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IMPROVING THE QUALITY OF ELECTRICITY IN THE NETWORKS OF NON-TRACTION CONSUMERS OF RAILWAYS BY CONNECTING TO THEM RENEWABLE SOURCES

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ПОКРАЩЕННЯ ЯКОСТІ ЕЛЕКТРОЕНЕРГІЇ В МЕРЕЖАХ ЖИВЛЕННЯ НЕТЯГОВИХ СПОЖИВАЧІВ ЗАЛІЗНИЦЬ ШЛЯХОМ ПІДКЛЮЧЕННЯ ДО НИХ ВІДНОВЛЮВАЛЬНИХ ДЖЕРЕЛ ЕНЕРГІЇ

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Abstract. The paper considers expedient schemes of connection of renewable energy sources (RES) to railway power grids. Today, the implementation of distributed generation (DG) based on RES in the railway grid is an **urgent issue**. Despite the fact that scientific and practical aspects of the development and implementation of DG systems are studied by many domestic and foreign scientists, there is still no reasonable opinion on the most appropriate use of a particular direction of RES in railway power supply systems. There are only recommendations for connecting RES to the tires of traction substations. Now it is profitable to create their own power plants with RES, connecting them to external networks, from which only then the railway receives power. **The purpose of the work** is to improve the quality of electricity in the supply networks of non-traction consumers of railways by connecting to them renewable energy sources. **Research methods** are based on modern methods of computational mathematics, statistics and information analysis using modern computer technology. **Research results.** The paper develops supply system for traction and non-traction consumers by electric mains to which wind power plants (WPPs) are connected, and a model of railway mains where RES is connected to transformer substation (TS) wiring of non-traction consumers. The introduction of wind turbines in the railway power supply system according to the above scheme can really significantly improve the quality of electricity in the power supply network of their non-traction consumers. But the approximation of this quality to the allowable values occurs only when the power of the additional source is not less than 35% of the nominal value of the total load of all connected to the winding 6.6 kV consumers. An example of connecting a photomultiplier tube to the railway network, which is carried out without the use of any storage of energy generated by them, is considered. The introduction of possible directions for the use of RES in railway power supply systems is chaotic and unsystematic, and so far there is no reasonable vision for the most appropriate option. **The originality** is the introduction of renewable energy sources in the power supply system of non-traction consumers of railway transport. **Practical implications.** The use of additional renewable energy sources to supply non-traction consumers minimizes electricity consumption.

Key words: renewable energy sources, distributed generation, non-traction consumers of railways, wind power plant, photovoltaic plant.

Introduction. As it is known, use of so-called distributed generation (DG) is one of the current tendencies to improve power supply systems making electricity more reliable and crushproof. It is considered that DG systems also reduce power losses during its transportation owing to closeness of sources to consumers. In this context, length of the main power lines and their number becomes less important. Moreover, accident consequences are less significant and mutual back-up of power generating capacities is provided.

As for the alternative energy use for the systems of the distributed electric power supply of railways, it is possible to single out following possibilities: supply of a traction power generation system by external mains within which renewable energy sources (RES), belonging to the railway, operate together with the traditional ones;

RES connection to traction transformer windings supplying directly non-traction consumers of railway mains; use of alternative energy in the amplifying points to intensify the traction network; connection of RES, located within the exclusion railway zones, directly to a catenary supplying both traction and non-traction consumers; and use of RES as a source for local supply systems of non-traction consumers with a possibility to supply them from traction network.

It should be noted, that use of one or another mentioned tendencies of RES implementation in railway mains is of chaotic and systemless nature. There is no substantiated idea which of them is the most expedient one. Unfortunately, the only thing is available, i.e. recommendations for RES connection to buses of traction substations formulated by [1]. The recommendations list the limiting factors determined by authors: capacities of the key reducing transformers of substations; commutation potential of switchers within the connection areas; the required relay protection as a part of the corresponding distributing devices of TS; and sensitivity level of the protection.

Literary review. Theoretical and practical aspects to design and implement DG systems are considered by many national and foreign scientists. A.V. Kyrylenko, A.V. Prakhovnyk, V.G Sychenko, S.P. Denysiuk, A.V. Kriukov, Ye.I. Sokol, O.S. Yandulsky, V.O. Kostiuk, R. Caldon, S.Conti and many others contributed much to solve the problem [2-10].

As for the railway mains, Professor K.G. Markvardt initiated the distributed power supply systems for their traction loads in the mid part of the last century [11-12]. He formulated power supply principles for a catenary with the help of amplifying points connected to longitudinal high voltage transmission line of direct current or alternative current. Location of such amplifying points, operating on the principle of the distributed system, between operating substations injects the catenary with no increase in the basic aggregate power output.

Currently, numerous scientific sources are focused on the improvement of the distributed generation within the railway consumers of electric power. Such studies as [1, 13-15] concern RES integration into the systems of traction and non-traction electric power supply as amplifying points as well.

It is known [16, 17], that the indicators of the quality of electrical energy in the power supply systems of traction and non-traction consumers of railway transport do not comply with regulatory documents and standards that regulate the above indicators. Currently, this problem is present in the power supply networks of the railways of Ukraine [17] and in foreign countries [18-20].

For example [18, 19], in India, today an electric traction system is used based on drives of electric motors of DC locomotives and is powered from a network with a voltage level equal to 25 kV. The quality of electrical energy in the above networks is the main problem, since the latter is associated with very high power and high voltage of consumers. One of the ways to improve the power quality indicators is the use of wind power plants directly connected with the power supply system of railway locomotives.

The authors of the paper [20] propose to provide railway traffic safety installations, that must operate continuously and with nominal parameters, in order to reduce electricity consumption and increase the reliability of power supply, an alternative solution for their power supply, that provides for the supply of electricity from a photovoltaic system installed next to the box for household appliances. At the same time, the photovoltaic system, together with the existing power supply system, provides a redundant power source for consumers powered through the junction box.

The paper [21] is devoted to the study of the issues of improving the quality of electricity in traction power supply systems of trains by integrating renewable energy sources into existing power supply systems, namely, photovoltaic solar panels.

The paper [22] is devoted solving the problem of replacement of energy supply sources at the railroad transport, in particular the sources used to feed signaling, centralizing and interlocking (SIB) devices, that are non – traction consumers, from generators operating on DGA type diesel fuel, to renewable energy sources, to solar photovoltaics stations of small and medium capacity.

Despite the fact that the energy generated by RES is still too expensive, the world tendency is to increase the amount of implementation of such sources. That depends upon the environmental pollution by modern power industry and deficit of fossil fuel. Moreover, it stimulates their use in railway systems as well. It takes place even in spite of the impossibility to have governmental support in the form of the "green tariff". The implementation may be illustrated by a pilot project of parallel operation of solar power plant and external power supply of 10 kV buses at a traction substation Sambir (Western Railway) [1].

The purpose of the work is to consider the possibility of developing generation capacity on the railway to provide energy to its own consumers through the introduction of mini power plants using a local renewable resources - wind energy and solar radiation.

It is the most profitable idea now to build own RES electric power stations connecting them to external mains which will then energize a railway. It is the only case when electric power, generated by RES, enters a power market and obtains all the "green tariff" advantages which make the implementation economically attractive. However, the abovementioned cannot solve any problem concerning the departmental mains. Thus, the example of the implemented pilot project in Sambir is still a sole one. Unfortunately, it is not very successful connection of solar power station.

Material and results of research

Analyzing electricity quality indices within the system of non-traction consumer supply inclusive of wind power plant (WPP) connected to it

A network, which wiring diagram is shown in Fig. 1., may exemplify tendency of RES use. In the context of the wiring diagram, three-winding transformer, which 27.5 kV traction winding is brought on the power supply system of electric propelled vehicles (EPVs), is connected to a common power line (PL) with U=115 kV. Another 6.3 kV winding of the transformer supplies non-traction consumers. Alternative RES-based source is connected to a distributing point (DP). Output voltage of the source corresponds to 6 kV voltage of departmental PL.

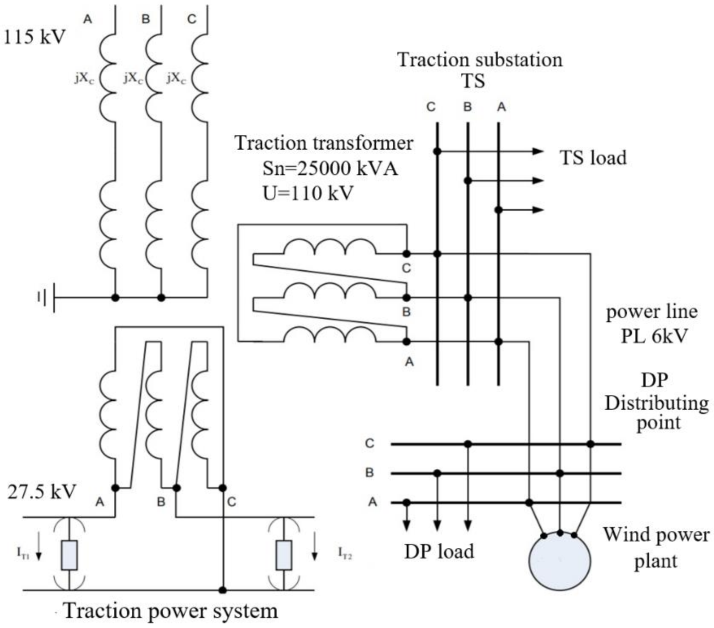


Figure 1 – Supply system for traction and non-traction consumers by electric mains to which WPPs are connected

To analyze a possibility of electric power quality improvement within the considered supply network for non-traction consumers, its model, which wiring diagram is represented in Fig. 2 (general model)., is applied for the required experiments. Figure 3a) shows the elements of Subsystem 1, 3; figure 3b) shows the elements of Subsystem 2; figure 4 shows the elements of Subsystem 4. The modeling was performed within MatLab environment using Simulik software package.

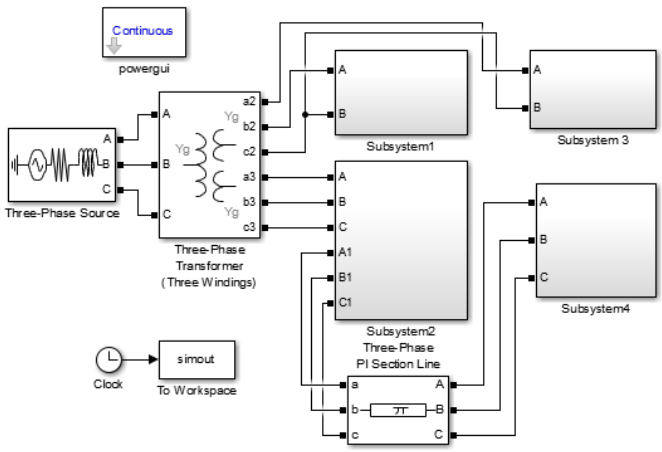


Figure 2 – General model of railway mains where RES is connected to transformer substation (TS) wiring of non-traction consumers

The analysis involved 115 kV power supply and a transformer, corresponding to characteristics of traction transformer Sn=25000 kVA. The transformer voltage is 115/27.5/6.6 kV. Two electric locomotives are connected to a traction winding of the transformer. Total current of each locomotive is 300 A; reactive power factor is tgφ=1.

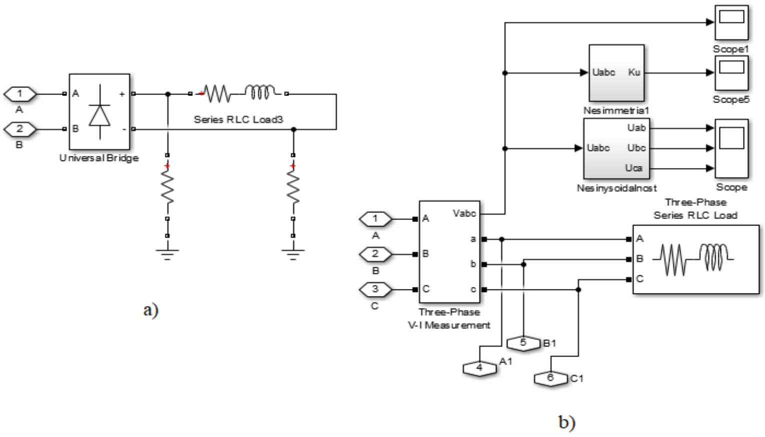


Figure 3 – Models of Subsystems: a) Subsystem 1, 3; b) Subsystem 2

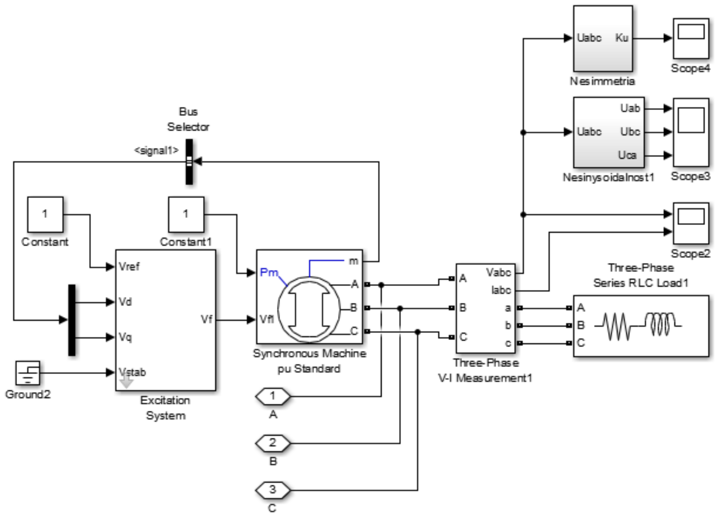


Figure 4 – Model of Subsystem 4

Additional source, simulating WPP operation, is connected to 6 kV distributing point supplying power to consumers not belonging to railway. Its nominal output and cosφ of the latter may vary gradually in the process of the experiment from zero value (the source disconnection from the mains) up to 4000 kW power ant cosφ=1. Synchronous generator model in Simulink turned out to be the most adequate. Total output of all consumers, supplied by 6.6 kV winding, was 8 MW. 6 kV PL has 6 km length and following parameters: $R_0 = 0.2590\, Ohm/km$; $x_0 = 0.4\, Ohm/km$ which corresponds to AC–120/19 wire.

As an example, Fig. 5 demonstrates the obtained oscillogram of linear BC voltage on DP buses when WPP is disconnected from the mains. The calculated values of inharmonicity and asymmetry coefficients, in terms of a negative sequence and voltage deviations, corresponding to it, are $R_{non-sinusoidal} = 13.1\%$; $R_{asymmetric} = 15.8\%$; and $\Delta U = 8\%$ respectively. As it has been predicted, the quality values exceed significantly the acceptable values.

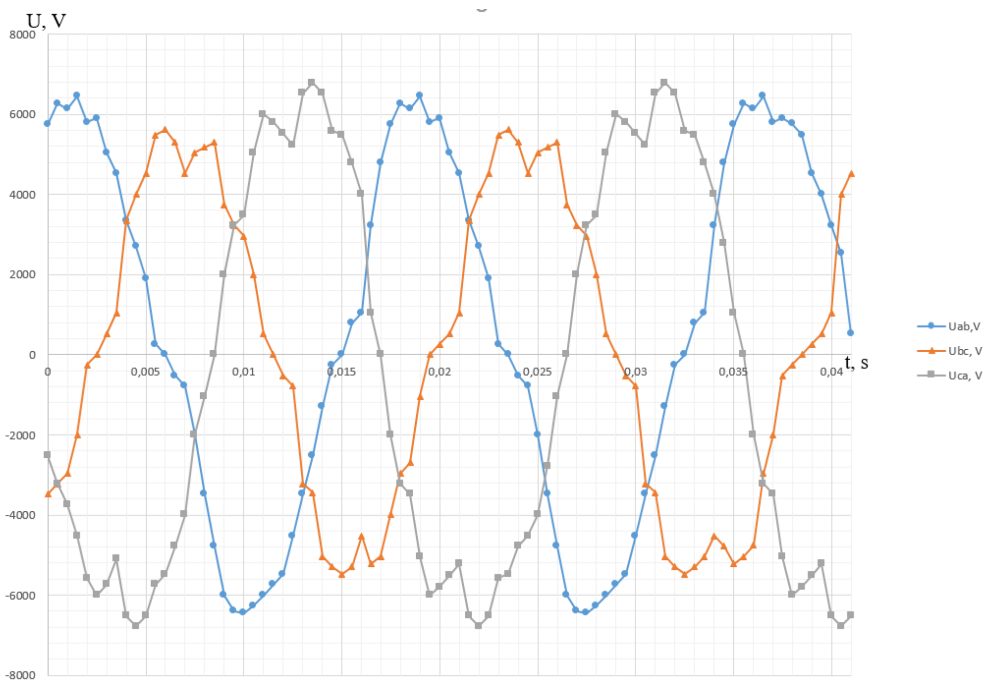


Figure 5 – Voltage oscillogram on DP buses when WPP is disconnected

Fig. 6 shows the obtained range of the mentioned linear voltage as well as its temporal changes. As it is understood, the range involves dozens of harmonics with rather large amplitudes. However, that is unacceptable for non-traction supply power grids.

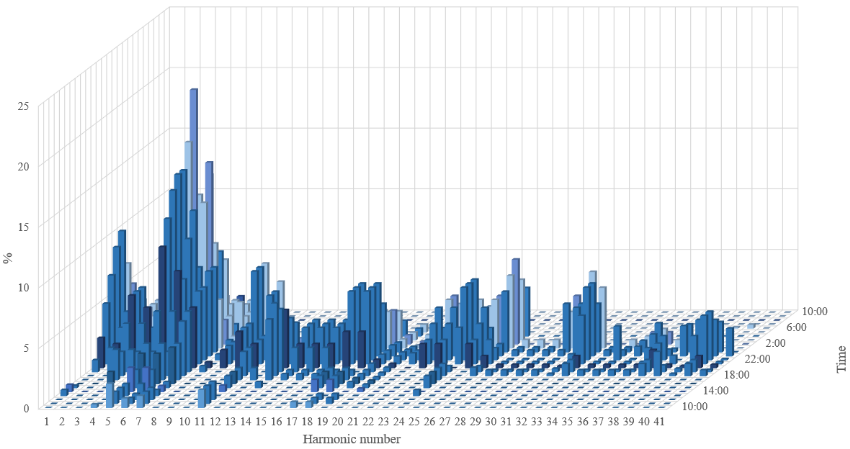


Figure 6 – Range of linear BC voltage on DP buses before WPP connection

If WPP is connected to the mains in terms of the coupling then the indices experience their gradual improvement along with increase in the renewable source voltage. When voltage was 4000 kW, their values were 6.02%; 3%; and 3.8% respectively. Fig. 7 explains the changes in linear BC voltage.

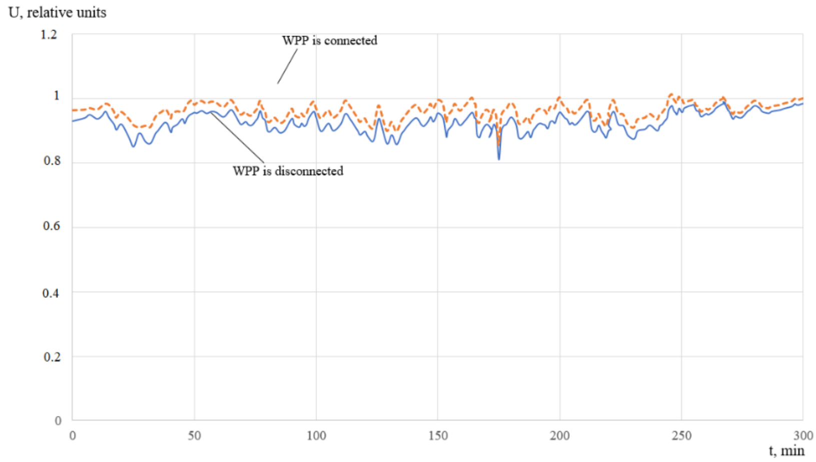


Figure 7 – Variations in linear BC voltage during a locomotive travel when

WPP is connected and disconnected- Figures 8, 9, and 10 demonstrate dependences of the coefficient and deviations of linear voltage from the output of the connected renewable source. The dependences result from the experiments. They mean that such WPP implementation in the railway mains can improve significantly the electricity quality within a supply network of their non-traction consumers as well as non-departmental ones. Nevertheless, approximation of the quality indices to acceptable values is only possible when output of the additional source is not less than a nominal value of total load of all the consumers connected to 6.6

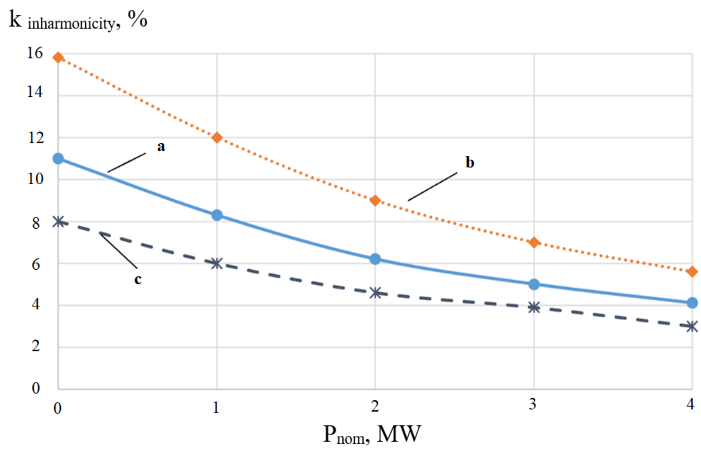


Figure 8 – Dependence of the inharmonicity coefficient of linear voltage within DP upon WPP output: a) AB; b) BC; and c) CA

kV winding. As it has been already mentioned, the latter was 8 MW in terms of the simulated case.

As for the influence of a power factor (cosφ) of additional source on the electricity quality indices, it has been found that if it varies within 0.5-1.0 then their value deviation is not more than 1.5%. Thus, it may be assumed that in terms of such a diagram of WPP connection, the parameter will not influence the electricity quality within the mains.

Ultimately, if one pays attention to variations in output of wind power plants, which can be constructed in south-eastern Ukraine, it becomes understood that the efficient system is required to accumulate electric energy generated by them during a day and to balance the capacity in terms of seasons. The system should combine adequately different types of plants with their number and type optimization according to the mentioned alternative of WPP use for a railway and guarantee electricity quality within the supply sources for its non-traction as well as non-departmental ones.

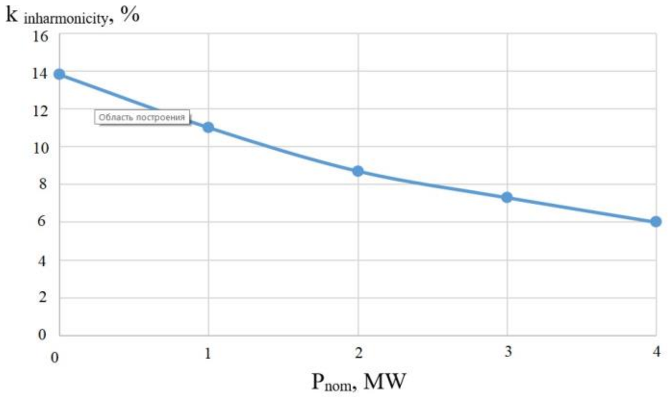


Figure 9 – Dependence of the voltage asymmetry coefficient in terms of the negative phase sequence within DP upon WPP output

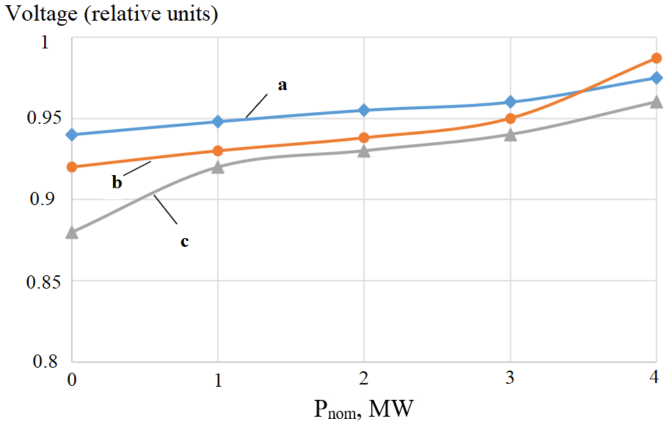


Figure 10 – Dependence of the linear voltage deviation within the WPP area connection upon the output of the latter: a) AB; b) BC; and c) CA

Determining features of influence of photovoltaic plants (PVPs), connected to supply systems of non-traction consumers, on electricity quality within the latter

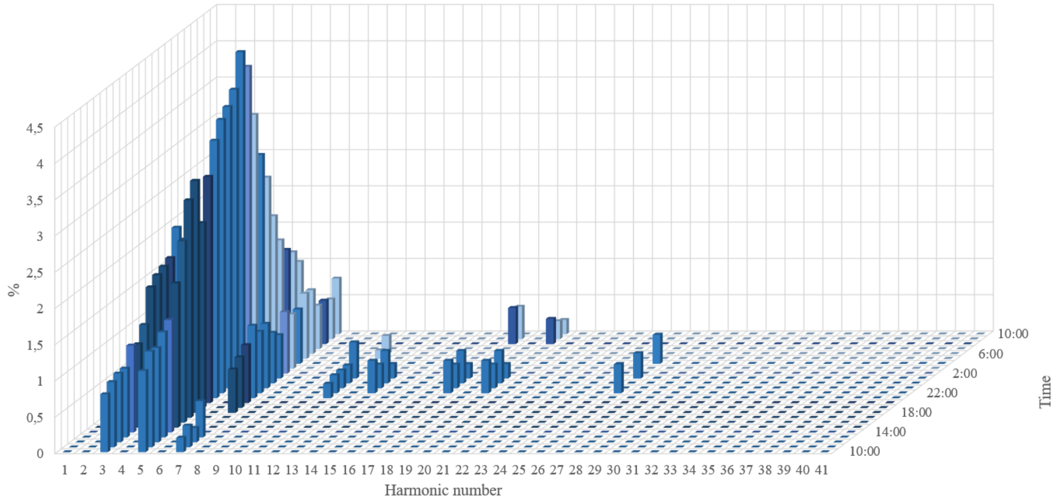
Several different diagrams are available to couple power circuits and transformers within TS. Traditionally, a diagram with double transformation is applied. Other cases apply a single transformation diagram, when consumers are supplied through a traction transformer which primary winding is connected directly to the general mains, i.e. with no extra transformation.

From the viewpoint of photovoltaic plants (PVP) connection to the mains, the two mentioned cases (exclusive of traction DC power grids) use an inverter transforming electric energy from solar batteries or accumulators into AC being acceptable for supply systems of non-traction consumers. Thus, to analyze PVP influence on the electricity quality within the mentioned system, it is quite sufficient to use e-analogue of railway mains while replacing its generator model by inverter model.

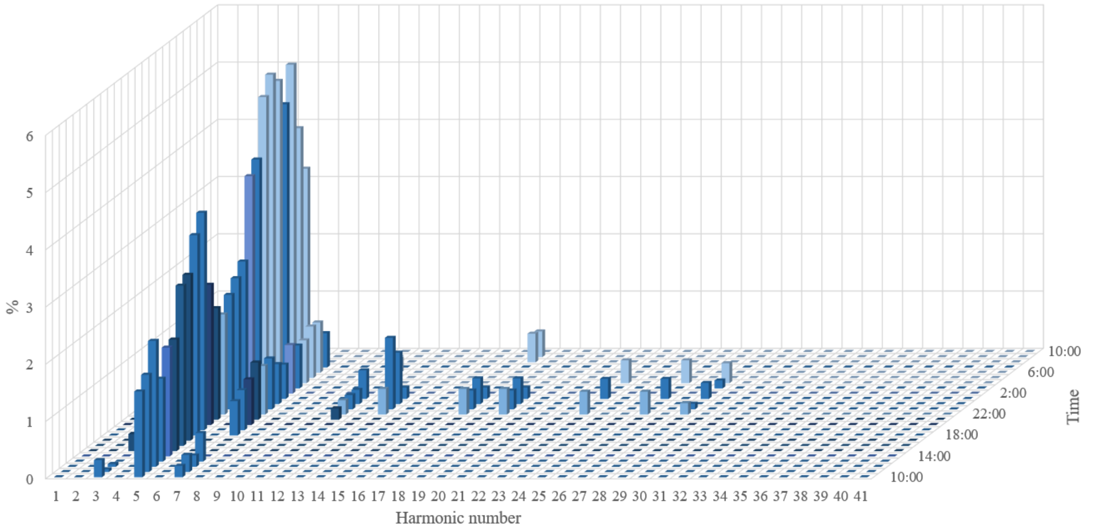
General nature of additional power source parameter influence on inharmonicity and asymmetry coefficients in terms of the reverse voltage sequence and voltage variation in the case of PVP use remains almost invariable. Approximation of the quality indices to the allowable values is only possible if PVP output is not less than 35-40% of the value of the total load of non-traction consumers. As for the voltage range, the case has demonstrated certain specific features.

Fig. 11 shows the obtained ranges of linear voltage on DP buses when PVP is connected to it in accordance with the stated diagram. In comparison with the corresponding range before the additional source connection (Fig. 6), electricity quality demonstrates its significant improvement both in terms of harmonic composition and in terms of harmonics left. However, attention should be paid to the fact that 3^{rd} and 5^{th} harmonics are singled out which was not demonstrated while WPP connecting. Even if PVP output is 3000 MW (i.e. 37% of the considered load of non-traction consumers), their coefficients are 4 and 5.5% respectively despite the fact that the allowable indices are 3 and 4%.

Taking into consideration the information from [24], it has been assumed that within the voltage range, 3^{rd} and 5^{th} harmonics are stipulated by operation of the used inverters. To support the idea, voltage range has been obtained at the output Fronius inverter (Austria) connected to the experimental solar power plant (Fig.12). The inverters are meant to operate as a part of the photovoltaic systems. The facilities are rather popular now.



a)



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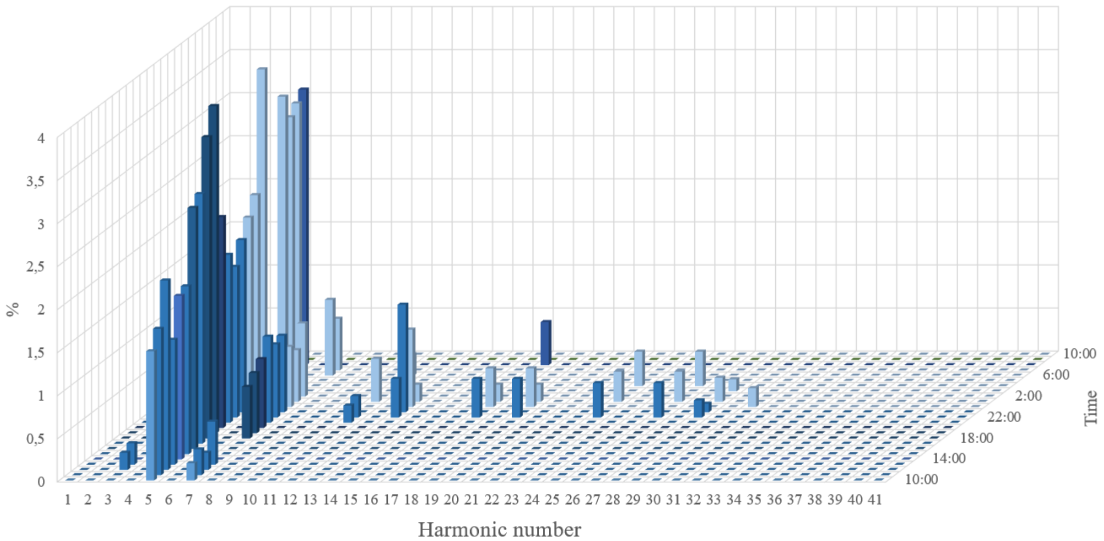

c)**Figure 11 – Linear voltage ranges on DP buses of the supply system for non-traction consumers when PVPs are connected to them: a) AB; b) BC; and c) CA**

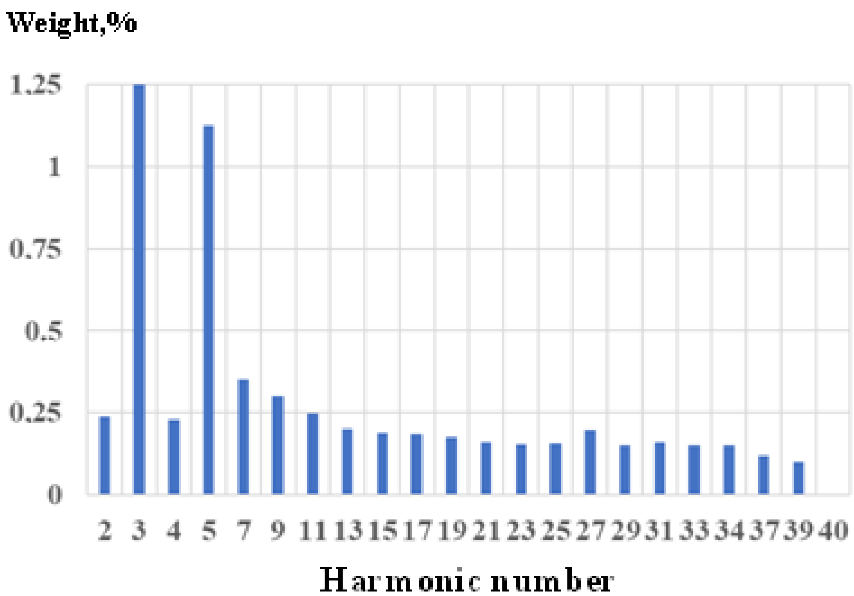

Figure 12 – Weight composition of harmonics as a part of voltage range at the output of Fronius inverter

It turns out that to compare with the electromechanical converters when WPP are applied, PVP connection through inverters is undesirable procedure since it needs additional use of filters for the frequencies. The most expedient idea is to connect PVP directly to DC traction power grid or find out other ways to connecte them to supply system of non-traction consumers omitting inverters. The matter is that railways have both necessary and large alienated territories. Hence, they can be used to place such distributed sources.

A system with connection of the distributed solar generators, proposed by [15], may exemplify the mentioned PVP use. Fig. 13 demonstrates its diagram where solar panels are interconnected series parallel in photovoltaic modules (PVMs) located along the rail at the alienated territories. Each PVM is connected to an adapting converter (AC) separating it galvanically from further supply system part. Output DC voltage of each AC is not more than 50 V corresponding to the electrical safety conditions.

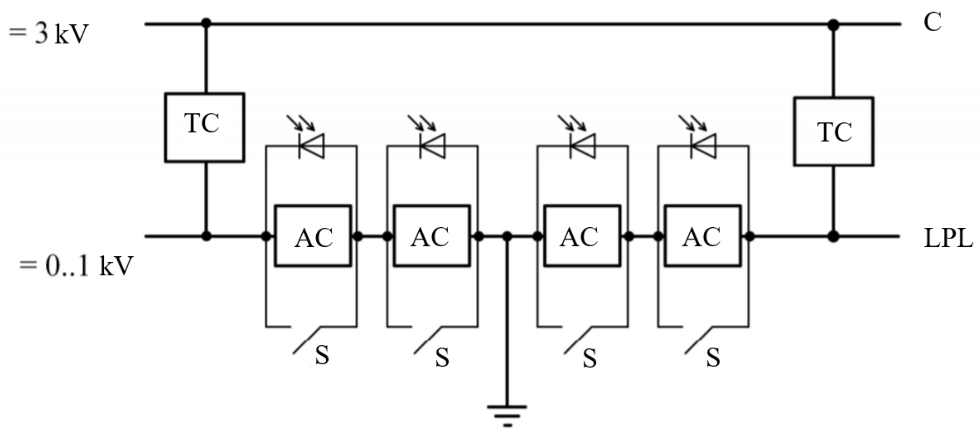

Figure 13 – Diagram of PVP connection to DC railway catenary

In parallel with the catenary, single-wire longitudinal power line (LPL) is installed using either the catenary supports or separately at the alienated territory. The PLP connects separate photovoltaic modules into one point-to-point circuit. The latter consists of sections with 1 kV output voltage; each of them is connected to the catenary through a transient converter. The rail itself may be used as a ground wire for LPL.

Switches (Ss), shunting each photovoltaic module, prevent from the emergency mode if breakdown takes place. In terms of serial connection, the circuit results in the integrating system failure. Hence, in terms of the case, the damaged module is shunted with the help of the switch, and other part of the system continues its operation although its output voltage decreases.

Fig. 14 explains a diagram of a shunting switch. If a photovoltaic module circuit is disconnected then voltage $U_м$ increases up to a breakdown stabilizer value VD_c, and i_y current opens VS four-layer switch while passing within its control electrode circuit.

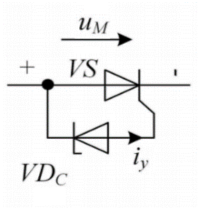

Figure 14 – Diagram of a shunting switch

Transient converter is connected to LPL section. It consists of input filter (two Ca condensers and primary winding of bushing transformer (BT); voltage inverter (VI), rectifier (R), and output LC-filter (Fig. 15). Output TC clamps are connected right to a catenary with 3 kV voltage.

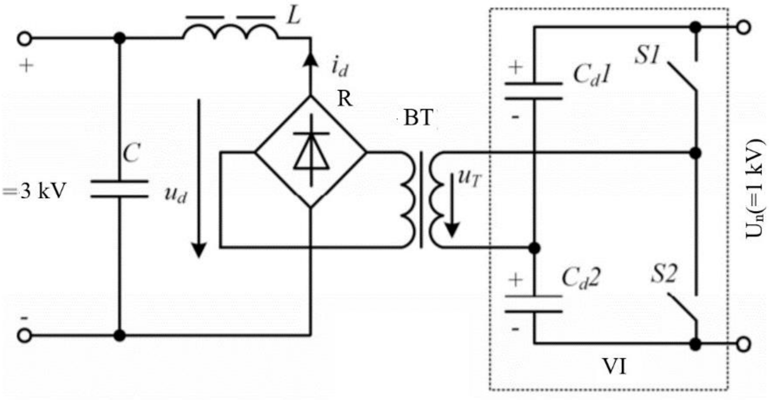

Figure 15 – Diagram of transient converter to supply a DC catenary using PVPs

The converter is a traditional forward TC used to energize electronic equipment [25]. The both considered examples (i.e. TC and AC) are small enough to be installed right on catenary supports.

Actually, the considered case of PVP connection to railway mains involves no accumulator for the energy generated by it. The fact predicts possibilities of simultaneous use of wind power plants as well which would help stabilize the electricity generation amounts. Taking into consideration the fact that first ones have DC output voltage and last ones have AC output voltage, they can be integrated into one system of non-traction consumer supply system while applying some specific power grid with the combined use of different energy accumulators.

Conclusions

Implementation of possible tendencies to apply RES for railway electric power supply systems is of chaotic and systemless nature. No substantiated idea is available as for the most expedient alternative.

Development of proper electric power stations with RES and their connection to external mains, energizing the railway subsequently, is the most advantageous. However, it cannot solve any problem concerning the departmental mains.

RES introduction into railway electric supply systems by means of connection to 6 kV DPs, energizing non-traction consumers and non-departmental ones and being connected to traction 115/27.5/6.5 kV transformer improves significantly electricity quality within the mains of the mentioned load. Nevertheless, negative sequence coefficients of voltage inharmonicity and asymmetry as well as voltage deviations to the allowable values is possible if only the source output is not less than 35% of the output of the mentioned loads.

Taking into consideration the fact that use of inverters to connect PVPs to the mains results in extra voltage distortions (especially, that concerns 3rd and 5th harmonics), it is the most practical idea to connect solar power plants directly to DC traction power supply system; if not, it is necessary to identify other ways to connect them to supply systems of non-traction consumers.

Taking into consideration the fact that PVPs have direct output voltage and WPPS have alternative one, they should be integrated in one supply system for non-traction consumers by means of combination of various energy accumulators.

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АНОТАЦІЯ

У роботі розглянуто доцільні схеми підключення відновлювальних джерел енергії (ВДЕ) до залізничних електромереж. На сьогодні впровадження розподіленої генерації (РГ) на основі ВДЕ у залізничні електромережі є **актуальним питанням**. Незважаючи на те, що науково-практичні аспекти розробки і впровадження РГ систем досліджуються багатьма вітчизняними і зарубіжними вченими, досі не існує обґрунтованої думки щодо найбільш доцільного використання того чи іншого напрямку впровадження ВДЕ в системи електропостачання залізниць. Є лише рекомендації щодо приєднання ВДЕ до шин тягових підстанцій. Зараз вигідно створювати власні електростанції з ВДЕ, підключаючи їх до зовнішніх мереж, від яких лише потім отримує живлення залізниця. **Мета роботи** полягає у покращенні якості електроенергії в мережах живлення нетягових споживачів залізниць шляхом підключення до них відновлювальних джерел енергії. **Методика дослідження** ґрунтується на сучасних методах обчислювальної математики, статистики та аналізу інформації з використанням сучасних комп'ютерних технологій. **Результати дослідження.** У роботі розроблено схему живлення тягових і нетягових споживачів від залізничної електромережі, до якої підключені ВДЕ, та модель залізничної електромережі з підключенням ВДЕ до обмотки трансформаторної підстанції (ТП) нетягових споживачів. Впровадження вітроенергетичної установки (ВЕУ) в систему електропостачання залізниць за наведеною схемою може дійсно суттєво покращить якість електроенергії в мережі живлення їх нетягових і невідомчих споживачів. Але наближення показників цієї якості до допустимих значень наступає лише тоді, коли потужність додаткового джерела дорівнює не менш ніж 35% від номінальної величини загального навантаження всіх підключених до обмотки 6,6 кВ споживачів. Розглянуто приклад підключення фотоенергетичної установки (ФЕУ) до залізничної мережі, який здійснюється без використання будь-якого накопичувача згенерованої ними енергії. Впровадження можливих напрямків використання ВДЕ в системах електропостачання залізниць відбувається хаотично й безсистемно, і поки що не існує обґрунтованого бачення щодо найбільш доцільного варіанту. **Наукова новизна** полягає у впровадженні відновлюваних джерел енергії в систему електропостачання нетягових споживачів залізничного транспорту. **Практичне значення.** Використання додаткових відновлюваних джерел енергії для живлення нетягових споживачів призводить до мінімізації витрат електроенергії.

Ключові слова: відновлюючи джерела енергії, розподілена генерація, нетягові споживачі залізниць, вітроенергетична установка, фотоенергетична установка.

АННОТАЦИЯ

В работе рассмотрены целесообразные схемы подключения возобновляемых источников энергии (ВИЭ) в железнодорожных электросетях. На сегодняшний день внедрение распределенной генерации (РГ) на основе ВИЭ в железнодорожные электросети является **актуальным вопросом**. Несмотря на то, что научно-практические аспекты разработки и внедрения РГ систем исследуются многими отечественными и зарубежными учеными, до сих пор не существует обоснованного мнения по наиболее целесообразному использованию того или иного направления внедрения ВИЭ в системы электроснабжения железных дорог. Есть только рекомендации о присоединении ВИЭ к шинам тяговых подстанций. Сейчас выгодно создавать собственные электростанции с ВИЭ, подключая их к внешним сетям, от которых только потом получает питание железная дорога. **Цель работы** заключается в улучшении качества электроэнергии в сетях питания нетяговых потребителей железных дорог путем подключения к ним возобновляемых источников энергии. **Методика исследования** основывается на современных методах вычислительной математики, статистики и анализа информации с использованием современных компьютерных технологий. **Результаты исследования.** В работе разработана схема питания тяговых и нетяговых потребителей от железнодорожной электросети, к которой подключены ВИЭ, и модель железнодорожной электросети с подключением ВИЭ к обмотке трансформаторной подстанции (ТП) нетяговых потребителей. Внедрение ветроэнергетической установки (ВЭУ) в систему электроснабжения железных дорог по приведенной схеме может действительно существенно улучшить качество электроэнергии в сети питания их нетяговых и неведомственных потребителей. Но приближение показателей этого качества до допустимых значений наступает только тогда, когда мощность дополнительного источника равна не менее 35% от номинальной величины общей нагрузки всех подключенных к обмотке 6,6 кВ потребителей. Рассмотрен пример подключения фотоэнергетической установки (ФЭУ) к железнодорожной сети, осуществляется без использования каких-либо накопителей сгенерированной ими энергии. Внедрение возможных направлений использования ВИЭ в системах электроснабжения железных дорог происходит хаотично и бессистемно, и пока не существует обоснованного видения наиболее целесообразного варианта. **Научная новизна** заключается во внедрении возобновляемых источников энергии в систему электроснабжения нетяговых потребителей железнодорожного транспорта. **Практическое значение.** Использование дополнительных возобновляемых источников энергии для питания нетяговых потребителей приводит к минимизации затрат электроэнергии.

Ключевые слова: возобновляемые источники энергии, распределенная генерация, нетяговые потребители железных дорог, ветроэнергетическая установка, фотоэнергетическая установка.

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