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Power quality issues in smart grids with photovoltaic power stations

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Problems of power quality and electric energy accounting often occur in networks with large pervasion of photovoltaic (PV) elements on rooftops of household and office buildings. In smart grids, including PV arrays electricity, which is sold back to the distribution network, requires approval of its parameters and quality control. Distributed power inverters generate higher harmonics which affect relay protection, automation systems, smart meters and power system's reliability. In this article the influence of photovoltaic elements on the accuracy of electric energy metering and power quality questions are analysed.

Keywords: smart meter, harmonics, power quality, pulse-width-modulated inverter, smart grid

INTRODUCTION

Several governments and utilities all over the world support the use of renewable sources for distributed power generation with subsidies and customer programs. Lots of examples include "green" suburban areas, where roofmounted photovoltaic (PV) arrays are installed on the roofs of individual dwellings, apartments, commercial and communal buildings [5, 14].

The direct current (DC) power, generated by solar panels, can be used for DC loads directly power supply, stockpiled in batteries for later use or peak loads covering, converted into three-phase alternating current (AC) for AC electrical equipment powering or transmitted into the general network.

Solar energy is converted into AC electricity according to the generally adopted scheme. The voltage of the series and parallel connected elements is converted into an alternating voltage by an inverter and fed the load through the filter (may be absent) [15].

The currently used PV systems are often of a grid-tie type (Fig. 1) and are connected to the regional smart grid [6]. The smart grid envisages a two-way dialogue where electricity and information can be exchanged between the supply company and its customers. It is an evolving network of communications, management tools, computers, automation, contemporary technologies and tools working together to make the grid more efficient, secure, reliable and "greener". This intelligent network allows the integration of new technologies, such as solar and wind energy production. Here the issues of accuracy of electric energy metering appear. Modern smart meters (digital power meters) are used for this purpose [14].

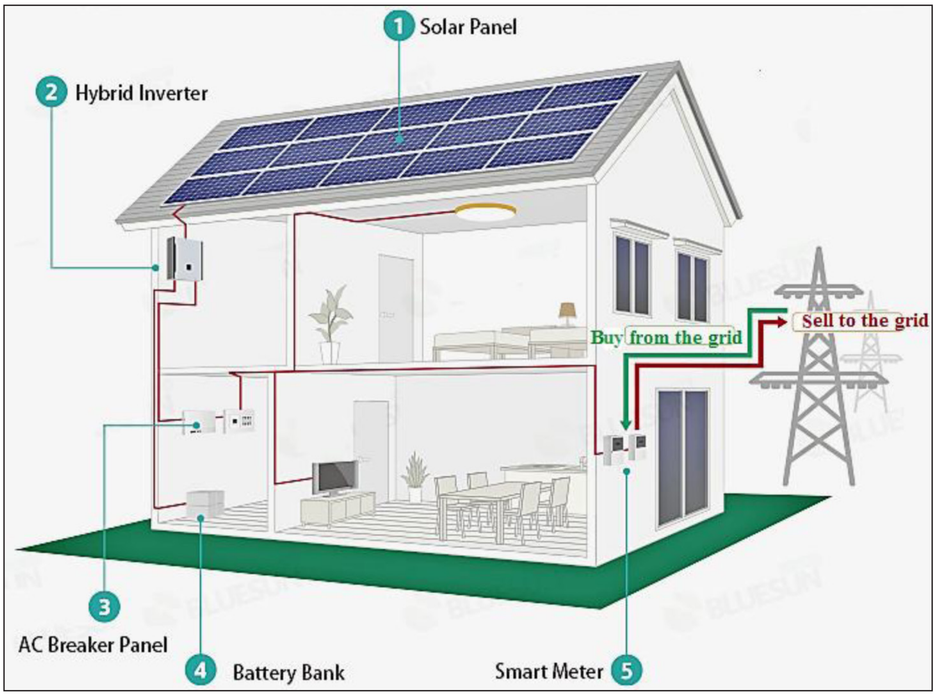

Fig. 1. Performance of the photovoltaic power station connected to the distribution network (part of a smart grid) (dwelling with a grid-tie type PV system)

Photovoltaic power stations and small generating units using PV panels can also be tied up with the network and give it extra power. The issues of electric energy accounting in networks with PPS stations and the connection of electric energy metering devices to the information exchange of means of the automated system of commercial accounting of electricity (ASCUE) are also relevant [12].

When connecting a photovoltaic station to the grid, the requirements of international and state standards for power quality [7–11] must be respected.

PV INVERTERS AS GENERATORS OF HIGHER HARMONICS

Generation of power by PV panels and their connection to the network through current converters affect power quality. High frequency of inverters switching can erect additional harmonics and reduce the network efficiency due to violation of sources' stability and failures in the inverters operation [1, 2, 13–15].

Also, due to fluctuations in the value of electricity produced by photovoltaic power stations and supplied to the grid, which depends on the day time, year period, solar radiation intensity, cloud cover, steadiness and, correspondingly, reliability of power system is infringed [2, 12].

In solar systems of grid-tie type bridge circuits of inverters are used [3]. With respect to standards [7–11] inverters use pulse-width modulation (PWM) controllers to generate sinusoidal output currents. Practically, switching frequencies of 20 kHz – 0.5 MHz are applied in different power stages with mainly insulated gate bipolar transistors (IGBTs) as switching elements for these photovoltaic inverters.

Up to date inverter topologies can be represented by two figures [5]:

- Single-stage pulse-width-modulated (PWM) DC-AC converter topology (push-pull or H-bridge), directly connected to the network through a low-frequency isolation transformer and filter (Fig. 2).
- Multistage PWM DC-AC converter front end including a high-frequency isolation transformer, a high-frequency rectifier and a line-frequency unfolding bridge connected to the grid via small filter elements (Fig. 3).

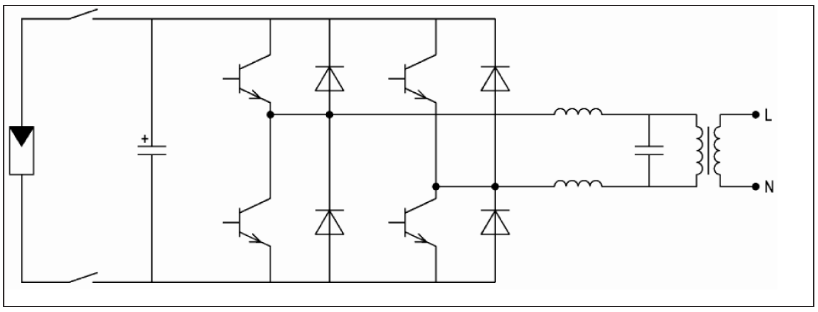

Fig. 2. Single-stage PWM converter, filter components and line-frequency transformer

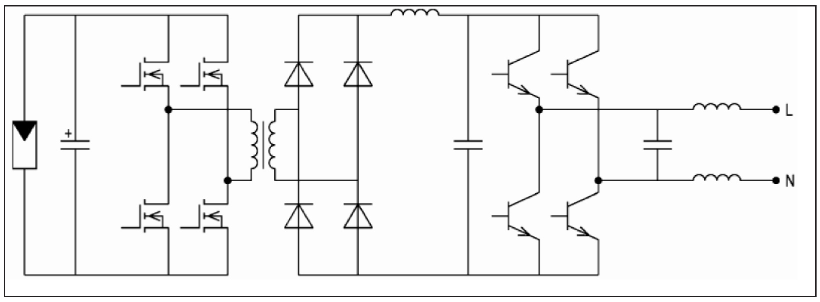

Fig. 3. Multistage PWM converter with high-frequency transformer and low-frequency unfolding bridge

PWM inverters on IGBT transistors are controlled by pulse-width signals, which are modulated by sinusoidal law and form the pulse voltage sequence. The output voltage of the PWM inverter's switch contains the main harmonic of 50 Hz, the magnitude of which is proportional to the selected modulation factor, and high-frequency harmonics centred in the field of multiple integers of the switching frequency

$$fn = afk \pm bf1, \quad (1)$$

where $f1$ – fundamental frequency (first harmonic);

fk – the switching frequency of the inverter transistors;

$a = 0, 1, 2\ldots$ – the multiplicity of the high-frequency harmonics group;

$b = 1, 2, 3\ldots$ – the multiplicity of the fundamental frequency in the group of high-frequency harmonics.

Simple single-phase inverters of low and medium power have the output voltage of sawtooth or triangular waveform, Fig. 4 [3]. Only electric heaters can operate at such voltage. As for electric motors, fluorescent and LED lamps, transformers and other household appliances, then with this kind of input signal they will work with problems or will not operate at all.

Depending on the selected form of the reference (modulating) signal (saw or triangle), some values of the multiplicity b can be absent in the spectrum (Fig. 4).

In terms of minimizing the size and cost of filter elements it is advisable to have a high switching frequency. However, it is selected basing on the efficiency of the inverter, since at high frequencies switching losses are a significant component in overall losses [3].

If the task is to develop an inverter with an unpolluted sinusoidal output voltage waveform, even if the grid voltage is contaminated with harmonics, the inverter's output impedance, which is a function of the frequency, must be high. In practice, the output impedance of the inverter must be high for harmonics up to the 40th inclusive, in order to avoid the penetration of a harmonic current into the grid. This can be achieved with passive filters used alone or combined with active filters built into the inverter controller [5, 7].

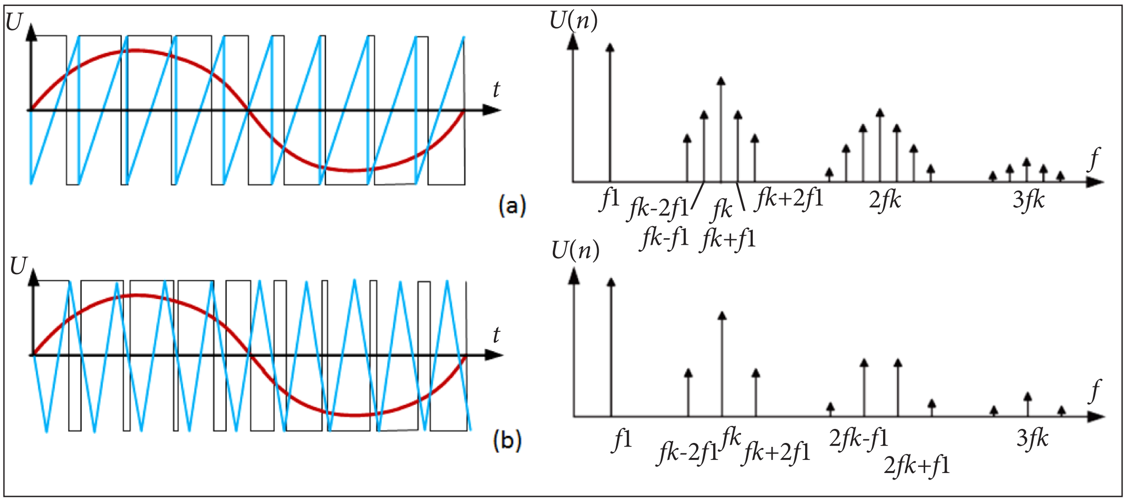

Fig. 4. Spectra of PWM-voltage: (a) for sawtooth modulating signal; (b) for triangular modulating signal

To generate a proper output voltage and current source, the controller with a sufficiently high-gain-bandwidth product of the current feedback-loop is required [15].

The resonance phenomenon for networks with large numbers of distributed power inverters coupled with the low-voltage network 0.4 kV can be divided into the following:

1) Series resonance, Fig. 5(a), of the network capacitance and the supply inductive resistance resulting from externally generated or injected distortion. In this situation, the background supply voltage distortion is the generating mechanism. Here, the impedance at the resonance is low, resulting in higher current distortion through the load and inverter capacitance.

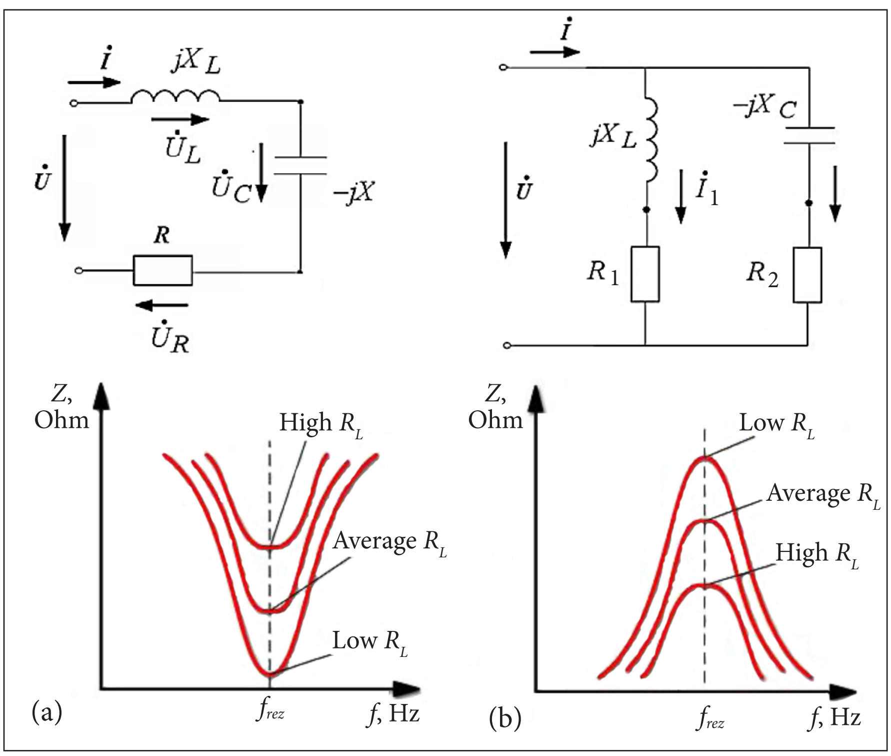

Fig. 5. Mechanisms of (a) series and (b) parallel resonance; here R_L is the active impedance of the inductor

If the inverter's output impedance is low at different background harmonics, this effect will be enhanced.

2) Parallel resonance, Fig. 5(b), of the parallel network capacitance (inverter, dwelling and cable) and the supply inductance (transformer leakage and cable) resulting from distortion currents generated internally, that is, within the point of common coupling. In this instance, the inverter can be considered as generating harmonic source I_h. Thus, the impedance at the resonance is high, resulting in higher voltage distortion at the point of common coupling, or where the inverter and the dwelling's load are connected.

The two above-mentioned phenomena are linked in one circuit and both the increased voltage and current disturbances are practically measured.

It's simple to calculate the series and parallel resonance by using the following formula [5]:

$$f_{rez} = \frac{1}{2\pi\sqrt{LC}}, \tag{2}$$

where f_{rez} – resonance frequency; L and C – equivalent inductance and capacitance in the series or parallel circuit, respectively.

ANALYSIS OF THE INFLUENCE OF HARMONIC POLLUTION ON ELECTRIC ENERGY ACCOUNTING

Bidirectional meters are used to organize electric energy accounting between a consumer with an autonomous PV power station and an electricity utility. Therefore, electricity supplied to the network can be taken into account by the "green tariff" [16].

To estimate the power and amount of electricity transmitted to the network when non-sinusoidal voltage, consider two extreme (boundary) cases:

- when the waveform is sawtooth;
- when the waveform is triangular.

The sawtooth function is odd and is written as:

$$u(t) = \frac{2B}{\pi}(\sin\omega t - \frac{1}{2}\sin 2\omega t + \frac{1}{3}\sin 3\omega t - ... + \frac{(-1)^{-n+1}}{n}\sin n\omega t), \tag{3}$$

$$u(t) = \frac{2B}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^{-n+1}}{n}\sin n\omega t. \tag{4}$$

For the triangular voltage waveform time dependence is written

$$u(t) = \frac{8B}{\pi^2}(\sin\omega t - \frac{1}{9}\sin 3\omega t + \frac{1}{25}\sin 5\omega t - ... + \frac{(-1)^{-\frac{n-1}{2}}}{n^2}\sin n\omega t), \tag{5}$$

$$u(t) = \frac{8B}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^{-\frac{n-1}{2}}}{n^2}\sin n\omega t. \tag{6}$$

Here B – the amplitude of the voltage.

The real power of periodic AC arbitrary waveform current is defined as the average power over the whole period T:

$$P = \frac{1}{T}\int_0^T u(t)i(t)dt, \tag{7}$$

where T – period, sec.

Voltage waveforms are known (defined by the equations (4) and (6)). There remains to determine the current function.

By the principle of superposition, the instantaneous current in a steady state circuit is equal to the total of instantaneous current values which would occur under the independent action of the DC component, fundamental sinusoid and higher harmonics singly [4].

Let us consider that the excess of electric energy of non-sinusoidal form after the inverter is transmitted to the network with an active-reactive load type. With the constant values of active resistance R, inductance L, capacitance C, the operating voltage breaks down into three components at any moment: ohmic voltage drop, inductive electromotive force (EMF), and capacitive EMF:

$$u = iR + L\frac{di}{dt} + \frac{1}{C}\int_0^t idt. \tag{8}$$

The actual current in a circuit is calculated by the equation:

$$i = \sum_{n=1}^{n=\infty} \frac{U_{mn} \sin(n\omega t + \psi_n - \varphi_n)}{\sqrt{R^2 + \left(n\omega L - \frac{1}{n\omega C}\right)^2}}, \qquad (9)$$

where φ_n – the angle of phase shift of n-th harmonic.

Let us consider that the surplus of electricity is transmitted to the AC network of industrial frequency (50 Hz) with the following load parameters: active impedance R = 200 Ω, inductance L = 600 mH, and capacitance C = 200 μF. The peak value of the voltage waveform is assumed to be 311.13 V.

Consider the three forms of the supply voltage curve. Their shapes up to 17th harmonic are shown in Fig. 6.

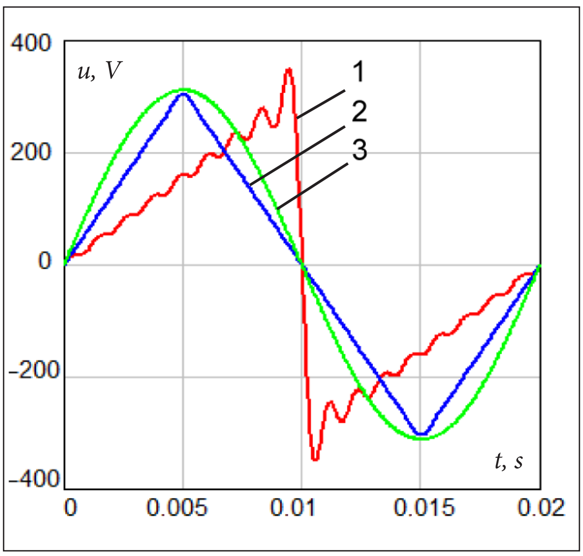

Fig. 6. Voltage curves: 1 – sawtooth; 2 – triangular; 3 – the ideal sine wave

The simulation of the AC network of industrial frequency (50 Hz) is made in the MATLAB software. The network (Fig. 7) includes 32 homes with PV arrays and inverters and has the following load parameters: active impedance R = 200 Ω, inductance L = 600 mH, and capacitance C = 200 μF. The peak value of the voltage waveform is assumed to be 311.13 V.

The various inverters are considered using a self-developed individual MATLAB inverter patterns at each of the connection points.

The surplus of electricity is transmitted to the AC network with the above-mentioned load parameters.

The parameters of inverters were sequentially changed so that their voltage curve had three different forms. Their shapes up to the 17th harmonic are coincided with the curves in Fig. 6.

Since the impedance for each of the harmonics will have its own special value and a shear angle, then the components of current sine waves will have the amplitudes not proportional to the amplitudes of the components of voltage (power supply) harmonics [4].

The active power of periodic alternating currents of arbitrary shape is determined in accordance with the formula (7). The results of simulation in MATLAB well congruent with calculations and they are shown in Table. The power curves are shown in Fig. 8.

In accordance with [4], state-of-the-art active power smart meters take into account electric energy which is consumed by the load at the frequency of fundamental and higher harmonics:

$$W_P = \Sigma U_n \cdot I_n \cdot \cos\varphi_n \cdot t = \sum_{n=0}^{40} P_n \cdot t. \qquad (10)$$

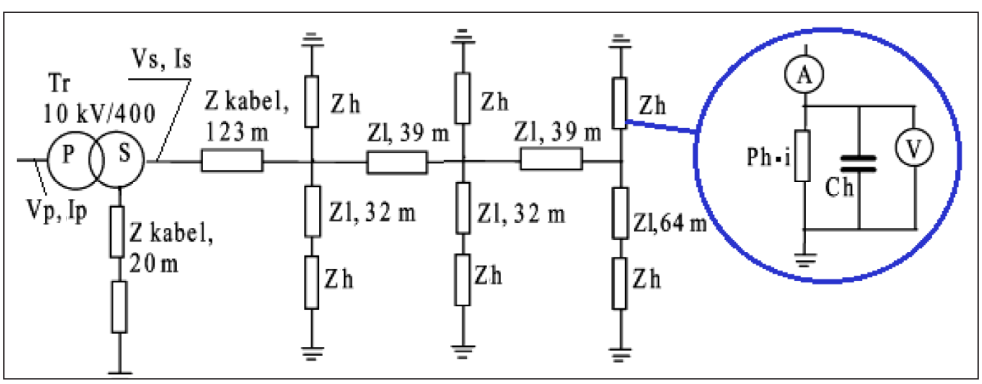

Fig. 7. Substitution circuit of the residential network with PV inverters

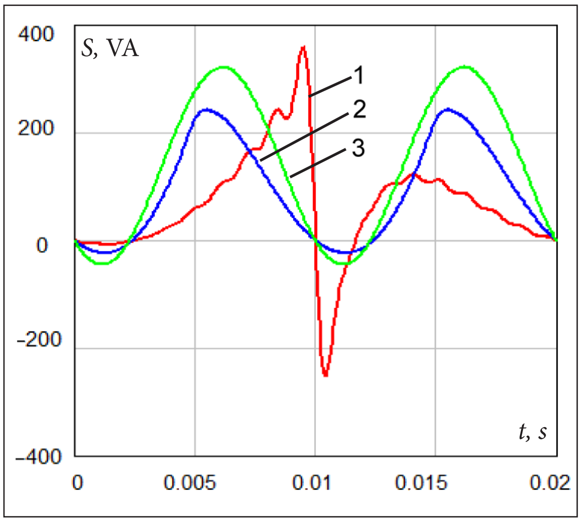

Fig. 8. Apparent power curves: 1 – sawtooth; 2 – triangular; 3 – ideal sine

Table. **The simulated (calculated) results of power values**

Waveform	Active power *P, W*	
	Calculated values	Simulation results
Sawtooth	63.711	63.801
Triangular	91.304	91.373
Ideal sinusoidal	138.789	138.713

Provided t = const., the electric energy consumed in electrical network is proportional to power magnitude: $W_P \equiv P$.

Using the data of Table 1, for sawtooth voltage waveform the amount of electric energy input (for the specified electric grid) will be by 117.42% lower than for sinusoidal supply voltage, and for triangular by 51.81% lower. The amount of active power consumed under ideal sinusoidal voltage is regarded as 100%.

CONCLUSIONS

Power stations with photovoltaic cells (PV arrays) transmit to the network voltage and currents that are polluted with higher harmonics. Parallel and series resonance phenomena between the grid and photovoltaic converters are responsible for higher than expected current and voltage distortion deviations in distributed power grids. To improve the inverter power quality characteristics in a network, the following adjustments are recommended:

1) The reference current of the inverter should be generated internally from a sine table inside the controller.

2) The output inverter's resistance should be significant up to the 40th harmonic, which corresponds to the range of harmonics specified in [7].

3) A low-output capacitor should be applied as filter.

4) It is better to measure voltage and currents directly in the output clips [5].

During commercial metering of electric energy transmitted in the network from photovoltaic cells, smart meters operating by the formula (10) will show 117.42% less energy supply in case of sawtooth waveform of voltage and 51.81% less in case of triangular voltage waveform, compared with ideal sinusoidal waveform. This means that if the vendor transmits to the network electricity with a distorted waveform (different from sinusoidal), the vendor can obtain less profit on the "green tariff" than in the case of a pure sinusoidal signal. Thus, for the seller it is feasible to use more qualitative controllers and inverters.

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References

1. Mastromauro R. A., Liserre M., Kerekes T., Dell'Aquila A. A Single-phase voltage-controlled grid-connected photovoltaic system with power quality conditioner functionality. *IEEE Transactions on Industrial Electronics*. 2009. Vol. 56. P. 4436–4444.

2. Guerrero J. M., Loh P. Ch., Lee T.-L., Chandorkar M. Advanced control architectures for intelligent microgrids – P. II: Power quality, energy storage, and AC/DC microgrids. *IEEE Transactions on Industrial Electronics*. 2013. Vol. 60. P. 1263–1270.

3. Klimov V. Chastotno-energeticheskie parametryi ShIM-invertorov sistem bespereboynogo pitaniya. *Silovaya Elektronika*. 2009. Vol. 4. P. 66–71.

4. Volokhin V. V., Diahovchenko I. M., Kurochkina V. S., Kanálik M. The influence of nonsinusoidal supply voltage on the amount of power consumption and electricity meter readings. *Energetika*. 2017. Vol. 63. No. 1. P. 1–7.

5. Enslin J. H. R., Heskes P. J. M. Harmonic interaction between a large number of distributed power inverters and the distribution network. *IEEE Transactions on Industrial Electronics*. 2004. Vol. 19. P. 1586–1593.

6. Boxwell M. *The Solar Electricity Handbook*. UK: Greenstream Publishing Ltd, UK, 2016. 248 p.

7. GOST13109-97: Normy kachestva jelektricheskoj jenergii v sistemah jelektrosnabzhenija obshhego naznachenija.

8. IEC TR 61000-3-6: EMC limits. Limitation of emissions of harmonic currents for equipment connected to medium and high voltage power supply systems.

9. IEC TR 61000-3-7: EMC-limits. Limitation of voltage fluctuations and flicker for equipment connected to medium and high voltage power supply systems.

10. DSTU EN 50160:2008: Harakteristiki naprugi elektropostachannya u rozpodilchih merezhah zagalnoyi priznachenosti.

11. IEC 61000-3-2: EMC limits. Limits for harmonic current emissions (equipment input current ≤16 A per phase).

12. Batsala Ya. V., Glad I. V., Nikolin U. M. Analiz pokaznikiv yakosti elektroenergii sonyachnoyi elektrostantsii. *Rozvidka ta rozrobka naftovih i gazovih rodovisch.* Vol. 4. Iss. 49. 2013. P. 81–90.

13. Dehbonei H., Nayar C., Borle L. A combined voltage controlled and current controlled "Dual Converter" for a weak grid connected photovoltaic system with battery energy storage. *Proceedings of the 33rd IEEE Power Electronics Specialists Conf. (PESC'02), Cairns, Australia, June 23–27, 2002*.

14. Chidurala A., Saha T. K., Mithulananthan N. Harmonic impact of high penetration photovoltaic system on unbalanced distribution networks–learning from an urban photovoltaic network. *IET Renewable Power Generation*. 2016. Vol. 10. No. 4. P. 485–494.

15. Yazdani A., Dash P. P. A control methodology and characterization of dynamics for a photovoltaic (PV) system interfaced with a distribution network. *IEEE Transactions on Power Delivery*. 2009. Vol. 24. No. 3. P. 1538–1551.

16. Volokhin V. V., Diahovchenko I. M., Derevyanko B. V. Electric energy accounting and power quality in electric networks with photovoltaic power stations. *IEEE International Young Scientists Forum on Applied Physics and Engineering*. 2017. P. 36–39.

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ELEKTROS ENERGIJOS KOKYBĖS IŠŠŪKIAI IŠMANIUOSIUOSE TINKLUOSE SU FOTOVOLTINĖMIS JĖGAINĖMIS

Santrauka

Su elektros energijos kokybės ir elektros energijos apskaitos iššūkiais dažnai susiduriama tinkluose su fotovoltiniais (PV) elementais ant privačių ir biurų pastatų stogų. Išmaniuosiuose tinkluose su fotovoltiniais elementais, kuriuose elektra yra parduodama skirstomiesiems tinklams, reikia suderinti parametrus ir atlikti kokybės patikrą. Paskirstytosios galios inverteriai (keitikliai) generuoja aukštesnes harmonikas, kurios veikia relių apsaugas, automatines sistemas, išmaniuosius skaitiklius ir elektros sistemos patikimumą. Šiame straipsnyje nagrinėjama fotovoltinių elementų įtaka elektros energijos matavimų tikslumui ir elektros energijos kokybei.

Raktažodžiai: išmanieji skaitikliai, harmonikos, elektros energijos kokybė, pulsiniai moduliuojami inverteriai, išmanusis tinklas