does not require an additional output inverting stage, since the inverting stage is already in the car. Therefore, it is possible to provide charging points in the infrastructure, where the charging points are simply output sockets of the power supply network, which reduces the cost. In addition, the infrastructure network cost goes down, which enables an increase in the number of charging sites to provide charging services to a greater number of car users [21–24].

A battery charger (1) consists of an input rectifier stage (6) configured to be connected to the power supply network (3) and an output inverting stage (7) configured to be connected to the battery (2). There is a device for regulating the average value of the current received from the input stage (6) relative to the value of the current obtained based on the maximum current supplied by the power supply network (3) and in accordance with a factor

that is at least equal to the ratio of the maximum voltage rectified by the input stage (6) to the battery voltage (2). The charger may include filters built into the vehicle to filter the current drawn by the charger from the supply mains.

The paper discusses the design of an electric vehicle charging station on the example of the 10/0.4 kV Teatralnaya substation in Novosibirsk (Table 2).

B Analysis of network transfer capability for establishing charging stations

The network assessment is required by reason of the need to correctly calculate and select the capacity of the electrical network components and consider the main conditions for choosing the network components (wire cross-section, location of the TP, power transformer, switches, and others).

The loads were calculated using the data of the terms of reference in accordance with RM-2696 “Instructions for the calculation of electrical loads” [12] and in accordance with SP 31-110-2003 “Design and installation of electrical plants of residential and public buildings” given the discrepancy between the maximum loads of the premises and buildings belonging to the same complex.

Since the load is given by the installed capacity and the number of individual power receivers, the electrical

TABLE 3. Purposes and Functions of the Wired Interface Components and Signals for Charging Station Systems of Type A.

Charging station, EV, conductors and signals	Symbol	Explanation
Charging station	d1	Control signal (CP) to control the charging start/stop signals from the station to EV
	d2	CP to control the charging start/stop signals from the station to EV
	j	Signal reader to detect if EV is ready/not ready to receive power
	+V DC	DC power supply to EV contactors
Electric vehicle (EV)	C1, C2	Disconnect switch for DC power lines (EV contactors)
	e	Relay for switching on EV contactors
	f	Signal reader for determining status of d1
	g	Signal reader for determining status of d2
	h	Signal reader to detect EV connection/disconnection
	k	Switch to start/stop charging
Conductors and signals	DC+	DC power supply (positive)
	DC-	DC power supply (negative)
	CP	Control signal indicating the start/stop status of the station
	CP2	Control signal indicating the start/stop status of the station
	CS	Control signal indicating the connection status of the EV connector
	CP3	Control signal confirming the EV readiness for charging
	COM1	Signal line pair for digital communications
	COM2	
	PE	Protective wire between the station and the EV for detecting the first DC earth fault

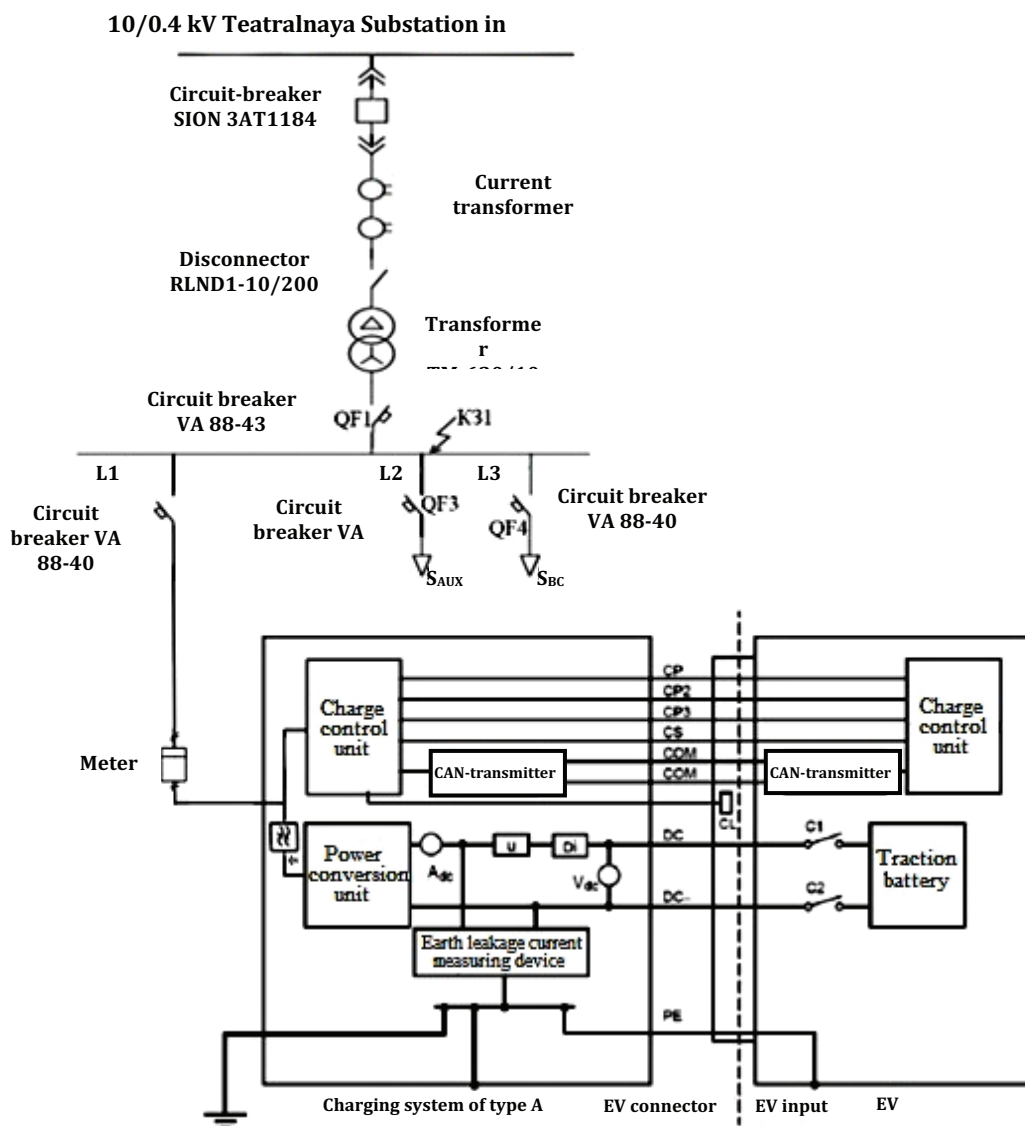


Fig. 4. Scheme of electrical connections of complete TS.

loads are calculated using the demand factor method. We took the load of the business center auxiliaries S_{aux} in the amount of 10% of the rated power.

Choice of power supply scheme. The operation of power supply systems, their reliability and quality are determined by the reliability of their constituent components. The choice of a single-line complete transformer substation scheme is made following the basic requirements [25–27]:

- The reliability of power supply to consumers in normal, repair, and post-emergency conditions;
- The scheme should be as simple, visual, and economical as possible.

Since the power supply system (PSS) under consideration belongs to the 3rd category of power supply, we assume one transformer substation (TS).

The notations and roles of the wired interface components and signals for charging station system of type A are shown in Table 3.

The developed power supply scheme is shown in Fig. 4.

The sequence of digital data exchange during the operation of the charging station is shown in the diagram below (Fig. 5).

All selected equipment meets the modern short-circuit current requirements.

III ANALYSIS OF THE INFLUENCE OF EV CHARGING STATIONS ON THE QUALITY OF POWER SUPPLY TO THE CONSUMER IN NOVOSIBIRSK 10/0.4 kV ELECTRICAL NETWORKS

The power quality (PQ) in power supply systems is currently one of the most acute issues in the energy sector, since PQ is a significant factor affecting the performance of the power system and consumers, especially in the era of the “capricious consumer.” The quality of electricity is determined by the reliable and stable power transmission.

This problem is especially pressing in low-voltage

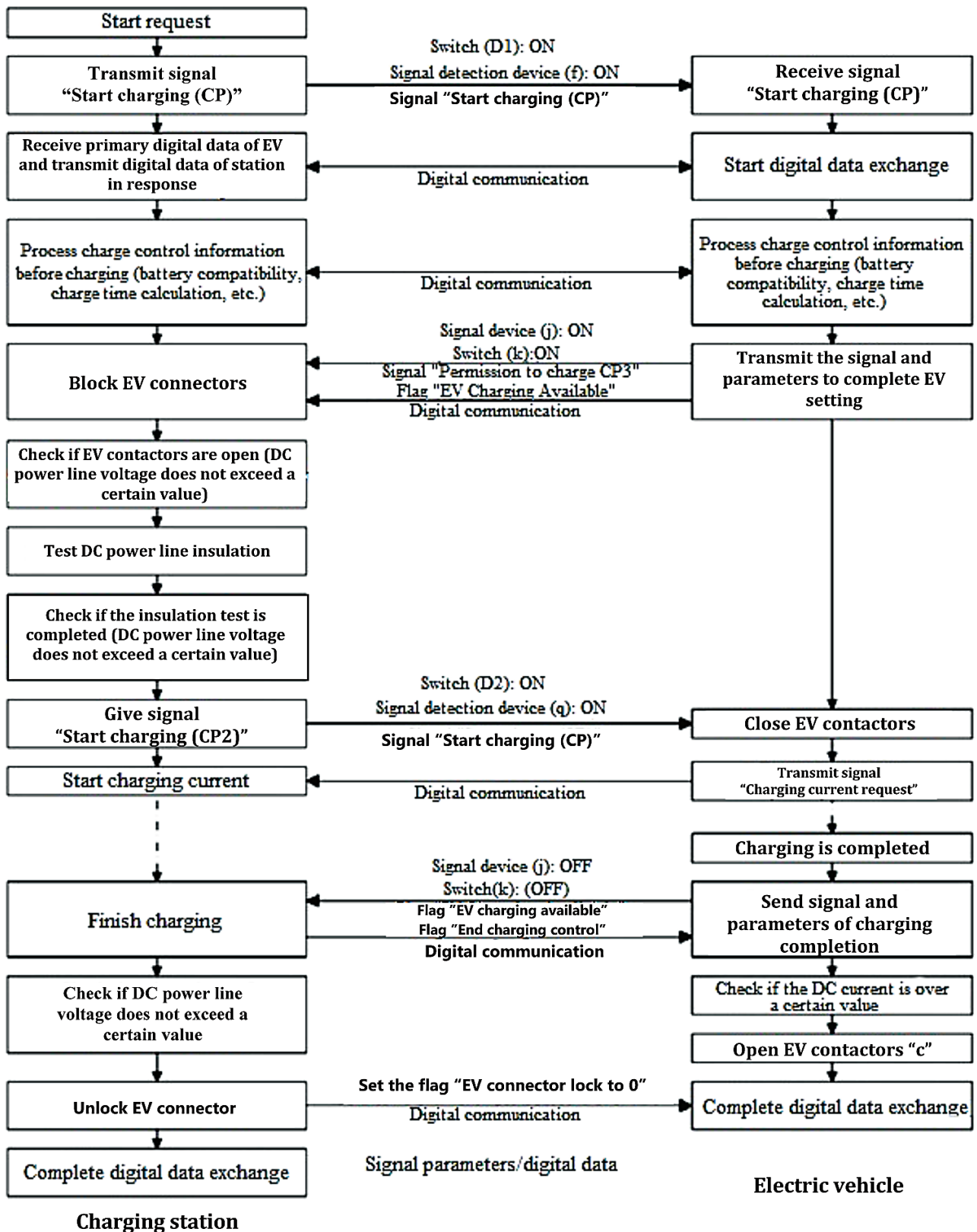


Fig. 5. The sequence of actions for digital data exchange during the operation of the charging station.

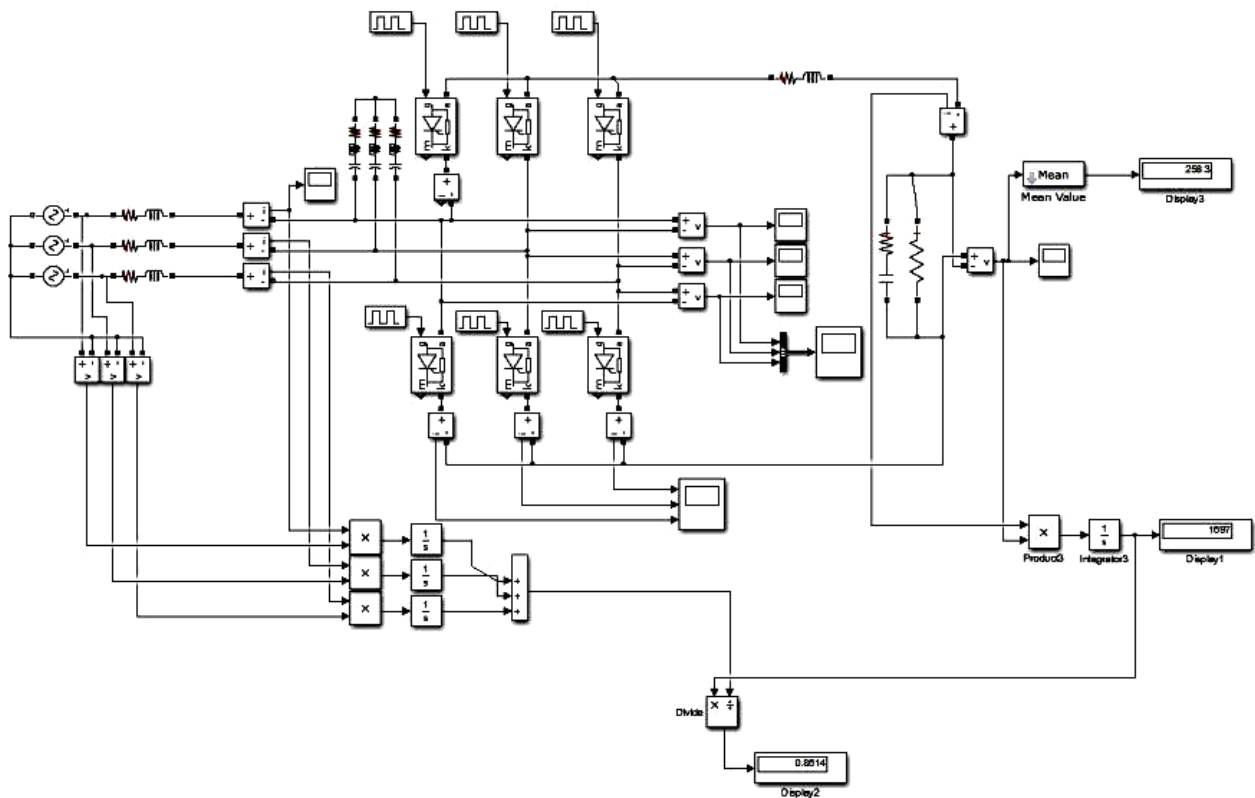


Fig. 6. Model of a three-phase bridge rectifier with filter.

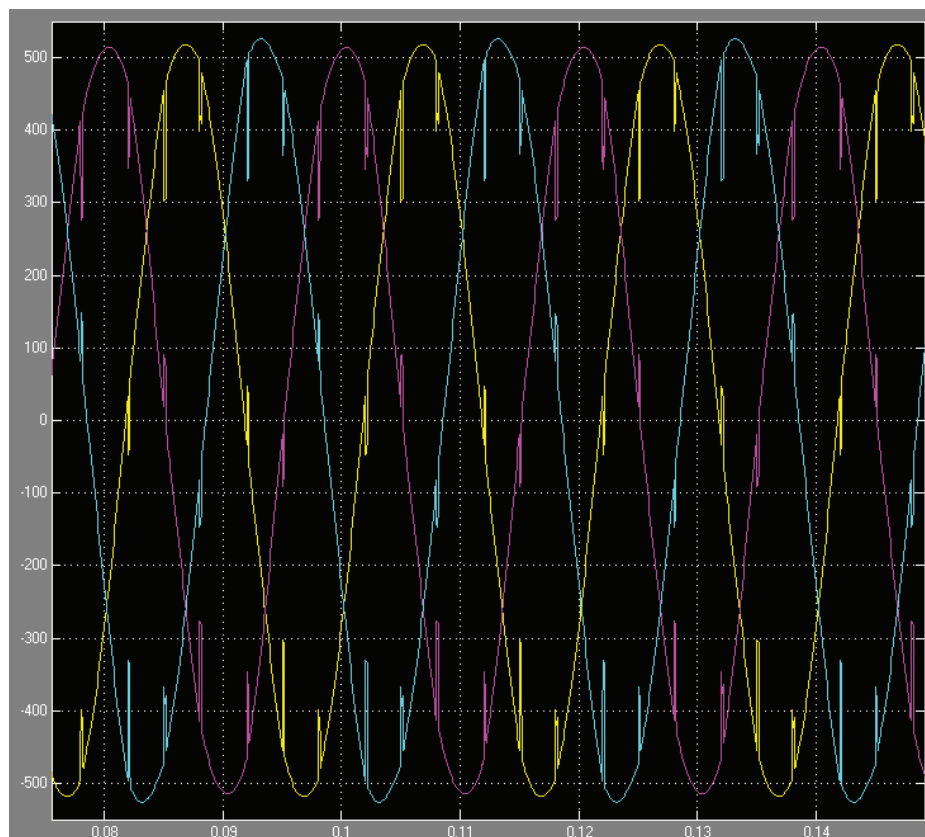


Fig. 7. Thyristor voltage graphs.

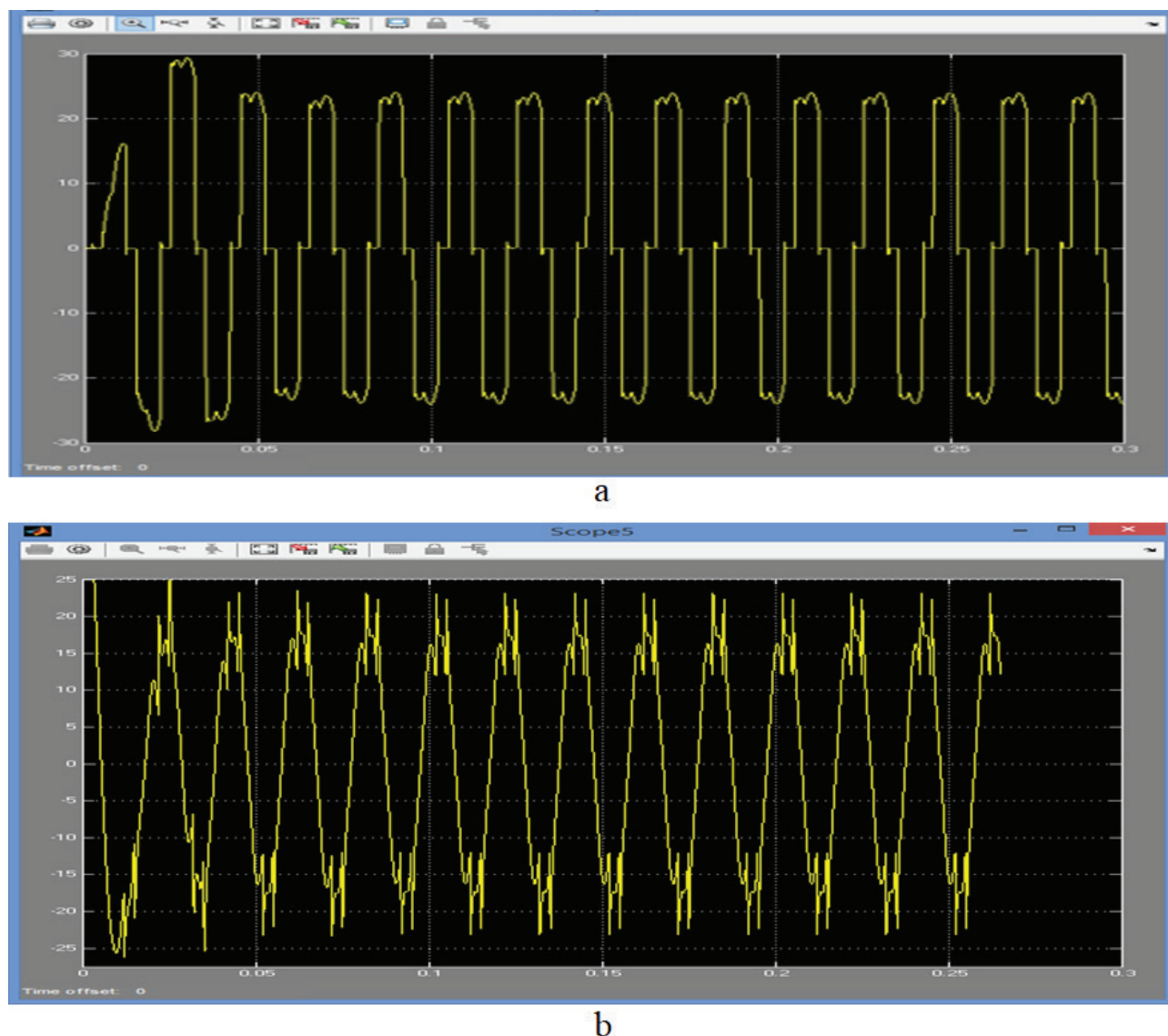


Fig. 8. Oscillograms of currents without (a) and with (b) filter.

networks, since the number of small non-linear electrical consumers (computer equipment, television equipment, audio and video equipment, household appliances, chargers, and others) is increasing at a fast pace. One of the reasons for the decline in power quality is non-linear loads that generate electromagnetic interference, which distorts the sinusoidal current and voltage curves, thereby reducing the power quality.

The charger of an electric vehicle is a non-linear load and, in addition to increase in the load on the power grid infrastructure, can deteriorate the quality of electricity through harmonic distortions, which is why it is necessary to analyze the effect of electric vehicles on the quality of power supply to consumers according to State Standard (GOST) 32144-2013.

Harmonic distortion leads to an increase in power consumption and a decrease in power quality. The harmonic current of the electrical network causes some

consequences, including:

- additional power losses in distribution transformers and wires [17, 20];
- interference that affects the normal functioning of the connected equipment [13];
- reduction in the service life and transfer capability of the electrical network [28];
- increase in the danger at hazardous production facilities [29].

Thus, any electrical network has always harmonic currents of frequencies that are multiples of 50 Hz. During the day, the total harmonic factor varies within 0.9–1.4% (the highest maximum permissible value of the harmonic factor according to GOST 32144-2013 is 5%). The main sources of harmonics in low-voltage networks are power consumers, including a rectifier with a powerful capacitive filter.

A controlled rectifier, which on an industrial scale

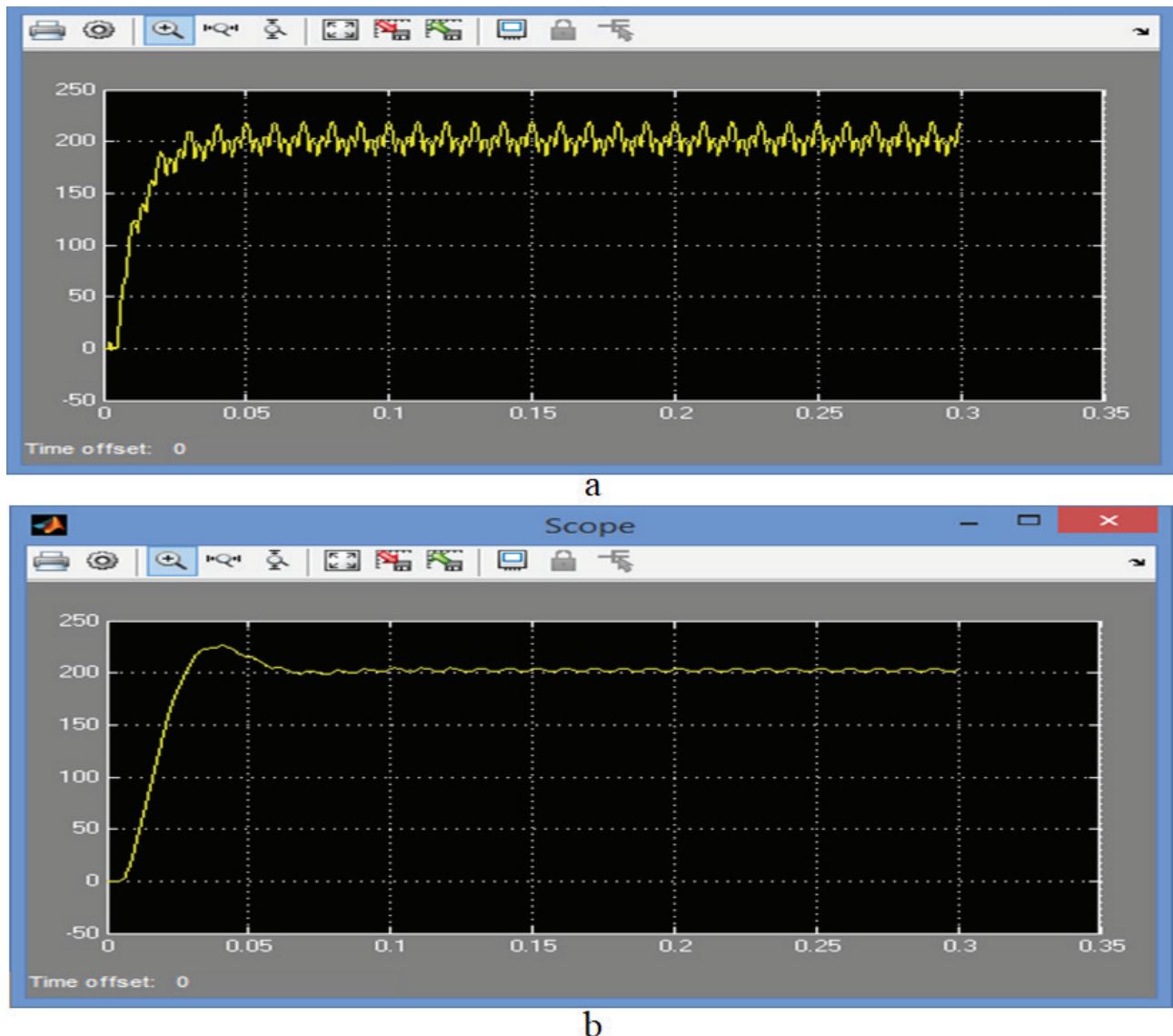


Fig. 9. Graph of the rectified voltage without (a) and with (b) filter.

relies on a three-phase bridge circuit, is required to charge the batteries (Fig. 6). The operation of this device causes harmonics. Therefore, it is necessary to analyze the impact of the charging station on the quality of the power supply to the consumer for the presence of harmonic current and voltage, since it is this indicator that has the most significant impact on power losses in networks up to 1000 V. Consider the model of a three-phase bridge voltage rectifier made in the MATLAB program (Fig. 6).

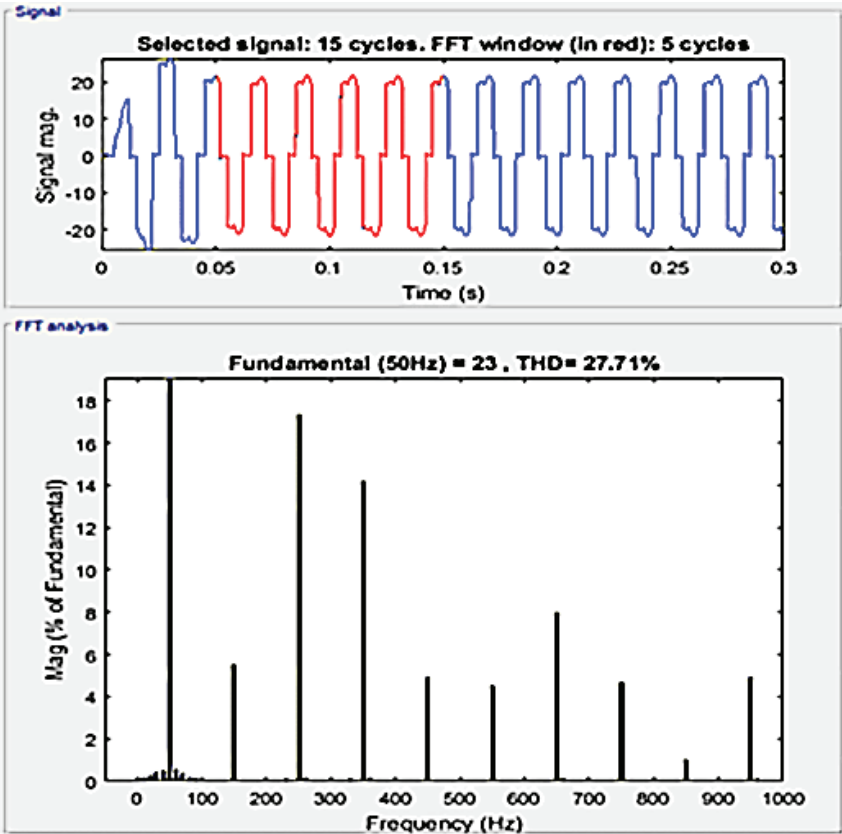
Thyristor is used as a non-linear component in this circuit. The graphs of the operation for each of the rectifier arms are shown in Fig. 7. As shown in the Figure, there is a distortion in the shape of pulses, which is a consequence of high-frequency harmonic distortions. This can also be seen in Fig. 7.

The universal device AFG-0.4-50 UHL 4 was used as a compensation filter. Figure 8 shows the oscillogram of the current at the input of an EV charging station without

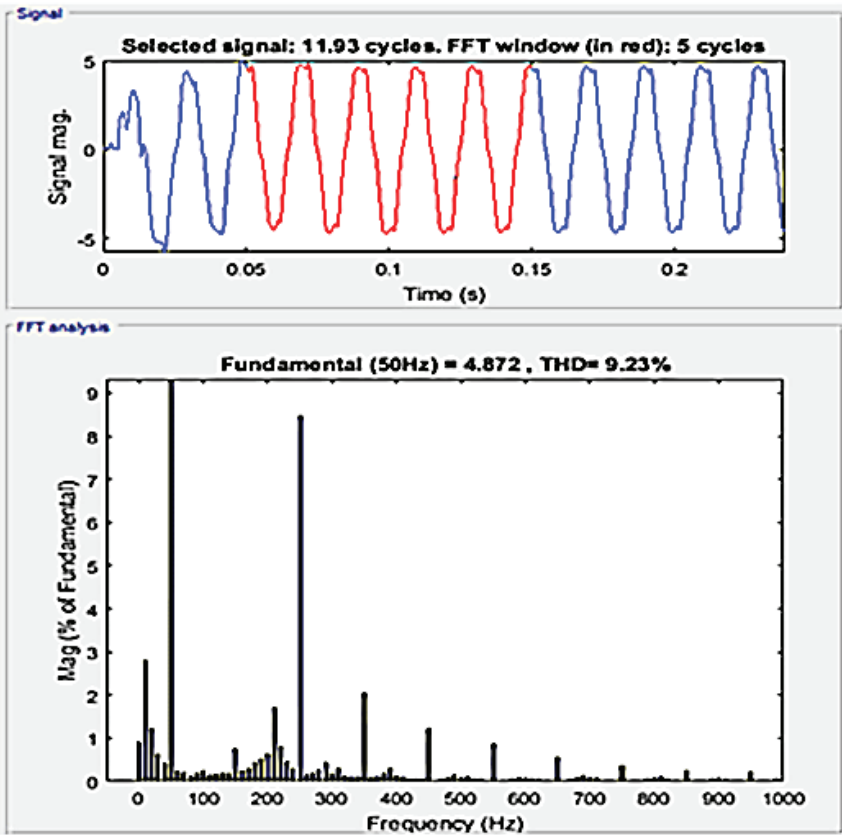
filter and with it, respectively. As can be seen from the oscillogram, the use of filter made it possible to reduce the harmonic components at the power supply network input. The graph of the rectified voltage is shown in Fig. 8. It is worth noting that the use of filter both at the input and at the output of the power converter is justified. It significantly reduces the ripple of the output voltage (Fig. 9).

The main indicator of the power quality is the total harmonic distortion (THD), which shows how much the signal shape differs from the sinusoidal one. This is also a value for quantifying the nonlinear distortion of a periodic signal. Thus, the primary ways to reduce the level of harmonics in low-voltage electrical networks are to use passive filters, filter compensators, hybrid filters, and active filters. In electrical systems, filters are used to reduce the current or voltage amplitude for one or several fixed frequencies [30].

As the analysis shows, the THD value without filter



a



b

in the case of the charging station is 27.7%, which is unacceptable and indicates the need to use a filter. With the filter compensator used, this value goes down to the value allowed by the State Standard and reaches 9.23% (Fig. 10).

IV CONCLUSION

The paper is concerned with the installation and design of the charging station for electric vehicles as a load for a power supply system. A detailed calculation and selection of power supply system equipment are made.

- The study examines how the operation of the charging station affects the electrical network and other electricity consumers and if it meets the requirements of State Standard (GOST) 32144-2013 in terms of the non-sinusoidality of the current and voltage curves, which have the greatest impact on power losses in networks up to 10 kV.
- The MATLAB Simulink software was employed to analyze the influence of the charging station on the quality of power supply to consumers. The measures to reduce the harmful effects of harmonics on the electrical network and the neighboring consumer are proposed. The active filter AFG-0.4-50 UHL 4 was chosen as a measure. The THD reached the permissible values and amounted to 9.23% (according to the standards, the permissible THD level is 10%) against the value of 27.7%, which was in the system before the implementation of compensatory measures.

The study shows the effectiveness of the developed power supply scheme for the electric vehicle charging station and indicates the possibility of giving power back to the grid and solving the problem of power shortage in the region. Moreover, the large-scale introduction of EV charging stations in megacities will significantly improve the environmental situation there. All this makes charging stations competitive to traditional energy supply sources in terms of electricity supply to the grid.

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