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Use of renewable sources in the industrial power system during military operations

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Original article

Abstract

The article examines the possibilities of using renewable energy sources for distributed generation in the Ukrainian power system. Potential risks and possible scenarios for the occurrence of resonance phenomena in the circuits of large-scale grid-connected solar power plants are discussed. The results of amplitude–frequency characteristic modeling identify the limiting ranges of resonance frequencies under varying numbers of STATCOM devices and different power supply system parameters. The issue of electromagnetic compatibility between solar inverters and a centralized power system with limited capacity is investigated. The effect of higher-order current harmonic absorption resulting from changes in the power of industrial load nodes is described. Studies of the electromagnetic interactions between solar power plants and industrial loads are essential for the further development of electromagnetic compatibility theory.

Keywords

- solar power plants
- voltage quality
- electromagnetic compatibility

Authors contributions

A – Preparation of the research project
B – Assembly of data for the research undertaken
C – Conducting of statistical analysis
D – Interpretation of results
E – Manuscript preparation
F – Literature review
G – Revising the manuscript

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Conflict of interest

None declared.

Introduction

Currently, under martial law conditions, Ukraine's power system operates in atypical modes characterized by generation and transmission constraints. These constrained operating conditions have enabled researchers to study emergency modes caused by military actions and to develop a database of typical damage scenarios for designing rapid response protocols and restoring power supply to critical infrastructure facilities. It has been established that each emergency process is characterized by unique electromagnetic traces that can be observed at a certain distance from the fault location [1–3]. These traces are defined by a set of markers obtained from spectral analysis, including higher harmonic and interharmonic components, voltage fluctuation characteristics, and the evolution of amplitude–frequency characteristics at power system load nodes.

The scientific hypothesis concerning the individual electromagnetic traces of electricity consumers equipped with valve converters was proposed by researchers at Dnipro University of Technology based on many years of studies of non-sinusoidal currents and electromagnetic compatibility indicators at large mining and metallurgical enterprises [4–5]. Valuable operational experience was also gained during the island-mode operation of solar power plants following disconnection from the main power system. During the military invasion, large-capacity solar power plants (exceeding 100 MW) demonstrated a significant contribution to maintaining the stability of Ukraine's energy system.

At the same time, the causes of resonance phenomena were identified under conditions of reduced system power and partial transition to autonomous island operation. These resonance phenomena are characterized by changes in amplitude–frequency characteristics and shifts in resonance frequencies within the range of higher harmonics and interharmonics [4–5]. The physical phenomenon of voltage resonance occurs under specific operating conditions of a weakened power system. Resonant frequency zones and the shape of the amplitude–frequency characteristic of an electrical load node may therefore serve as indicators for assessing regime stability.

In Smart Grid power networks, such operating modes can be mitigated through the application of fast-acting reactive power compensation devices, such as STATCOMs. Solar power plants play an important role in maintaining the stability of Ukraine's power system by contributing to frequency stabilization and active power balance under conditions of scheduled power supply restrictions. However, if a solar power plant remains in island mode as a result of military actions, electromagnetic compatibility issues become significantly more pronounced. Research results indicate cyclical increases in the K-factor during the operation of solar inverters.

The challenge of maintaining power system stability is further intensified when it becomes necessary to operate high-power industrial equipment in priority sectors of the economy, such as metallurgy, mining, and the chemical industry. The feasibility of sustaining industrial processes under power system capacity constraints or island-mode operation is assessed based on permissible levels of electromagnetic interference [6–7]. As the structure of electricity generation and transmission during hostilities is continuously changing, ongoing verification of both static and dynamic system stability is required. To ensure reliable operation of Ukraine's power system and effective maneuvering of generation capacities, fast and efficient methods for assessing stability margins are essential. Information on the actual operating state of power facilities is therefore a critical input for static and dynamic stability assessment methods used by dispatching services for rapid operational response.

Materials and methods

The decline in the cost of photovoltaic power generation below the price of electricity supplied from the grid may encourage consumers to prefer energy from photovoltaic installations. This, in turn, can lead to a significant reduction in the load on the electricity grid, creating substantial challenges for distribution system operators and utilities. At the same time, due to the intermittent nature of photovoltaic power generation, the capacity of electricity grids limits the ability to connect a large number of photovoltaic power plants. In the absence of proper management, excessive deployment of such plants can cause voltage fluctuations and other technical problems within the grid [8].

Therefore, research on the integration of renewable energy sources (RES) into specific distribution networks is of paramount importance. The development of optimal management and operational methods will enable the maximum utilization of RES potential while ensuring the stability and reliability of the power system. Figure 1 presents an example of electrical load profiles at different levels of RES integration (CP) into the power system [2]. The figure illustrates a daily active power profile (P^* is the relative power value).

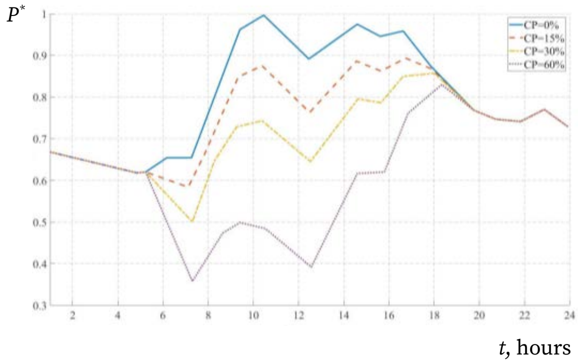


Figure 1. Differences in electrical load schedules at different levels of integration of RES into the power system

Capacity integration (CP) is a metric that reflects the ratio between the maximum annual capacity of photovoltaic (PV) plants and the maximum annual load on the system in a specific region. Energy companies typically use CP to assess the ability of distributed renewable power to support regional load [9, 11].

$$CP(\%) = \frac{P_{PV\ MAX}}{P_{LOAD\ MAX}} \cdot 100\% \tag{1}$$

where:
$P_{PV\ MAX}$ – the maximum output power of the solar power plant per year;
$P_{LOAD\ MAX}$ – maximum load per year.

PV efficiency coefficient (PUR):

$$PUR(\%) = \frac{E_{PV}}{E_{PV-GE}} \cdot 100\% \tag{2}$$

where:
E_{PV-GE} – annual generation of the solar power plant.

Figure 2 shows the ratio between installed RES capacity and annual maximum load, which is 43%.

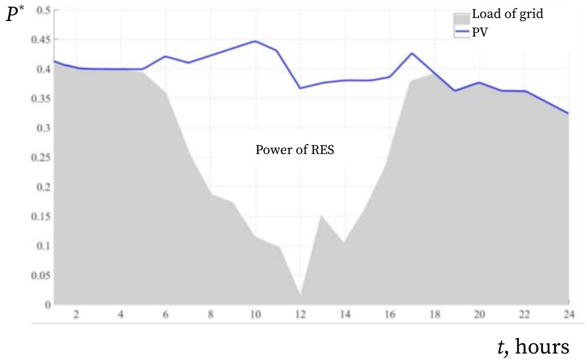


Figure 2. Substation load curve at CP = 43%

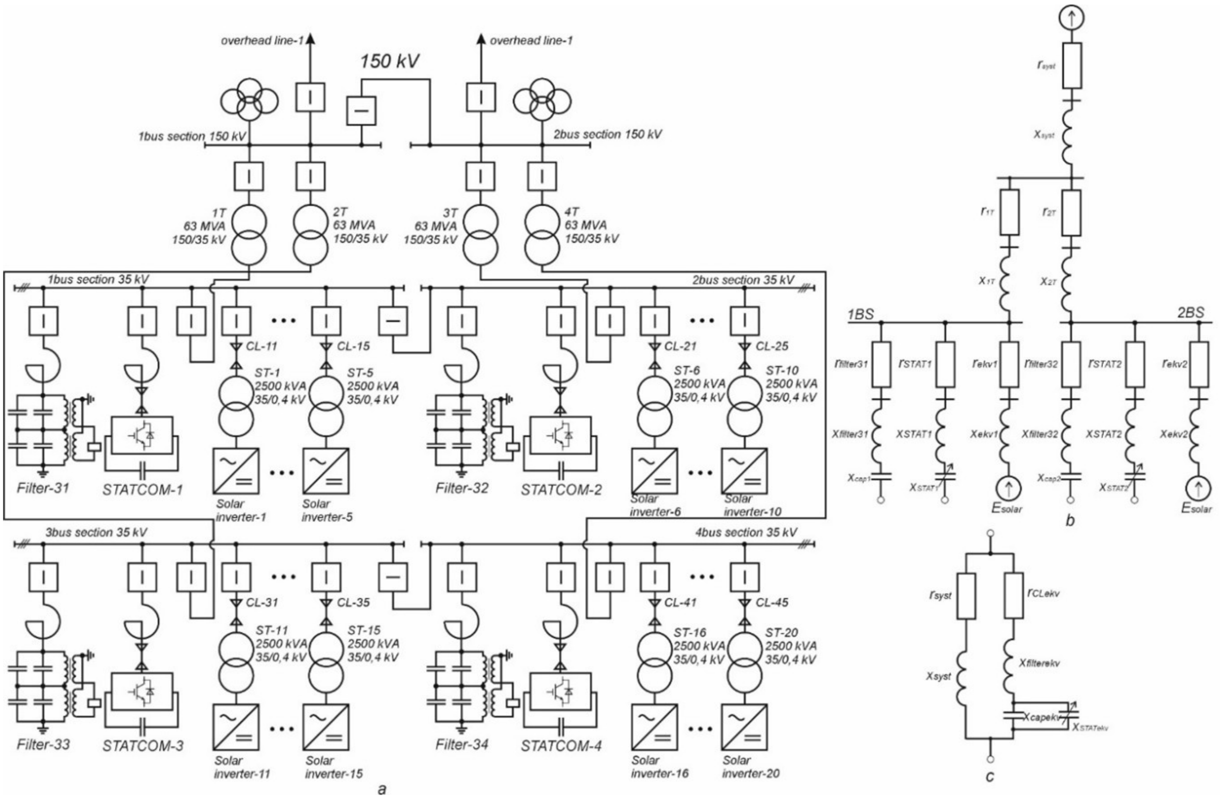
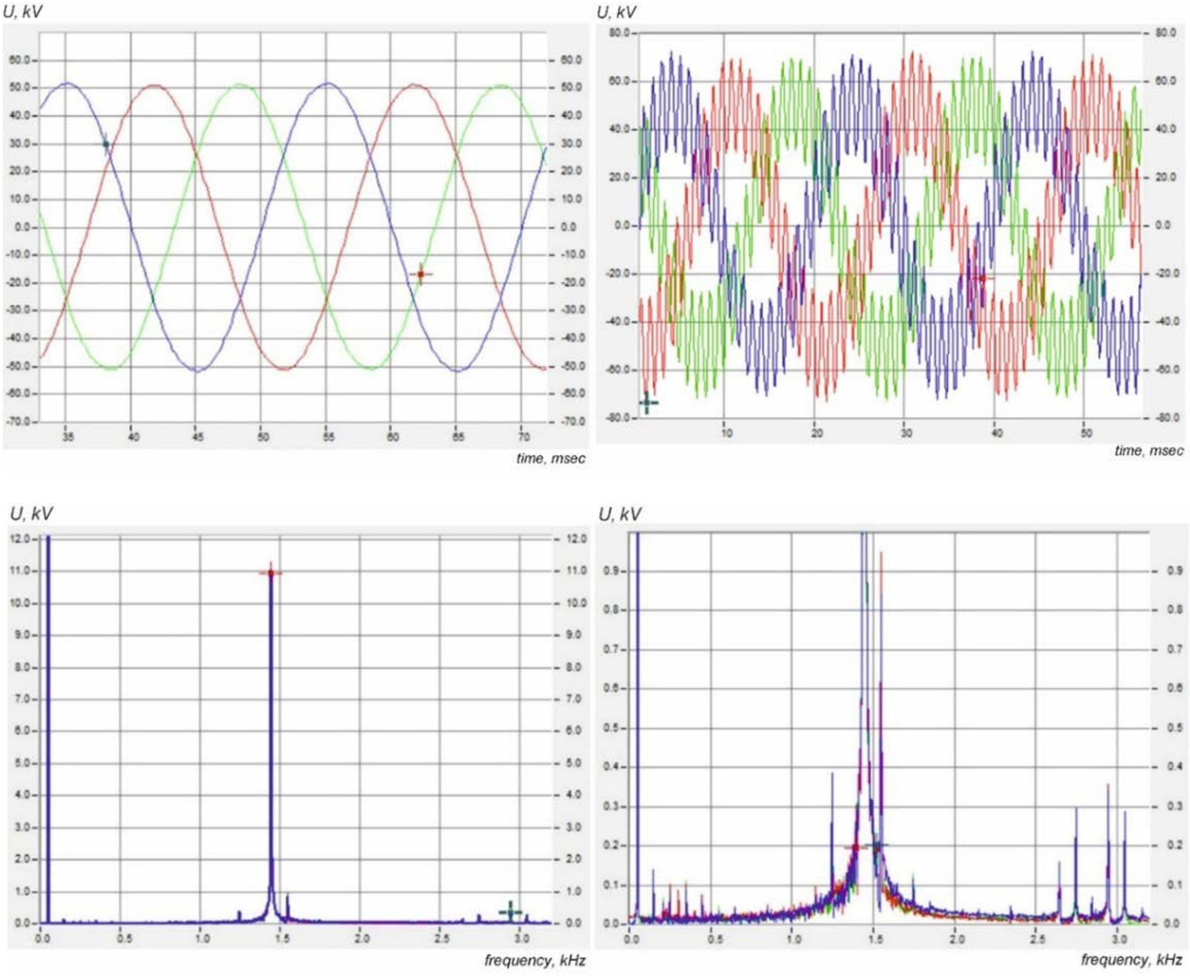


Figure 3. Scheme of a solar power plant with a capacity of 240 MW and a substitution scheme for modeling resonance phenomena


a)

b)

Figure 4. The occurrence of voltage resonance in a weak power system (a) and the evolution of amplitude-frequency characteristics (b)

Results

As a result of experimental monitoring of voltage quality indicators and the operating modes of a solar power plant on the 150 kV side, a significant level of non-sinusoidal voltage was recorded, exhibiting stochastic variations. Figure 5 presents the network current waveform with an angular frequency of $\omega_m = 2\pi \times 50\text{Hz}$. The amplitude spectrum of the network current is shown in Figure 6. A significant level of harmonics in the frequency range of 150–350 Hz can be observed. The 5th- and 7th-order harmonics are canonical harmonics formed as a result of modulation of the network current waveform [10].

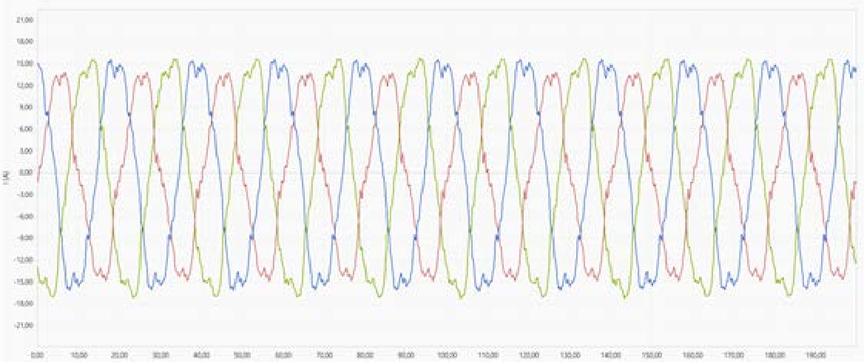


Figure 5. Solar inverter grid current curve

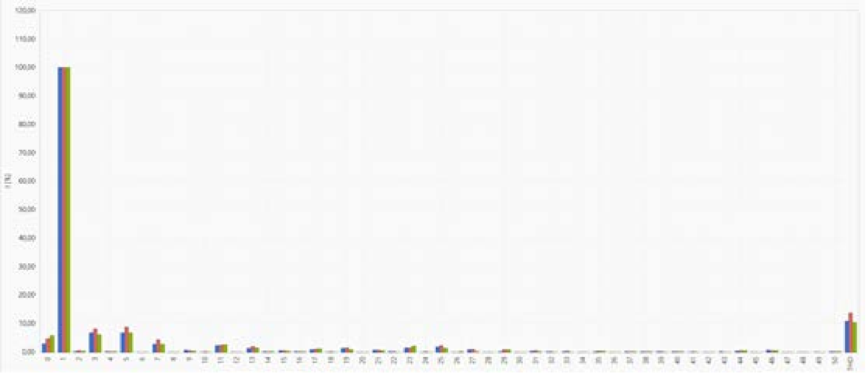


Figure 6. Amplitude spectrum of the inverter mains current

The main component of a solar power plant is the inverter, which is a power electronic device vulnerable to malfunctions caused by harmonic distortion. Pulse-width modulation typically requires accurate determination of voltage zero crossings and other voltage parameters. Harmonic distortion can cause shifts in voltage zero-crossing instants or in the points at which one voltage phase exceeds another. These points are critical for many electronic control circuits and may lead to their incorrect operation.

To prevent the aforementioned adverse effects, inductive and capacitive harmonic filters are installed in modern inverters. In solar power plants with large (industrial-scale) capacities, the effect of harmonic compensation can be observed in distribution networks located at considerable distances. Figure 7 presents power quality parameters measured on 10 kV busbars at a substation located approximately 20 km from the solar power plant. Compensation (absorption) of harmonic and interharmonic distortions during the operating hours of the solar inverters is clearly visible [12].

The primary indicator of the operation of large-scale solar power plants within power supply systems is the K-factor, which characterizes load nonlinearity, i.e., the level of harmonic current distortion introduced into the power grid by the solar power plant. The K-factor is calculated using the following formula:

$$K_{fact} = \frac{\sum_{1}^{50}(i_h \cdot h)^2}{\sum_{1}^{50} i_h^2} \tag{3}$$

where:
h – the harmonic number;
i_h – the root mean square value of the harmonic curent at number h

The limitation of the expression to 50 harmonics results from the capabilities of the Metrel MI 2892 power quality analyzer. The calculation method is also described in IEEE Standard 1100-1992.

$$K_{fact} = \frac{\sum_{i=1}^{n} i^2 \cdot RMS_i^2}{\sum_{i=1}^{n} RMS_i^2} \tag{4}$$

where:
i – harmonic number;
n – number of harmonic components.

Root mean square value of harmonic with number i (RMSi):

$$RMS_i = \sqrt{Real_i^2 + Imag_i^2} = \sqrt{Power_i^2} \tag{5}$$

where:
$Real_i$ – active power of harmonic number i;
$Imag_i$ – reactive power of harmonic number i.

The basis of the solar inverter circuit design is a DC/AC converter. Below is the expression for the instantaneous value of the network current:

$$\begin{aligned} i(t) = \frac{-3*\sqrt{3}}{\pi^2} u_{lm} \Bigg[\sum_{s=-n}^{n} \Bigg[\sum_{q=-n}^{n} \frac{(-1)^s*(-1)^q}{(6*q+1)*(6*s+1)*Z_{(s)}} \\ \Big[sin\Big[(6*q+6*s+2)*\omega_m*t-\omega_I*t-\frac{2\pi}{3}+\varphi(s)\Big]+ \\ sin[(6*q-6*s)*\omega_m*t+\omega_I*t]-\frac{2\pi}{3}-\varphi(s)\Big]\Bigg]\Bigg] \end{aligned} \tag{6}$$

The K-factor generated by the solar inverters of a 240 MW power plant is clearly observed at the 154 kV busbars of system substations. At the same time, the phenomenon of higher harmonic absorption with increasing load on the busbars is recorded.

The electromagnetic trace of the solar power plant operation on the 10 kV busbars under a single-phase load of 2 MW is shown in Figure 8.

Despite triple voltage transformation (0.4/35 kV, 35/154 kV, and 154/35 kV), the effect of filtering by modern grid-connected solar inverters remains noticeable. A reduction in total harmonic and interharmonic distortion at the frequencies of the 3rd and 5th harmonics is illustrated in Figure 8.

The development of renewable energy sources and distributed generation networks in Ukraine is driven by legislative changes, technological progress, and economic feasibility. An additional factor is the need to enhance power system resilience in the face of attacks on critical energy infrastructure. At the same time, the integration of RES is accompanied by several challenges, including generation intermittency and dependence on external factors, which complicate dispatching and power system operation forecasting.

Figure 7. Time evolution of the K-factor on the 154 kV busbars of the main step-down substation

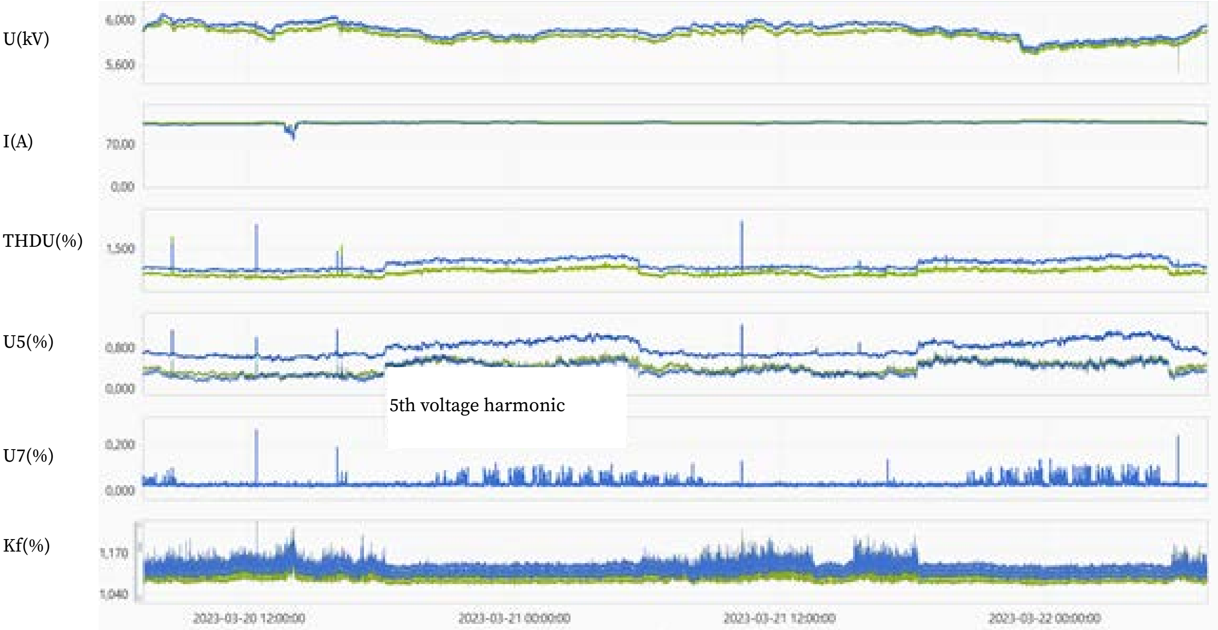


Figure 8. Power quality indicators on the 10 kV substation busbars

Conclusions

Based on a database of electromagnetic disturbances accumulated since February 2022 during wartime conditions, it is possible to develop a methodology for documenting war crimes using “electromagnetic traces” caused by various types of weapons. The experience of operating the Ukrainian power system under military conditions can be transformed into methods and protocols aimed at ensuring the stability, reliability, and power quality of electricity supply. The simultaneous operation of nuclear, thermal, hydroelectric, and renewable energy sources under continuous attacks has created a unique scientific research environment for studying power system behavior under wartime conditions.

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