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MODELING AND ANALYZING THE EFFECT OF CONNECTION TO THE NETWORK OF A HARMONIC SOURCE HAVING VARIOUS TOTAL HARMONIC DISTORTION FACTORS ON LOAD SIGNAL WAVEFORMS

This article examines the effect of a network connected source of harmonics having a total harmonic distortion factor varying from 5% to 15% on load voltage and current waveforms. When a source of higher harmonics is connected to the network, both in the network and in the load, the effective values of voltage and current increase, that can negatively affect the cable line insulation, accelerating its destruction and aging.

To analyze the consequences of a power quality deterioration, a 20 kV network was simulated, consisting of a 20 kV symmetrical generator, an XRUHAKXS-20(1x120/50) power cable line 20 km long, a step-down transformer 20/0.4 kV with a power of 2 MVA, with windings connected in delta-star, and a three-phase symmetrical load.

The values of the currents flowing through the cable conductor, obtained as the result of simulation were used to calculate the voltage drop between the cable conductor and its shield. Results obtained show that the connection of a harmonic distortion source to a network leads to a magnification of a current flowing through the cable conductor by more than 2%. The model proposed in the article can be used further for a more detailed study of solar photovoltaic plants connection to the grid.

One of the biggest problems regarding solar power plants is that its electricity generation is intermittent. Thus, future efforts should be focused on modeling and studying the higher harmonics generation during switching on and off of the solar photovoltaic plants.

***Keywords**: solar photovoltaic plants, total harmonic distortion factor, harmonic source.*

Introduction. Application of renewable energy sources is an important direction that increases the level of energy security and reduces related environmental impacts, including greenhouse gas emission. Currently, for environmental, economic and geopolitical reasons, there is an active transition to renewable energy sources and solar energy generation shares a significant part. In general, solar photovoltaic panels, as well as small wind turbines are classified as sources of distributed generation. When operating in the system, a source of distributed generation is connected to the distribution network at medium voltage up to 35 kV [1]. Connecting distributed generation source to a distribution network has a positive effect on its performance, but at the same time creates new challenges that have to be faced when managing power supply modes with distributed generation [1, 2]. Every year, the share of distributed generation in the world, including the use of local sources of solar energy, is constantly growing. At the same time, the integration of distributed generation sources can have a significant impact on the operation of the electrical distribution network, causing technical problems related to power quality, voltage stability and harmonic distortion [2-4]. Statistical data shows that there is a problem of power quality deterioration at the point of connection of photovoltaic power stations, specifically voltage increase [5] and harmonics increase [6]. Besides, solar power is intermittent. Since solar panels generate direct current, it becomes necessary to use inverters to convert direct current to alternating current, and then the voltage is supplied to a step-up transformer, after which it is fed to the grid. Photovoltaic inverters are considered the power electronic devices, which are the main sources of harmonic distortion [7]. It is obvious that when such a source is connected to the network, the non-sinusoidal signal in the network increases, which may lead to an increase in power losses, as well as to an overload of distribution networks due to an increase in the effective value of the current and voltage distortion. In particular, due to harmonics, the destruction and aging of the cable line insulation is accelerated. Voltage harmonics affect the electrical insulation by increasing partial discharge intensity [8]. Therefore, the purpose of this study is to simulate and analyze the effect of a non-sinusoidal signal produced by a source of harmonics on the insulation of the electrical network.

Purpose of work: The aim of this work is to analyze the impact of a non-sinusoidal alternating current voltage signal produced by a harmonic source on the electrical insulation of the cable line.

Research material. The quality of electricity must meet the requirements of international standard [9]. The current standards establish certain maximum deviations from the main indicators of the power quality from the established standard values. In this paper the voltage non-sinusoidal coefficient (voltage total harmonic distortion factor) was considered as the main criterion for the electric power quality.

To analyze the consequences of a power quality deterioration, a 20 kV network was considered, consisting of a 20 kV symmetrical generator, an XRUHAKXS-20(1x120/50) power cable line 20 km long, a step-down transformer 20/0.4 kV with a power of 2 MVA, with windings connected in delta-star, and a three-phase symmetrical load. The scheme diagram is shown below in Fig. 1.

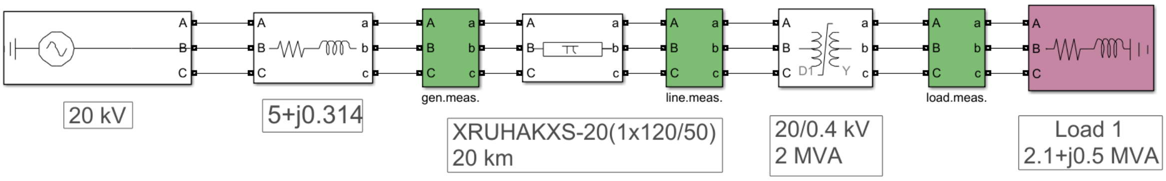

Figure 1 – Simulation of a 20 kV symmetrical network.

The electric network simulation was performed with a help of MATLAB® and Simulink® software [10, 11]. The obtained voltage and current waveforms are shown in Fig. 2, Fig. 3 and Fig. 4. The graphs show only linear values.

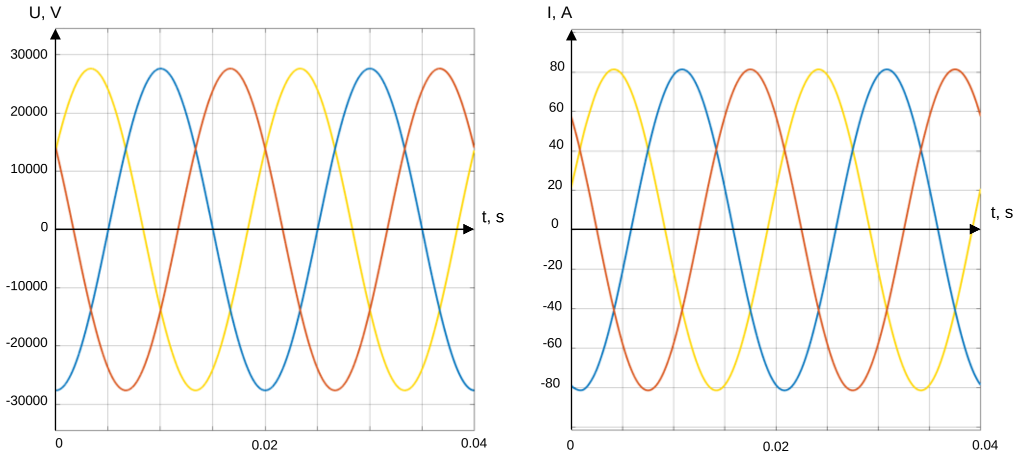

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Figure 2 - Generator voltage and current waveforms (gen.meas.): a – line voltage plots; b – line current plots.

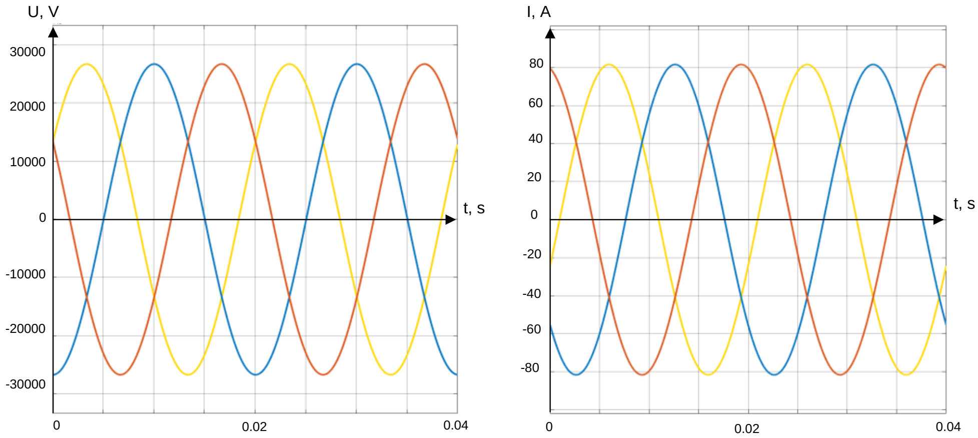

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Figure 3 – Voltages and currents waveforms at the end of the line (line.meas.): a – line voltage plots; b – line current plots.

The effective values of line voltages are $\dot{U}_{generator} = 19520.0$ V in Fig. 2-a; $\dot{U}_{line} = 18940.0$ V in Fig. 3-a and $\dot{U}_{load} = 370.3$ V in Fig. 4-b.

Renewable energy is a relevant and important energy industry, the role of which is growing every year around the world. However, as noted above, an increase in the number of connections of solar photovoltaic cells to the power grid can have an impact on the quality of electricity in the network, and the importance of improving the quality of electricity remains an urgent problem for both electricity producers and consumers, which is especially acute in low voltage networks. The occurrence of non-sinusoidal currents and voltages, voltage unbalance and its fluctuations are associated with a low power factor of non-linear loads on the part of consumers and a high level of current harmonics generated by solar photovoltaic inverters in a low voltage network on the part of electricity producers.

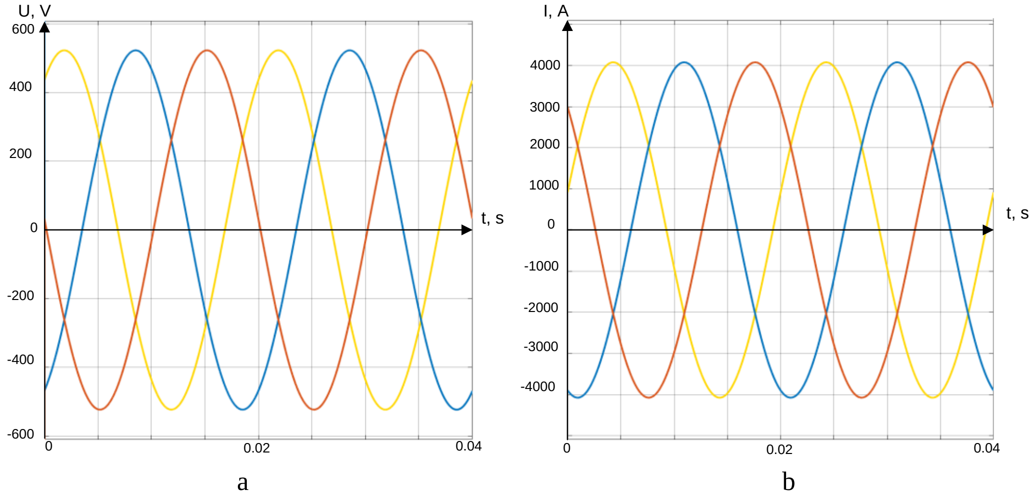

Figure 4 – Load voltage and current waveforms (load.meas.):
a – line voltage plots; b – line current plots.

Figure 5 shows the scheme diagram, where a harmonic source is connected to the network from the high voltage side with a total harmonic distortion factor of 5% and a voltage of 20 kV, at the output of which one obtain a non-sinusoidal symmetrical signal, shifted between phases by 120 degrees with the same harmonic content for each of the phases.

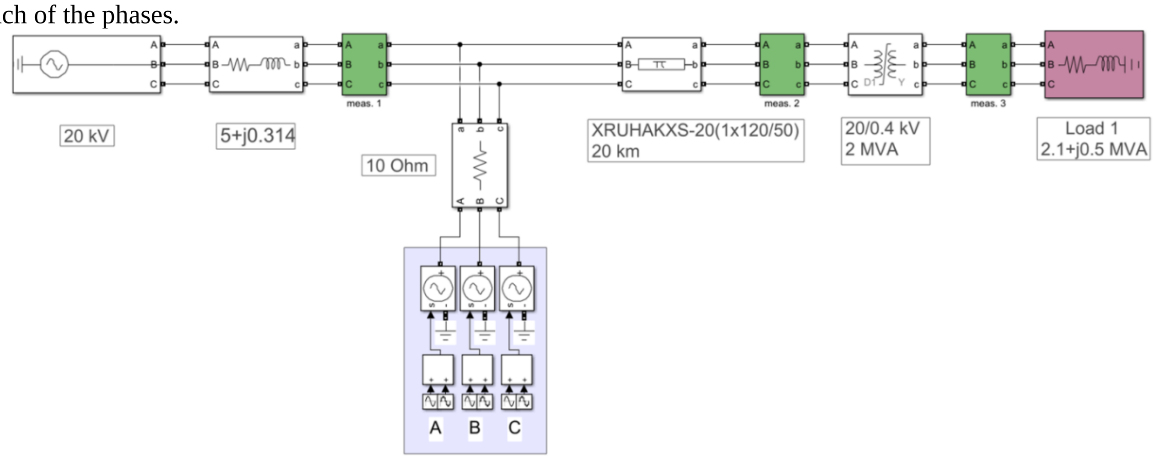

Figure 5 – Simulation of a 20 kV symmetrical network with a connected source of harmonics having a varying total harmonic distortion factor.

Three-phase symmetrical voltage with the same harmonic content for each phase of a non-sinusoidal signal with a 20 kV voltage is supplied to the output of the unit, obtained by adding two sinusoids to facilitate observation and control of the influence of a non-sinusoidal signal on a sinusoidal signal in the network. Changes in the 20 kV network will be studied at non-sinusoidal coefficients (total harmonic distortion factor) of 5%, 8% and 15%. In its turn, the obtained voltage and current waveforms are shown in Fig. 6, Fig. 7 and Fig. 8.

According to the results of the virtual experiment, it can be seen that the non-sinusoidal voltage increased due to the connection of a non-sinusoidal power source with a 5% total harmonic distortion factor. According to the graphs, at point after the power line, the non-sinusoidal voltage is increased, and the non-sinusoidal current is decreased. Changes are observed throughout the network, the effective values of line voltages have also changed. Specifically, generator voltage is increased by 170.0 V that is 0.87% greater than at a pure sinusoidal waveform; voltage at the end of line is increased by 190.0 V that is 1.0% greater than at a pure sinusoidal waveform; and finally, load voltage is increased by 3.9 V that is 1.05% greater than at a pure sine wave.

Model in Fig. 5 was used for simulation at 8% total harmonic distortion factor. Simulated voltage and current waveforms obtained in symmetrical network with a connected source of harmonics having an 8% total harmonic distortion factor are shown in Fig. 9, Fig. 10 and Fig. 11.

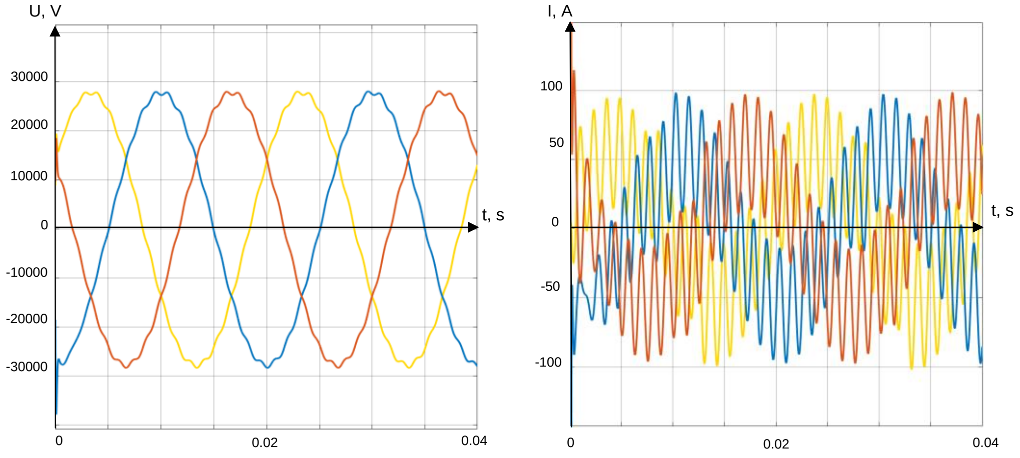

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Figure 6 – Generator voltage and current waveforms (meas. 1): a – line voltage plots; b – line current plots.

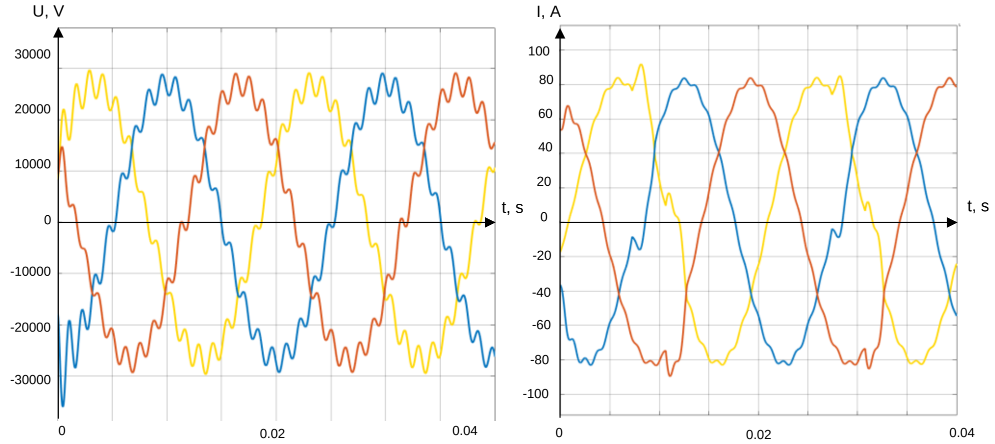

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Figure 7 – Voltages and currents waveforms at the end of the line (meas. 2):
a – line voltage plots; b – line current plots.

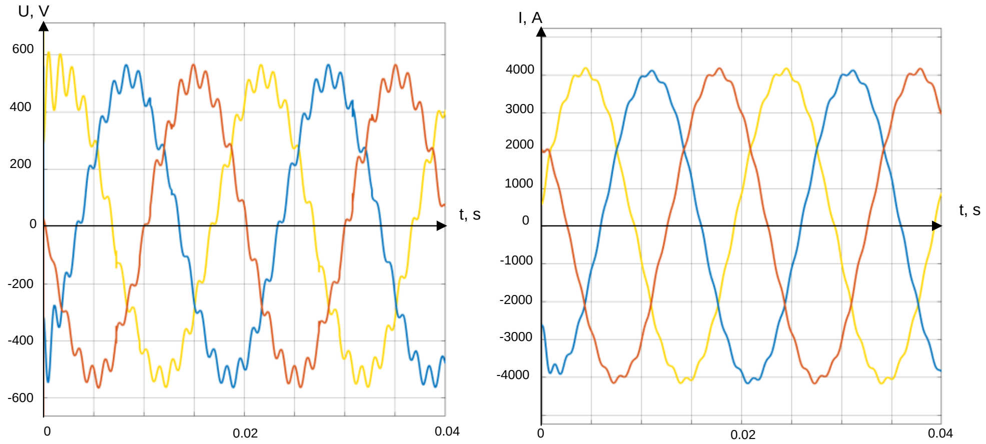

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Figure 8 – Load voltage and current waveforms (meas. 3): a – line voltage plots; b – line current plots.

Above plots show an increase in the harmonic content. The changes are more significant than when connecting a source with a total harmonic distortion factor of 5%, the effective values of the line voltages also have changed. Specifically, generator voltage is increased by 180.0 V that is 0.92% greater than at a pure sine wave; voltage at the end of line is increased by 310.0 V that is 1.64% greater than at a pure sine wave; load voltage is increased by 5.6 V that is 1.51% greater than at a pure sinusoidal voltage waveform.

In practice voltage total harmonic distortion factor is rarely higher than 15%. Therefore, such a case is of rather theoretical interest. Simulated voltage and current waveforms obtained in symmetrical network with a connected source of harmonics having a 15% total harmonic distortion factor are shown in Fig. 12, Fig. 13 and Fig. 14.

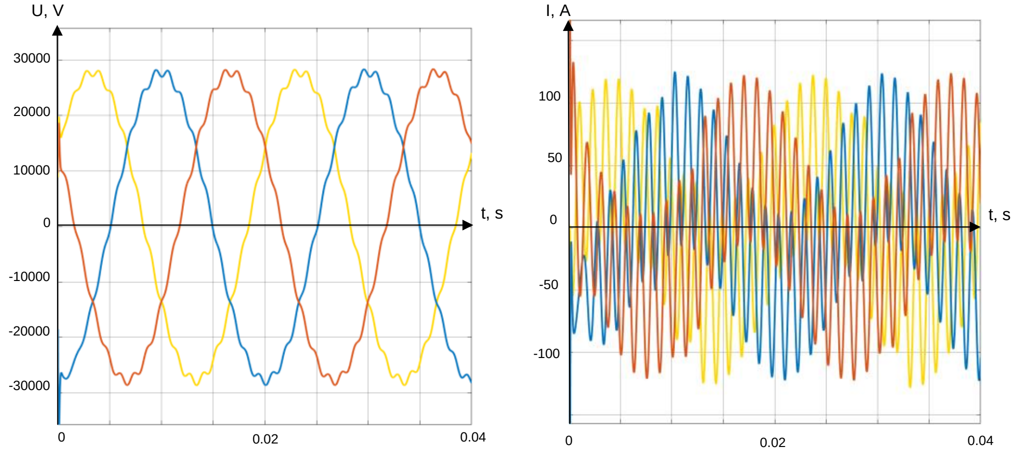

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Figure 9 – Generator voltage and current waveforms (meas. 9):
a – line voltage plots; b – line current plots.

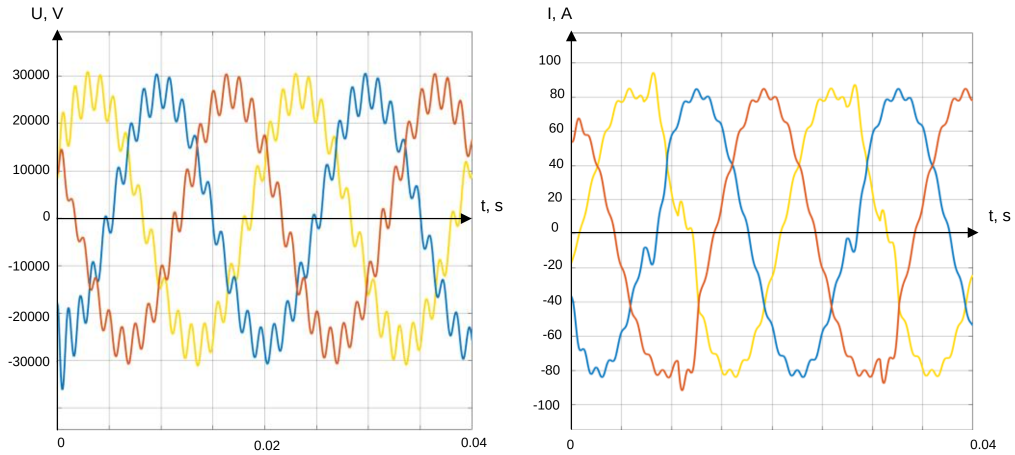

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Figure 10 – Voltages and currents waveforms at the end of the line (meas. 10):
a – line voltage plots; b – line current plots.

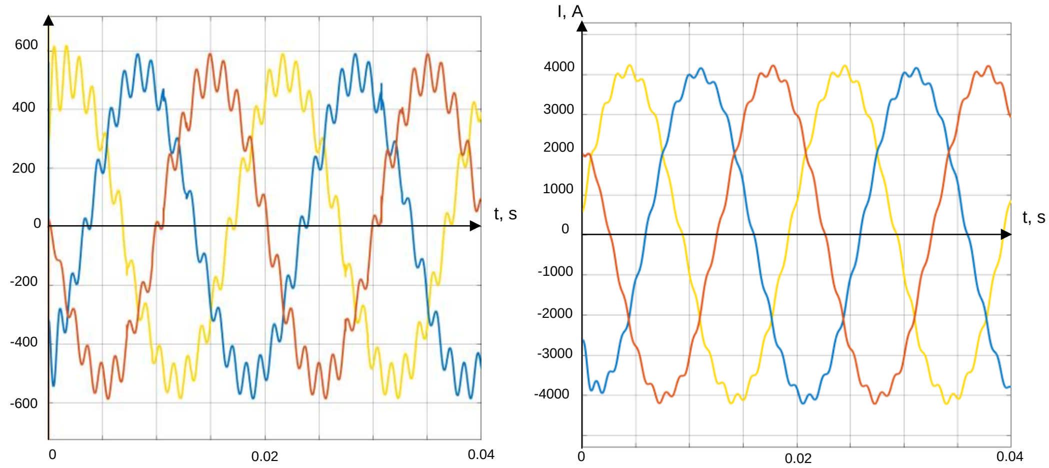

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Figure 11 – Load voltage and current waveforms (meas. 11):
a – line voltage plots; b – line current plots.

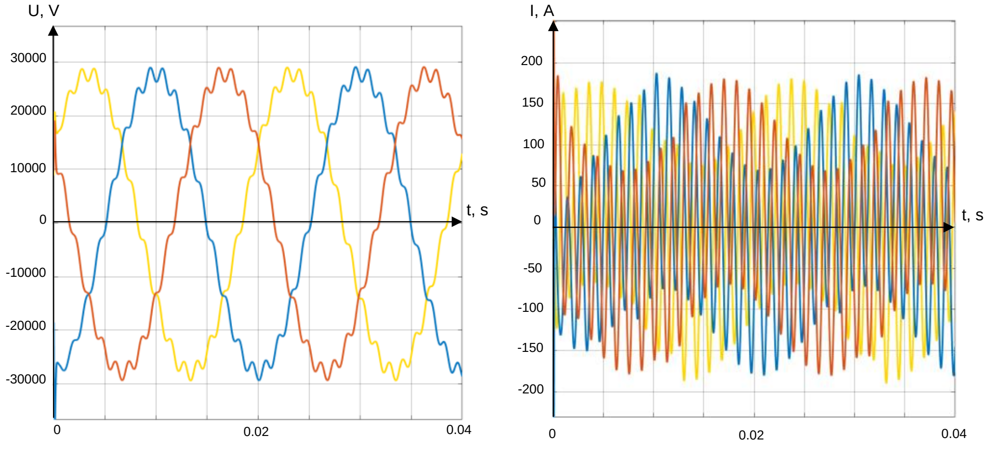

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Figure 12 – Generator voltage and current waveforms (meas. 13):
a – line voltage plots; b – line current plots.

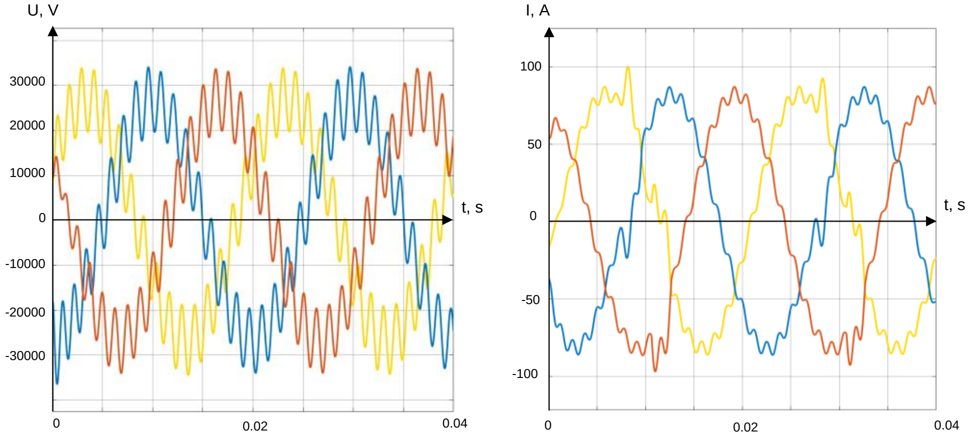

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Figure 13 – Voltages and currents waveforms at the end of the line (meas. 14):
a – line voltage plots; b – line current plots.

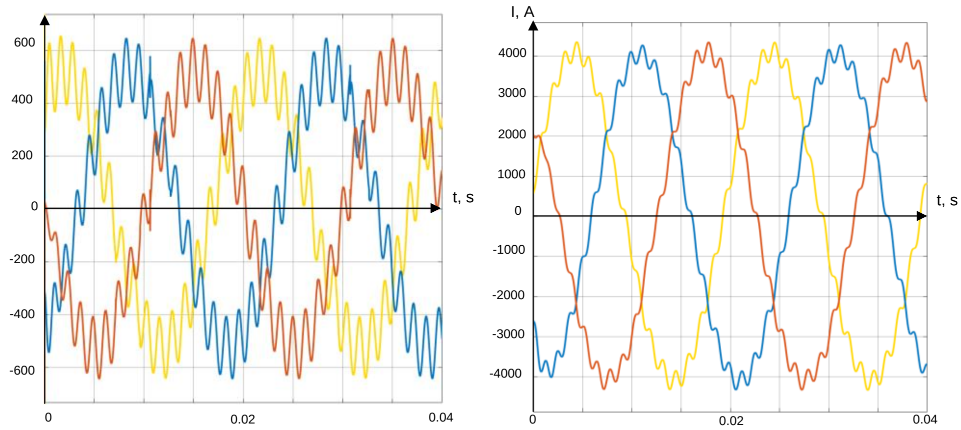

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Figure 14 – Load voltage and current waveforms (meas. 15):
a – line voltage plots; b – line current plots.

According to Fig. 12, Fig. 13 and Fig. 14, generator voltage is increased by 200.0 V that is 1.02% greater than at a pure sinusoidal waveform; voltage at the end of line is increased by 790.0 V that is 4.17% greater than at a pure sinusoidal waveform; and finally, load voltage is increased by 12.5 V that is 3.38% greater than at a pure sine wave. The simulation results are summarized in Table I.

Table I. The effective values of network line voltages, depending on total harmonic distortion factor of connected source of harmonics.

Total harmonic distortion factor of harmonic source, %	Effective line voltage in the network					
	Generator voltage, V	Voltage magnification, %	Voltage at the end of line, V	Voltage magnification, %	Load voltage, V	Voltage magnification, %
–	19520	–	18940	–	370.3	–
5	19690	0.87	19130	1.00	374.2	1.05
8	19700	0.92	19250	1.64	375.9	1.51
15	19720	1.02	19730	4.17	382.8	3.38

Since the harmonic issue is one of the most important in power systems, it is important to estimate harmonics risk to cable insulation, shortened life, etc. For a cable line with a given line length of 20 km, a shield grounding scheme with a full transposition cycle was chosen (refer to Fig. 15).

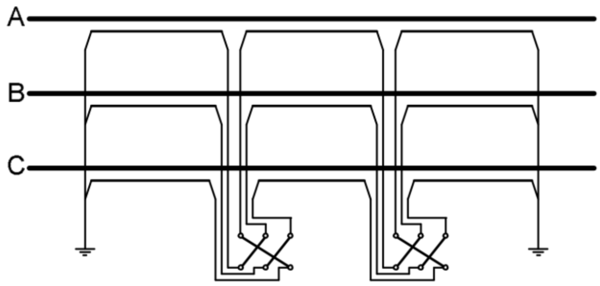

Figure 15 – Cable shield grounding scheme with a full transposition cycle.

Internal cable design is shown in Fig. 16.

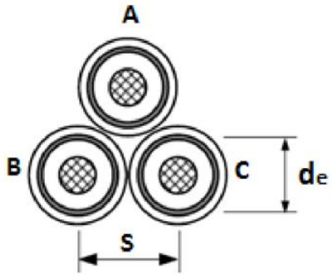

Figure 16 – A three-phase cable basic dimensions.

In Fig. 16: $d_e = 35\times10^{-3}$ m is cable diameter; $s = d_e$ is distance between the central axes of conductors, when triangular cable laying method applied.

The values of the currents flowing through the cable conductor, obtained from the simulation above, were used to calculate the voltage drop between the cable conductor and its shield. The calculation results are presented in Table II.

Table II. The effective values of voltage drop between cable shield and conductor, depending on total harmonic distortion factor of connected source of harmonics.

Total harmonic distortion factor of harmonic source, %	Effective value of phase current				Voltage between cable shield and conductor, V	Voltage magnification, %
	Load current, A	Current magnification, %	Current through conductor, A	Current magnification, %		
–	2881	–	57.76	–	16.770	–
5	2901	0.69	59.25	2.58	17.203	2.58
8	2902	0.73	59.28	2.63	17.212	2.64
15	290	0.87	59.40	2.84	17.246	2.84

According to Table II, the connection of a non-sinusoidal distortion source leads to a magnification of a conductor current by more than 2%. According to experimental measurements presented in [12], the current distortions caused by photovoltaic inverters may reach up to 2% of fundamental frequency current. Following expressions were used for computation.

Longitudinal linear resistance between the conductor and the cable screen (Ω/m) is given as follows:

$$Z_{c-s} = R_s + j \cdot \omega \cdot M_{c-s};\ Z_c = R_s + j \cdot \omega \cdot M_c .(1)$$

In expressions (1): R_s is an active resistance of the shield, Ω/m; M_{c-s} is a mutual inductance between the conductor and the shield, H/m. In its turn:

$$R_s = \frac{\pi \cdot \mu_0 \cdot f}{4};\ M_{c-s} = \frac{\mu_0}{2 \cdot \pi} \cdot \ln\left(\frac{2 \cdot D_e}{d_s}\right);\ M_c = \frac{\mu_0}{2 \cdot \pi} \cdot \ln\left(\frac{D_e}{s}\right).(2)$$

In expressions (2): $D_e = 2.24 \cdot \sqrt{\frac{\rho_s}{\omega \cdot \mu_0}}$ is an equivalent rated reverse current depth, m; $U_{c-s} = \frac{(Z_{c-s} - Z_c) \cdot I_c \cdot l_c}{3 \cdot N}$ is a voltage drop between the shield and the conductor, V. In its turn, ω means angular frequency in radians per second; $\mu_0 = 4 \cdot \pi \times 10^{-7}$ H/m is a magnetic permeability in a classical vacuum; I_c is a current flowing through the conductor, A; l_c is a power cable length, m; $N = 1$ is a number of transposition cycles.

Power electronic converters or inverters that do not create pure sinusoidal signals and are components in electricity generation by power plants based on non-traditional renewable energy sources, such as solar power plants, generate harmonics into the system when connected to a low voltage network. With an insignificant power capacity of such power generating installations, they do not cause significant distortions in the waveform of the voltage and current of the general power system into which the generation takes place. But with an increase in the power capacity of these power generating installations, when it becomes commensurate with the power of the general power system, distortions in the waveform of the voltage and current of the general network, which may occur, should be the subject of further study.

Conclusions. This article examines the effect of a network connected source of harmonics having a total harmonic distortion factor varying from 5% to 15% on load voltage and current waveforms. When a source of higher harmonics is connected to the network, both in the network and in the load, the effective values of voltage and current increase, which can negatively affect the cable insulation, accelerating its destruction and aging. Results obtained show that the connection of a harmonic distortion source to a network leads to a magnification of a current flowing through the cable conductor by more than 2%. The model proposed in the article can be used further for a more detailed study of solar photovoltaic plants connection to the grid. One of the biggest problems regarding solar power plants is that its electricity generation is intermittent. Thus, future efforts should be focused on modeling and studying the higher harmonics generation during switching on and off of the solar photovoltaic plants.

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МОДЕЛЮВАННЯ ТА АНАЛІЗ ВПЛИВУ ПІДКЛЮЧЕННЯ ДО МЕРЕЖІ ДЖЕРЕЛА ГАРМОНІК З РІЗНИМ СУМАРНИМ КОЕФІЦІЄНТОМ ГАРМОНІЙНИХ СПОТВОРЕНЬ НА ФОРМУ СИГНАЛІВ У НАВАНТАЖЕННІ

У цій статті досліджується вплив підключення до мережі джерела гармонік із сумарним коефіцієнтом гармонійних спотворень, що змінюється в межах від 5% до 15% на форму напруги та струму навантаження. При підключенні до мережі джерела вищих гармонік як в мережі, так і в навантаженні діючі значення напруги і струму зростають, що може негативно позначитися на ізоляції кабельної лінії, прискорюючи її руйнування і старіння.

Для аналізу наслідків погіршення якості електроенергії було змодельовано мережу класу напруги 20 кВ, яка складається з симетричного генератора 20 кВ, силової кабельної лінії XRUHAKXS-20(1x120/50) довжиною 20 км, понижувального трансформатора 20/0,4 кВ. потужністю 2 МВА, з обмотками, з'єднаними в трикутник-зірка, і трифазним симетричним навантаженням.

Отримані в результаті моделювання значення струмів, що протікають по жилі кабелю, були використані для розрахунку падіння напруги між жилою кабелю та його екраном. Отримані результати показують, що підключення до мережі джерела гармонійних спотворень призводить до збільшення струму, що протікає по провіднику кабелю, більш ніж на 2%. Запропонована в статті модель може бути використана надалі для більш детального дослідження підключення сонячних фотоелектричних установок до мережі.

Однією з найбільших проблем сонячних електростанцій є періодичність виробництва електроенергії. Таким чином, майбутні зусилля мають бути зосереджені на моделюванні та вивченні генерації вищих гармонік під час увімкнення та вимкнення сонячних фотоелектричних установок.

Ключові слова: *сонячні фотоелектричні установки, сумарний коефіцієнт гармонійних спотворень, джерело гармонік.*

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