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INCREASING THE ENERGY EFFICIENCY OF MODES OF DISTRIBUTION NETWORKS WITH PHOTOVOLTAIC STATIONS

Purpose. Establishing the regularities of changes in influence of power quality indicators caused by the operating modes of photovoltaic (PV) station inverters on the operating modes of distribution networks' equipment to improve their energy efficiency by reducing power losses.

Methodology. To solve the scientific problems, the following methods are used such as: the method of harmonic analysis (Fourier integral); decomposition of the current spectrum by amplitude-frequency component using Mdaq-14 hardware and software platforms and LabVIEW software; the method of data correlation analysis to determine the higher harmonic current dependence on the load of an on-grid inverter; mathematical and physical modeling in the development of a way to improve the energy efficiency of on-grid inverters of PV stations.

Findings. The conducted studies on electromagnetic compatibility indicators of grid photovoltaic station inverters in stationary and dynamic operation modes made it possible to establish the characteristic regularities of changes in the spectrum and amplitudes of higher harmonic components depending on the level of inverter loading. Hyperbolic dependences of the change in the sinusoidal signal distortion coefficients of the harmonic component on the level of inverter loading were experimentally established. A method has been developed for reducing the electromagnetic interference levels caused by photovoltaic station converters by implementing a circuit solution and algorithm for loading on-grid inverters in non-stationary modes in order to improve their electromagnetic compatibility and increase the energy efficiency of distribution networks with appropriate decentralized sources.

Originality. The regularities are established of influence of the operating mode's parameters of photovoltaic station inverters on the indicators of electromagnetic compatibility in their power supply system, including taking into account special circuit solutions, which allows increasing the energy efficiency of distribution network modes.

Practical value. The method for reducing the electromagnetic interference levels generated by photovoltaic station inverters by implementing the proposed circuit solution and algorithm for loading the on-grid inverters in non-stationary modes is universal and can be applied to any photovoltaic station. This will help to reduce the power losses and electromagnetic damage to equipment from the action of higher harmonic components. Granting the established regularities of higher harmonics influence will allow one to take into account the impact of the relevant indicators on the additional insulation heating of power supply system elements and to assess the corresponding electromagnetic damage, to provide recommendations for consideration of the modes in calculating methods and PV equipment selection.

Keywords: *distribution networks, photovoltaic stations, on-grid inverters, power quality, energy efficiency*

Introduction. The rapid development of distributed generation in Ukraine over the past 3–5 years is associated with the stimulation of investors to produce electricity from alternative energy sources under the so-called "green tariff". Today, the installed capacity of renewable energy sources in Ukraine is more than 8 GW [1]. At the same time the dominant position in the structure is occupied by grid photovoltaic stations (PVS), industrial and private ones, for which grid-tie inverters are used.

The main problem of energy generation from renewable sources is the stochastic mode of its production, low accuracy of its forecasting and significant dependence on weather conditions. Disregarding the technical and economic aspects in the large-scale implementation of distributed generation sources in different parts of the power grid in previous years created the preconditions for an unbalanced operation mode of the United Energy System of Ukraine (UES). Periodically, this causes the need to limit the generation of RES, when energy from them creates additional flows in the Ukrainian UES and disrupts the stability of the system as a whole [2].

The functioning of a single or a group of PV stations can have a significant impact on the loading mode of the main electrical equipment of the distribution network during the day, which will cause inefficient use of equipment [3] according to rated parameters. In addition, given the fact that the installed capacity of the PV stations is essentially the total rated capacity of the inverter equipment, there is a problem of electromagnetic compatibility of the relevant sources with the electrical grid, which to some extent may worsen the energy efficiency indicators of the operating modes of such combined systems. This happens due to the occurrence of additional power losses and electromagnetic damage caused by the influence of power quality indicators, in particular by harmonic components that appear in the networks during the operation of PV station inverters. The task of establishing and assessing the regularities of the influence of power quality indicators in the operation of decentralized power supply systems on power losses, as well as developing ways to improve the energy efficiency of their operating modes is relevant and important today.

Literature review. A number of papers are devoted to the study on operating mode parameters of PV stations, which are mainly aimed at mathematical modeling of the corresponding stations in power grids, justification of schemes and control systems, consideration of the principles of electromagnetic compatibility, assessment of the dynamics of changes in power losses in networks with distributed generation, and others.

In [4], aspects of control systems for on-grid inverters are considered and the corresponding mathematical models are presented. However, these models cannot be used to analyze the electromagnetic compatibility of PV station inverters in terms of power quality indicators, in particular, there is no possibility to take into account the effect of higher harmonic components (HHC) on the operating modes' parameters of the main grid equipment. These factors are important, which will be shown in the main part of this study.

In [5], the features of the operating modes of renewable energy sources are analyzed from the standpoint of the systematic appearance of power shortages in power systems caused by the parameters of stochastic operating modes of photovoltaic stations. The analysis is provided by aggregated indicators that do not take into account the aspects of the operation of converter equipment (inverter equipment of PVS) at the lower levels of the power distribution system hierarchy in the conditions of decentralized generation, in particular, from the standpoint of electromagnetic compatibility in the dynamic change in the output power array of PV stations, since the change in the generation mode is accompanied by transients associated with the inertia of the control systems of grid-tie inverters.

Paper [6] proposes the use of augmented reality systems in electrical power units, which can reduce inefficient equipment use time and its downtime in general. Thanks to innovations, the speed of engineers'work when using augmented reality technology in the maintenance of electrical installations can be increased by 20–35 %, and the accuracy – up to 96 %. Considering the advantages of using augmented reality systems in the operation of electrical installations and the practical absence of automated control systems for decentralized generation, the energy efficiency of processes is limited discretely in accordance with the requirements of dispatching. This requires the implementation of additional measures and algorithms for influencing the processes of controlling the power generation by PV stations in order to increase their energy efficiency.

Papers [7, 8] substantiate the feasibility and prospects of using electric vehicles as consumers-regulators and compensators of electric load in 0.4 kV networks of settlements to reduce losses from power flows. These principles are important and can be applied in feasibility studies for the installation of PV stations. Also, taking into account the expected mode of generation can be used to improve the accuracy of the choice of grid equipment and forecasting losses in them. However, insufficient attention has been paid to the issues of electromagnetic compatibility of charging station converters, which in Vehicle-to-Grid mode will operate in inverter mode, which will affect the energy efficiency of grid equipment similarly to PV stations.

In [9], an analysis of the processes associated with the peculiarities of control systems for on-grid inverters and factors influencing the distortion of the output current of the on-grid inverter due to the non-sinusoidality of the voltage waveform of the network is presented. The proposed methods of total harmonic distortion (THD) compensation by current by means of improving the algorithms of PI-regulators allow solving scientific and practical problems of increasing the efficiency of decentralized generation. However, there is a need to also take into account the aspects of existing facilities operation, where it is impossible to change the parameters of PI-controllers for already installed on-grid inverters and there is a need to find alternative methods and ways to reduce THD indicator by current in different operating modes of PV stations.

In [10], the modes and processes of synchronization between the grid and the inverter are analyzed.

In [11], the higher harmonics filters of on-grid inverters and their possible design were studied in order to optimize the operation parameters. The design of the passive higher harmonics filter of the on-grid inverter current allows reducing the level of output signal distortion only within the rated or close to the rated parameters, where an important factor is the load factor of the converter. At low on-grid inverter loading, not only the amplitude of the n^{th} harmonic increases, but also the initial phases of the HHC by current. The combination of all these factors requires the complication of the design of passive HHC filters and leads to a decrease in the inverter efficiency. Thus, additional loading of the on-grid inverter is one of the ways to solve the problem of the output current waveform distortion.

In [12], the possibility of using PV stations as compensators of reactive power components in case of deficit or in order to regulate the voltage at points of the power system by changing the pulse width modulation angle is considered. The method for adjusting the reactive power using a change in the power factor of the on-grid converter will compensate the reactive component of power and regulate the grid voltage at the place of the on-grid inverter installation. However, this method does not take into account the aspect of controlling decentralized generation in terms of converter loading and ensuring stable generation, since photovoltaic generation is significantly dependent on insolation.

In [13], the optimization of the quasi-Z control effect for inverters connected to an electric power source with fuzzy proportional complex integrated control (PCI) as a method of current internal loop control was studied by authors. However, the proposed method of control based on PCI using the quasi-Z effect requires the development of new types of inverters or intervention in the operation of existing PV inverters, which makes it impossible to use it at operational facilities of decentralized generation.

Paper [14] presents experimental studies on the inclusion of a Hall effect current sensor in the monitoring and control system of a transformerless network inverter in order to reduce the impact of the aperiodic current component from the on-grid inverter on power transformers.

In [15], the influence of the difference in line impedances between different inverters on the output power of on-grid inverters is considered and an improved method of voltage drop control is proposed to improve power distribution and increase efficiency in a parallel system of inverter and voltage source. The use of control systems for on-grid inverters to regulate statism in power grids is limited due to the specifics of PV stations, it is necessary to take into account the generation schedule of decentralized energy sources based on renewable energy sources. Regulation of statism in distribution networks is possible only at the expense of controlled sources of energy with a predictable or controlled generation schedule.

Purpose. The aim of the study is to establish the regularities of changes in the influence of power quality indicators caused by the operating modes of photovoltaic station inverters on the operating modes of distribution networks equipment to improve their energy efficiency by reducing power losses and electromagnetic losses.

Methods. To solve the scientific problems, the following methods are used such as: the method of harmonic analysis (Fourier integral); decomposition of the current spectrum by amplitude-frequency component using Mdaq-14 hardware and software platforms and LabVIEW software; the method of data correlation analysis to determine the higher harmonic current dependence on the load of on-grid inverter; reliability theory when calculating the influence of the electromagnetic environment on the reliability indicators of distribution network equipment; mathematical and physical modeling in the development of a way to improve the energy efficiency of the on-grid inverters of PV stations.

The object of research is the operating modes of combined electrical distribution networks with photovoltaic stations as a decentralized source of power generation.

The subject of the study is the power quality indicators in distribution networks during the operation of PV station converters and ways to reduce their impact on the value of additional power losses and electromagnetic losses.

Results. The study and establishing the regularities of formation and change of the output current harmonic spectrum of the on-grid inverter make an important aspect of the analysis of their operating mode. Determination of the main dependencies between the converter loading and the output signal shape is of scientific and practical interest from the point of view of electromagnetic compatibility in the corresponding elements of electrical engineering complexes in distributed generation systems.

Experimental data of HHC were obtained under the condition of discrete loading of the converter using a load block (Fig. 1), built on the basis of a three-phase rectifier and an active-inductive load with output power control.

The non-sinusoidality of the output signal by current THD_I is one of the important indicators of the power quality. Fig. 2 shows the results of the experimental studies in the form of amplitude-frequency characteristics of the signal obtained by analyzing the steady-state discrete operating modes of on-grid inverters under load. The corresponding values are obtained using the apparatus of the mathematical Fast Fourier Transform (FFT) using LabView software.

In order to verify and refine the results, the data analysis was carried out in parallel using the Microsoft Excel software package applying Fourier mathematical analysis.

According to the results of the experiment and data approximation, the equation of functional dependences of the amplitudes of current harmonic components spectrum of the n^{th} harmonic (up to the 19^{th} harmonic inclusive) on the output power (load) of the converter was obtained. Fig. 3 shows an example of the obtained dependence of the 5^{th} harmonic amplitude changes on the inverter load factor and its approximation. Similar regularities were obtained for other harmonics.

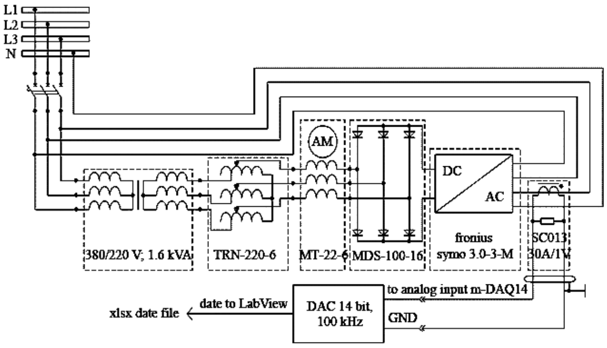


Fig. 1. Schematic implementation of discrete loading of the on-grid current inverter through the power regulator

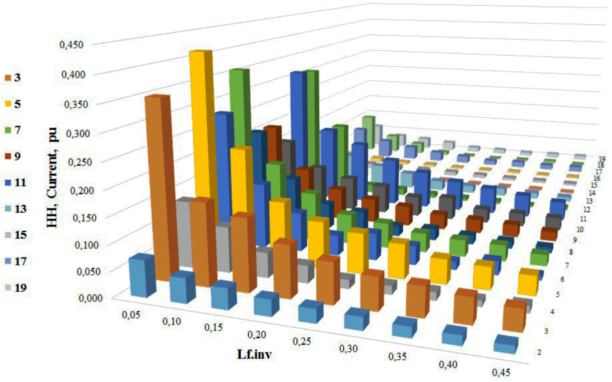


Fig. 2. Regularities of change in HHC amplitudes from the inverter load factor

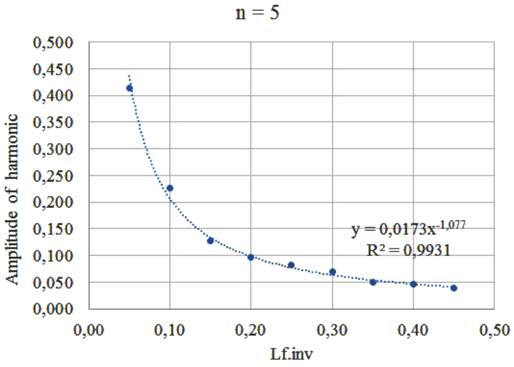


Fig. 3. Approximation of change in HHC amplitude values depending on the inverter load factor (5^{rd} harmonic)

Correlation analysis of the relation between the output power of the on-grid inverter and the values of higher harmonic components allowed obtaining negative correlation coefficients. This indicates the existence of an inverse relation between the output power (load factor) of the inverter and the HHC amplitudes (Fig. 4).

Experimental studies of THD_I and HHC levels, carried out using an industrial high-precision power quality analyzer FLUKE 1738 in dynamic mode, during the operation of the existing PVS, made it possible to obtain the following results (Fig. 5).

The operating modes, shown in Fig. 5, of the existing grid PV station with synchronous superimposition and display of two parameters – the output current (inverter loading) and THD_I – allow confirming the above correlation dependencies and experimental data on the regularities of transients and electromagnetic compatibility of PV station converters in stationary and dynamic load modes (Fig. 6).

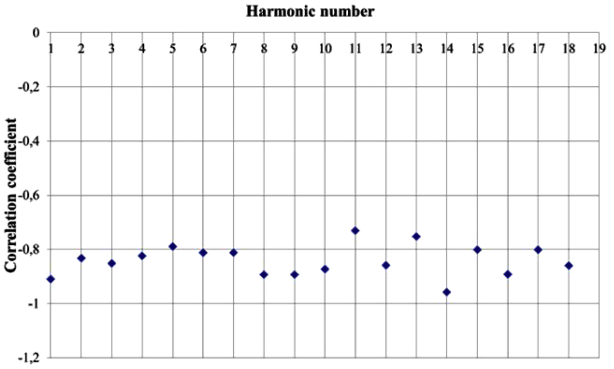


Fig. 4. Values of the correlation coefficients between the output power of the on-grid inverter and the HHC amplitudes

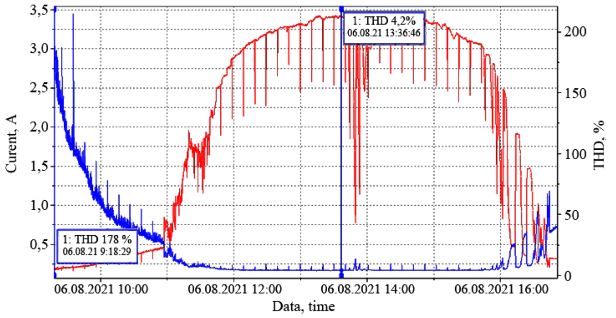


Fig. 5. Regularities of the relation between the output current of the on-grid inverter and the level of THD$_I$

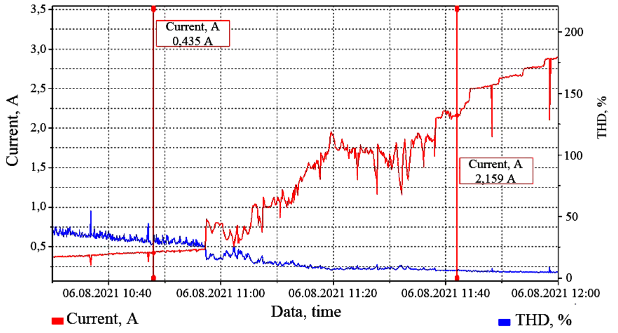


Fig. 6. Regularities of the relation between the inverter load and THD$_I$ *level*

As a result of the experimental study, the actual values of the electromagnetic compatibility indicators of the on-grid inverter by the coefficient of the sinusoidal current curve distortion for stationary operating modes were obtained. Taking into account the unified technical solutions of industrial on-grid inverters, this makes it possible to use them for similar photovoltaic generation facilities. The goal of determining additional power losses and electromagnetic losses to network equipment in real operating conditions is achieved, taking into account the systematic change in the level of converter loading caused by daytime insolation.

Taking into account the obtained results and regularities, we can conclude that the improved electromagnetic compatibility indicators are characteristic of efficient loading modes of on-grid inverters. In the range of output power variation 50–100 % of the rated value, it was found that the influence of HHC is insignificant and can be ignored. This applies both to the grid-tied inverter as a whole and to a separate MPPT input, i. e. a separate string of PV modules connected to the DC inputs of the inverter. Thus, one of the ways to improve the energy efficiency of the operating modes of electrical engineering complexes of photovoltaic stations in distribution networks can be to additionally load the converters and increase the duration of their energy-efficient operation, which will reduce the levels of THD$_I$, additional losses and electromagnetic losses to the main electrical equipment. For this purpose, the authors proposed a circuit solution for the method of additional loading of on-grid inverters. It consists in providing pairwise switching of the connection of individual strings (chains) of photovoltaic modules of several on-grid inverters to parallel operation in low insolation modes during the day, since the level of distortion of the output signal depends on the load of the converter.

The proposed circuit solution with sequential (pairwise) loading of the on-grid inverter is shown in Fig. 9. The main limitation is the rated string current of photovoltaic panels, which should not exceed the maximum value for the MPPT input of the inverter on the DC side. As a rule, the maximum current value of the MPPT input of the inverter allows the connection of two parallel strings. Since the current of photovoltaic modules and their generation power varies in proportion to insolation, the overcurrent of two parallel connected strings will not be observed when implementing the proposed switching principle. Taking into account the significant deterioration of the electromagnetic compatibility of on-grid inverters, especially at $L_{f.inv} < 0.5$, it is advisable to implement the method of pairwise loading at the appropriate level of inverter (string) loading from the rated value. The uniqueness of the proposed solution is that it can be implemented at operational PV stations both for one inverter with several connected strings and for a group of individual converters.

PV station converters are often located within the inverter complete transformer substation, that is, their installation location is convenient for the implementation of switching circuitry (Fig. 7).

The control system of the inverter (string) switching scheme can be built on the basis of any of the principles, but must provide hysteresis at the level of 0.5 values of the control range, as shown in Fig. 8.

Algorithms of the PV module string switching system are based on the data received from the on-grid inverter control system. One of the possible sources of data from the on-grid inverter is a Modbus card with data on the current output power of the station, which will allow using it for further switching algorithm. An important aspect of the control system algorithm is to create the necessary artificial hysteresis for a given power. By analogy with the relay principles of operation, the concept of "return coefficient" is introduced, as the ratio of the return value to the triggering value. The algorithm takes into account the fact that the return coefficient is less than a unity, which is a sign of the maximum action relay.

Fig. 9 shows the corresponding circuit solution of the string switching test bench. The peculiarity of the circuit is the use of IGBT-transistors, which allow switching of significant currents at high voltages and are high-speed, which allows

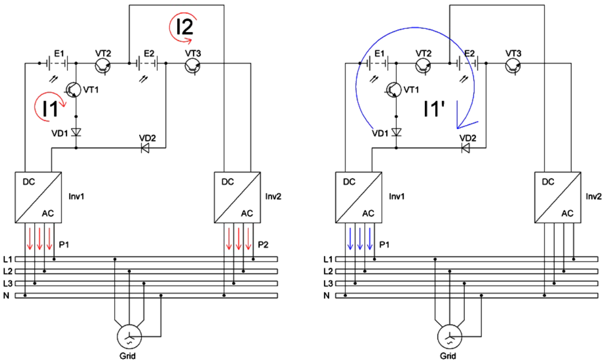
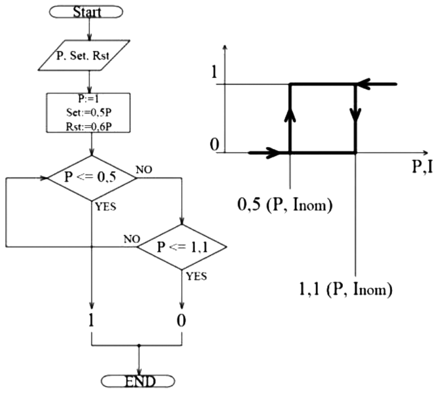


Fig. 7. Switching scheme of inverters (strings)



a *b*

Fig. 8. Algorithm of the inverter control system (string) (a) and diagram of the switching scheme operation (b)

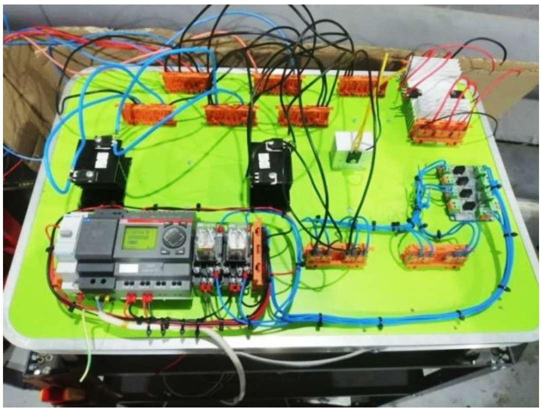


Fig. 9. Circuit solution of the string switching test installation

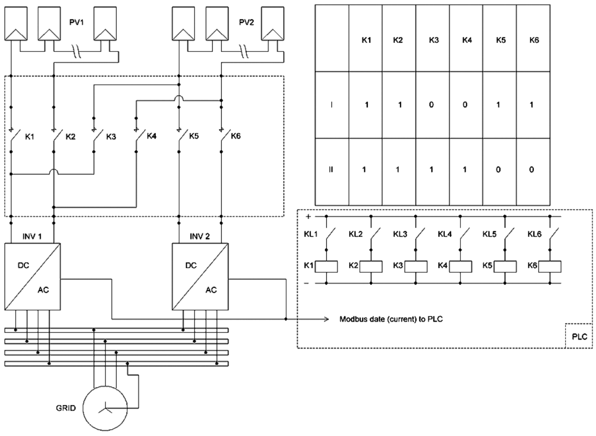
them to be used in the pulse width modulation (PWM) mode.

An alternative solution, which has advantages in terms of reliability, as well as satisfactory performance characteristics, is to build a control system based on DC contactors with a protection system against possible emergency modes. The corresponding schematic implementation of the switchgear of such a system is shown in Fig. 10.

The measuring complex for the study on the electromagnetic compatibility of the on-grid inverter was built using the Fluke 1738 industrial power quality analyzer, the Mdaq-14 hardware platform and the LabView software platform. The experiment was implemented for an operating photovoltaic station with a capacity of 10 kW with an inverter type FroniusSymo 10.0-3-M with a capacity of 10 kW, which has two strings with evenly distributed connection of photovoltaic modules (19 panels of JASolar 275 W each).

The results of the research indicate the effectiveness of the method of promptly changing the strings' connection configuration in order to load them and achieve the goals of improving electromagnetic compatibility. Switching between strings is accompanied by short-term power drops lasting 0.1–0.3 seconds. Support of the on-grid inverter generation process during string switching is ensured by the presence of an electrolytic capacitor in the DC path, i.e. the inverter does not "drop out" of the generation. Fig. 11 shows the corresponding diagram of the output current of the grid-tied inverter in the string switching mode.

To confirm the feasibility of implementing the method of additional loading of on-grid inverters in order to improve their electromagnetic compatibility, we will analyze the data of real daily generation measurements during 2021 for the inverters of a 7 MW grid-connected photovoltaic station. The corresponding measurements were carried out for typical days of each month, according to which the following schedules of loading of PV inverters are obtained (Fig. 12). The best insolation indicators and, accordingly, the loading of on-grid inverters (location of the station in Mezherich village, Dnipropetrovsk region) are observed in July, and the worst are in December-January. For these extreme cases we will present the results of measurements.



	K1	K2	K3	K4	K5	K6
I	1	1	0	0	1	1
II	1	1	1	1	0	0

Fig. 10. Schematic diagram of the DC switchgear for switching the string system

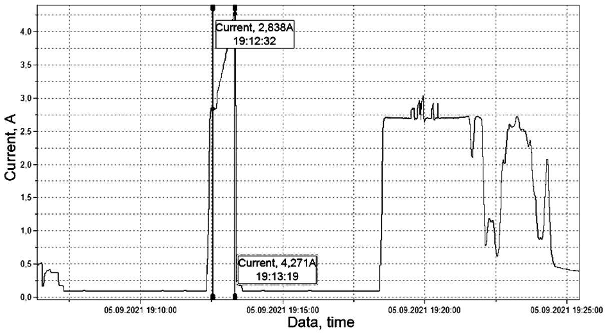


Fig. 11. Diagram of the output current of the on-grid inverter in the string switching mode

Thus, during even the season with the highest insolation, we have about 6 hours of inverter operation with a load factor of up to 50 % (Fig. 12, *a*), and during months with reduced insolation, the operation mode can be available throughout the day (Fig. 12, *b*). During the year, the duration of the reduced generation value in the range of up to 50 % is observed more than half of the inverter operation time. This indicates the relevance of using the method for improving energy efficiency in terms of electromagnetic compatibility in modes of reduced load of inverters.

To take into account the additional power losses caused by the action of HHC, as well as to assess the economic effect of the application of the developed method for improving the energy efficiency of power generation processes of the PV station by reducing the value of THD_I, it is advisable to determine the difference in power losses in the equipment of the electrical engineering complex of the station (AC power lines with a

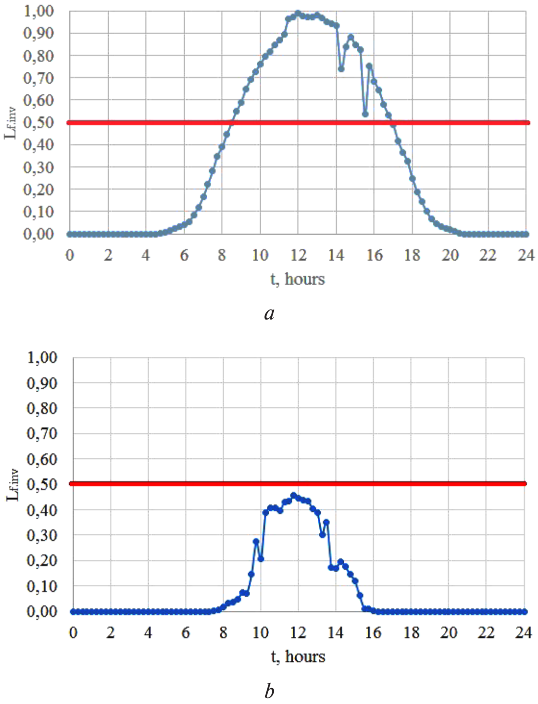


Fig. 12. Daily load indicators of inverters:
a – July; b – January

voltage of up to 1000 V, power transformers of the complete transformer substation).

Losses of active power from currents of higher harmonics in transformers are calculated according to the modified expression

$$\Delta P_{\sum\nu} = 3\sum_{\nu=2}^{n} I_{\nu T}^{2} R_{k} k_{\nu T},$$

where $I_{\nu T}$ is a current of the ν^{th} harmonic passing through the transformer; R_k is a short-circuit resistance of the transformer at industrial frequency; $k_{\nu T}$ is a coefficient that takes into account the increase in short-circuit resistance for higher harmonics due to the influence of the surface effect and the proximity effect. For engineering calculations, $k_{\nu T} = \sqrt{\nu}$ can be accepted.

Additional active power losses in overhead and cable power lines when non-sinusoidal currents flow are calculated as follows

$$\Delta P_{cl} = \left(1{,}41\sum_{n=2}^{40} \sqrt{n} I_{n}^{2}\right) R,$$

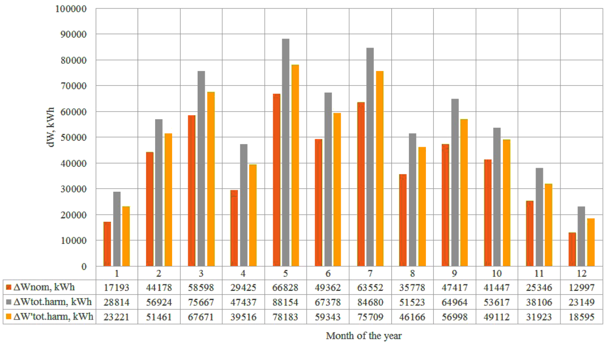
where I_1, I_2 are root-mean-square value of forward and reverse sequence currents; R is an active resistance of the phase of cable line.

The results of the calculations of the total rated, additional losses from HHC without the use and with the use of the inverter loading method during the year, performed on the basis of real data on the operation of the PV station, are shown in Table and Fig. 13.

The calculated data allow us to draw a conclusion: the additional power losses in the electrical engineering complex of PV stations that caused by the specifics of the mode of generation and operation of on-grid inverters in dynamic modes with non-stationary loading and the corresponding effect of HHC are commensurate with the standard calculated losses, in particular, for power transformers and reach values of 70–120 %. The developed method for additionally loading the inverter allows reducing additional power losses from HHC by 30–50 %. Regarding the generation volumes, additional losses in the equipment from the action of HHC are 1.6–11.5 %, and when applying the developed method of inverter overloading are 0.3–5.2 %.

Conclusions.

1. The conducted studies on the electromagnetic compatibility of inverters of on-grid photovoltaic stations in stationary and dynamic modes of operation allowed us to establish the characteristic spectra and amplitudes of higher harmonic components depending on the level of converter loading. The current amplitudes of the higher harmonics of the on-grid inverters of PV stations in the dynamic mode of operation with a load of up to 50 % of the rated value change hyperbolically, inversely to the level of loading of the converter. When the inverter load is 50–100 %, the influence of HHC on the modes and parameters of operation of the PV station electrical engineering complex can be neglected.



	1	2	3	4	5	6	7	8	9	10	11	12
🟥 ΔWnom, kWh	17193	44178	58598	29425	66828	49362	63552	35778	47417	41447	25346	12997
■ ΔWtot.harm, kWh	28814	56924	75667	47437	88154	67378	84680	51523	64964	53617	38106	23149
🟧 ΔW'tot.harm, kWh	23221	51461	67671	39516	78183	59343	75709	46166	56998	49112	31923	18595

Fig. 13. Comparative diagram of changes in indicators of power losses in the main equipment of the PV station during the year

2. As a result of the experimental studies and application of the obtained regularities of the electromagnetic influence of inverters on the operating modes of the PV power supply system, it was found that the additional power losses from the action of HHC are commensurate with the main losses calculated by standard methods and reach values of 70–120 % of them. This indicates the importance of taking them into account when assessing the energy efficiency of PV station operating modes and the choice of electrical equipment and electromagnetic losses suffered by the relevant equipment.

3. The proposed method, circuit solution and algorithm for additional loading of on-grid inverters in non-stationary modes allow reducing the level of electromagnetic interference, and the corresponding additional power losses in the main elements of the PV power supply system by 30–50 %, created by converters of photovoltaic stations. The solution is universal and can be applied to any photovoltaic station, provided that the on-grid inverters are centrally located within the inverter substation. This will reduce the power losses and electromagnetic losses to equipment from the action of higher harmonic components. The payback of the proposed circuit solution due to the reduction of power losses will be about 5 years.

4. The results of the research are suitable for use by manufacturers of on-grid inverters to provide for the serial circuitry implementation of inverter additional loading in characteristic modes in order to reduce the impact of HHC on the equipment of the electrical engineering complex of the PV station.

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Table

The results of the calculation of the power loss components in the elements of the PV station

	Generation	Power losses in transformers and cable lines, kWh and their ratio													
Month	W_{gen}, kWh	$\Delta W_{t.r}$, kWh	$\Delta W_{cab.r}$, kWh	$\Delta W_{t.hhc}$, kWh	$\Delta W'_{t.hhc}$, kWh	$\Delta W_{cab.}$ hhc, kWh	$\Delta W_{t.sum}$, kWh	$\Delta W'_{t.\mathrm{sum}}$, kWh	$\Delta W_{cab.\mathrm{sum}}$, kWh	$\Delta W_{\mathrm{t.sum}}/dW_{t.r}$	$\Delta W'_{t.\mathrm{sum}}/dW_{t.r}$	$\Delta W_{cab.\mathrm{sum}}/\Delta W_{cab.r}$	ΔW_{r}, kWh	$\Delta W_{sum.hhc}$, kWh	$\Delta W'_{sum.hhc}$, kWh
01	156,519	12,558	4634	11,299	5706	321	23,857	18,264	4956	1.90	1.45	1.069	17,193	28,814	23,221
02	424,196	16,966	27,212	12,353	6889	392	29,319	23,855	27,604	1.73	1.41	1.014	44,178	56,924	51,461
03	812,834	20,683	37,914	16,544	8547	525	37,227	29,230	38,440	1.80	1.41	1.014	58,598	75,667	67,671
04	879,334	14,662	14,762	17,456	9536	554	32,119	24,198	15,317	2.19	1.65	1.038	29,425	47,437	39,516
05	1,277,334	22,298	44,529	20,669	10,698	656	42,967	32,996	45,186	1.93	1.48	1.015	66,828	88,154	78,183
06	1,146,832	18,574	30,787	17,460	9426	554	36,035	28,000	31,342	1.94	1.51	1.018	49,362	67,378	59,343
07	1,403,670	21,655	41,896	20,477	11,506	650	42,133	33,161	42,547	1.95	1.53	1.016	63,552	84,680	75,709
08	1,238,992	16,205	19,572	15,259	9903	484	31,465	26,108	20,057	1.94	1.61	1.025	35,778	51,523	46,166
09	990,571	18,192	29,223	17,007	9040	540	35,200	27,233	29,764	1.93	1.50	1.018	47,417	64,964	56,998
10	841,562	17,317	24,129	11,760	7255	409	29,078	24,573	24,539	1.68	1.42	1.017	41,447	53,617	49,112
11	362,563	13,861	11,484	12,366	6183	392	26,228	20,045	11,877	1.89	1.45	1.034	25,346	38,106	31,923
12	108,077	11,734	1262	9839	5285	312	21,574	17,020	1574	1.84	1.45	1.248	12,997	23,149	18,595
Year	964,2483	204,710	287,412	182,494	99,978	5795	387,204	304,689	293,207	1.89	1.49	1.04	492,122	680,413	597,897

Note to the table. Wgen is the volume of PV power generation, kWh; $\Delta W_{t.r}$, $\Delta W_{cab.r}$ are the standard rated power losses in transformers and cable lines taking into account their operating mode, kWh; $\Delta W_{t.hhc}$, $\Delta W_{cab.hhc}$ are the additional power losses in transformers and cable lines caused by the action of HHC taking into account their operating mode, kWh; $\Delta W'_{t.hhc}$ are additional power losses in transformers caused by the action of HHC, taking into account their loading mode when using the proposed method of inverter loading, kWh; $\Delta W_{t.sum}$, $\Delta W_{cab.sum}$, $\Delta W'_{t.\mathrm{sum}}$ are total power losses in transformers and cable lines taking into account the effect of HHC and their operating mode, kWh; $\Delta W'_{t.sum}$ are total power losses in transformers taking into account the effect of HHC and their operating mode when using the proposed method for loading inverters, kWh

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Підвищення енергоефективності режимів розподільчих мереж із фотоелектричними станціями

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Мета. Встановлення закономірностей зміни впливу показників якості електричної енергії, викликаних режимами роботи інверторів фотоелектричних станцій (ФЕС), на режими роботи обладнання розподільчих електричних мереж для підвищення їх енергоефективності шляхом зниження втрат електроенергії.

Методика. Для вирішення наукових задач використані: метод гармонійного аналізу (інтегралу Фур'є); розкладання спектру струму за амплітудно-частотною складовою з використанням апаратно-програмних платформ Mdaq-14 і програмного забезпечення LabVIEW; метод кореляційного аналізу даних для визначення залежності струму вищих гармонік від завантаження мережевого інвертора; математичне й фізичне моделювання при розробці способу підвищення енергоефективності роботи мережевих інверторів ФЕС.

Результати. Проведені дослідження показників електромагнітної сумісності інверторів мережевих фотоелектричних станцій у стаціонарних і динамічних режимах роботи дозволили встановити характерні закономірності зміни спектру та амплітуд вищих гармонійних складових залежно від рівня завантаження перетворювача. Експериментально встановлені гіперболічні залежності зміни коефіцієнтів викривлення синусоїдальності сигналу гармонійної складової від рівня завантаження інвертора. Розроблено спосіб зниження рівнів електромагнітних завад, що спричиняється перетворювачами фотоелектричних станцій шляхом реалізації схемотехнічного рішення та алгоритму довантаження мережевих інверторів у нестаціонарних режимах з метою покращення їх електромагнітної сумісності й підвищення енергоефективності роботи розподільчих електричних мереж із відповідними децентралізованими джерелами.

Наукова новизна. Полягає у встановленні закономірностей впливу параметрів режимів роботи перетворювачів фотоелектричних станцій на показники електромагнітної сумісності в їх системі електропостачання, у тому числі – з урахуванням спеціальних схемотехнічних рішень, що дозволяє підвищити енергетичну ефективність режимів розподільчих електричних мереж.

Практична значимість. Спосіб зниження рівнів електромагнітних завад, що створюються перетворювачами фотоелектричних станцій шляхом реалізації запропонованого схемотехнічного рішення та алгоритму довантаження мережевих інверторів у нестаціонарних режимах є універсальним і може бути застосований для будь-якої фотоелектричної станції. Це сприятиме зниженню втрат електричної енергії та електромагнітного збитку для обладнання від дії вищих гармонічних складових. Урахування встановлених закономірностей впливу вищих гармонік дозволить ураховувати вплив відповідних показників на додатковий нагрів ізоляції елементів системи електропостачання та оцінити відповідний електромагнітний збиток, надати рекомендації для врахування в методах розрахунку режимів і вибору обладнання ФЕС.

Ключові слова: *розподільчі мережі, фотоелектричні станції, мережеві інвертори, якість електричної енергії, енергоефективність*

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