Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **71**, *3*, pp. 379–384, Bucarest, 2026

SPECIFIC ASPECTS OF DOMESTIC PHOTOVOLTAIC POWER PLANTS INTEGRATED INTO THE GRID

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Keywords: Photovoltaic power plant; Power control; Power transfer; Own load influence.

The paper analyzes several specific aspects that arise in the operation of domestic photovoltaic power plants (DPPPs) connected to the distribution network and that negatively affect their performance and network stability. These aspects were found experimentally and become problematic when the energy produced by the DPPP approaches its maximum capacity but is not fully consumed; instead, a significant portion should be injected into the network. The research proposed developing a method to highlight and analyze three aspects: the influence of the connection line on the distribution transformer; the influence of the own load; and the influence of other DPPPs connected on the same line. Thus, using the MATLAB-Simulink environment, the entire photovoltaic power plant (power and control parts) was modeled, along with the connection line and other components that may be present (consumers and other DPPPs). The analysis of the quantities of interest shows that this method can be used not only during the design stage but also to assess the performance of DPPPs in operation.

1. INTRODUCTION

The use of solar energy has seen spectacular growth in both residential and industrial applications [1–3].

Globally, at the end of 2024, the installed capacity of photovoltaic power plants (PVPPs) was 2.26 TW and could generate 2,950 TWh of electricity, representing 10% of global consumption or the equivalent of 1,045 tons of CO_2 emissions. The growth rate of new capacity was significant, at 29% in 2024 compared to 2023 [4].

Europe remains the world leader in installed capacity from photovoltaic (PV) sources [5].

In the second quarter of 2025, 122,317 GWh of net electricity generated in the EU came from photovoltaic sources, which represents 19.9% compared to 2024.

Also, in June 2025, for the first time in history, solar energy became the main source of electricity in the EU, accounting for 22% of total generation.

At the European level, it is estimated that by 2030, total installed solar capacity in the EU will reach 718 GW.

Initial EU documents [6] set a target of 32% renewable energy consumption by 2030, but in 2023, the target was increased to 42.5% [7–9].

Romania had the highest growth in photovoltaic power plants in Europe in 2025, up 45% from 2024. Forecast for 2030: we will have 24,000 MW in solar installations alone [10].

In 2025, Romania added approximately 2.5 GW of new photovoltaic capacity, outpacing the growth rate of other established European markets. This rapid evolution is supported by substantial private investment, European funds, and the growing interest of prosumers and large solar project developers.

At the end of 2025, the total installed PVPP capacity in Romania, after adding about 2.5 GW of new capacity, exceeded 7 GW, placing Romania 12th in the European ranking. It is worth noting that about 49% of installed capacity is accounted for by prosumers [5].

The use of low-capacity distributed energy resources (DER) close to users has become a significant support for centrally produced energy and has led to important technical and environmental benefits [11,12]. DER power is generally limited to 50 MW [13].

On the other hand, the increase in the share of photovoltaic power plants connected to the centralized energy system, especially DPPPs, has led to the emergence of negative phenomena that affect its proper operation and the quality of energy delivered to consumers.

Thus, although photovoltaic panels can provide the nominal power, the use of the corresponding energy is conditioned by a series of factors, the most important of which are: voltage limitation at the inverter terminals; energy consumed by the own load; distance of the connection line to the distribution transformer; existence of other DPPPs connected on the same line and the value to which the voltage at the inverter output is limited.

The research aimed to develop a method to highlight and analyze three specific aspects: the influence of the power factor at the inverter output; the effect of voltage limitation at the inverter terminals; and the influence of another DPPP connected on the same line.

Thus, in Section 2, the structure of the analyzed conversion and distribution system is presented, with emphasis on the control part. Then, using the MATLAB-Simulink environment, the entire photovoltaic power plant (power and control parts) was modeled, along with the connection line and other components that may be present (consumers and other DPPPs). The complete model allows highlighting the quantities that characterize the system formed by the DPPP, the connection line to the distribution transformer, and other elements with which the plant interacts.

Next, the operation and performance of a power plant located at a significant distance from the network transformer is analyzed. The results are presented both in numerical and graphical form and refer to: the voltage at the inverter output; the active power given by the inverter; the RMS value of the inverter current; the own load current; the network current; the phase shift between the network voltage and current; the active power in the transformer secondary.

In Section 5, the influence of a DPPP connected on the same line is analyzed. Section 6 presents experimental verification that confirms and supports the correctness of the model's results.

Finally, some conclusions are outlined, and useful recommendations are made for both the design and operation of DPPP, as well as for the design of distribution lines and the operation of related transformers.

2. PHOTOVOLTAIC SYSTEM STRUCTURE

A three-phase photovoltaic power plant is considered to provide the electrical energy needed for its own consumption, and the remaining difference is sent to the distribution network (Fig. 1). The power part includes the

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DOI: 10.59277/RRST-EE.2026.3.7

components necessary to perform the function of photovoltaic conversion and distribution of electricity to consumers connected on the same line and to the main network.

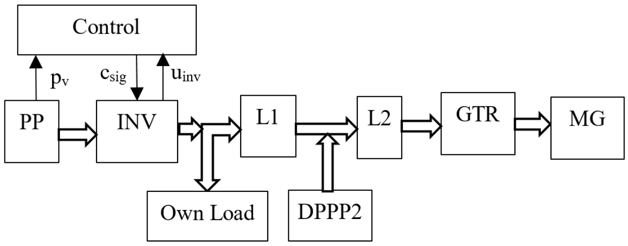

Fig. 1 – Structure of the photovoltaic system.

Photovoltaic panels convert solar energy into DC electricity, which they transfer to the three-level inverter (INV) containing a sine filter [14–16]. It is driven by the grid frequency and supplies AC electricity with a voltage level determined by the control part. The energy obtained is distributed to the own load according to its needs and to the main grid (MG) through the connection line, which is divided into two sections (L1, L2), and the grid transformer (GTR). The connection line was divided to highlight the positioning of a second photovoltaic power plant (DPPP2).

The control part communicates bidirectionally with the power part via the signals p_v (power from the photovoltaic panels), u_{inv} (voltages at the inverter output), and c_{sig} (PWM signals for the inverter control). Its structure is similar but not identical to those used in practice and was designed to allow highlighting the factors that influence the voltage level and the power transmitted to the transformer (Fig. 2). The control part performs the closed-loop regulation of the power supplied by the photovoltaic panels, through the control applied to the inverter.

Thus, the error between the prescribed power (p_v^*) and real power (p_v) is applied to the proportional-integral (PI) controller (Rp_v) whose output (c_R) signifies the peak value of the voltage at the inverter output. This is processed in the VL block that performs the function of limiting the voltage to the imposed level (U^*_{inv}), which is multiplied by the three-phase system of reference voltages with unity amplitude ($3u_{sinc}$), and the control signal (u_c) for the sinusoidal PWM block is obtained. Finally, the control signals of the IGBT transistors (c_{sig}) result.

The reference voltage (synchronization) $3u_{sinc}$ is obtained from the inverter output voltages using a phase-locked loop (PLL) that provides the initial phase of phase A (phi) [17].

By adding the appropriate value ph_0, the final phase ph results, on which the synchronization voltage ($3u_{sinc}$) is generated, are obtained in the G_{usinc} block.

The ph_0 phase allows the inverter to be controlled so that it operates with a unity power factor, inductive or capacitive.

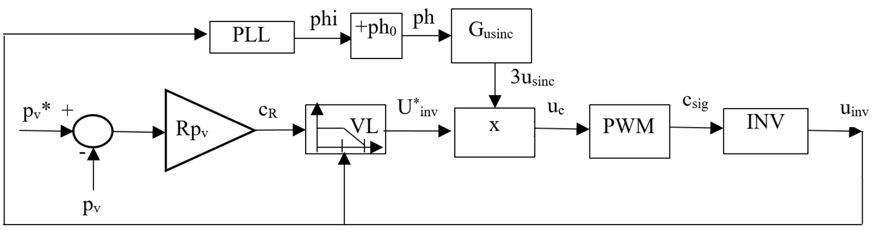

Fig. 2 – Structure of the control part.

3. PHOTOVOLTAIC SYSTEM MODELING

The photovoltaic system was modeled in the MATLAB-Simulink environment using the existing blocks in the application library.

The photovoltaic panel model represents a controlled voltage source and is based on the current-voltage characteristic (Fig. 3). This is due to the way the panels are connected: 5 strings in parallel, each of 18 panels in series, for a total power of 46 kWp. The LONGI LR5-72HPH-540M panels with which the power plant is equipped were considered, and experimental determinations were made.

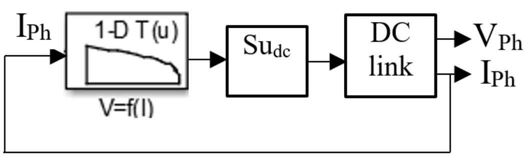

Fig. 3 – Structure of the PP.

The lookup table block V = f(I) implements the I-V curve in Fig. 4 [18]. The block's output controls the DC voltage source, which, via the DC link, supplies the Huawei SUN2000-40KTL-M3 inverter with P_n = 40 kW and P_{max} = 44 kW. The DPPP connected on the same line (DPPP2) has power characteristics like those of the analyzed plant and is modeled as a three-phase, voltage-controlled source. The synchronization voltage is generated based on the voltage at the connection point.

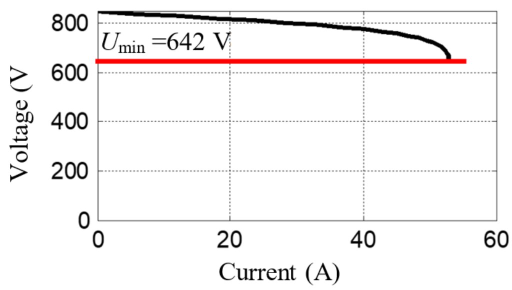

Fig. 4 – Output voltage-current characteristic of photovoltaic panels.

The distribution network from the transformer station to the photovoltaic system is approximately 2000 m long, and DPPP2 is located 200 m from the power plant under analysis.

4. INFLUENCE OF INVERTER CONTROL

By controlling the inverter, power transfer from the PP to its own load and to the line to which the inverter is connected is controlled, as is the power factor at its AC terminals.

The plant's performance was determined by assessing whether the PP delivers 40 kW in the limiting case where its own load does not consume energy, and by evaluating the effect of the inverter's output power factor on the terminal voltage.

4.1 UNITY POWER FACTOR CONTROL

The quantities of interest were the following:

Pv – output power of the photovoltaic panels;
Iv – output current of the photovoltaic panels;
Uv – output voltage of the photovoltaic panels;
Iinv – inverter output current;
Uinv – inverter output voltage;
Pinv – active power at the inverter output;
Is – phase current in the transformer secondary;
Us – phase voltage in the transformer secondary;
Ps – active power in the transformer secondary.

Their numerical values (Table 1) reveal several remarks:

- The power at the PP output is the prescribed one, namely 40 kW;
- The power at the inverter output is 39.4 kW after covering the losses;
- The power transferred to the transformer secondary is 34 kW;
- The voltage at the inverter terminals is 271 V, 7.5% above the limit set by the standards (253 V) [19].

Table 1

Numerical values of the quantities of interest for unity power factor control.

Pv [kW]	Iv [A]	Uv [V]	Iinv [A]	Uinv [V]	Pinv [kW]	Is [A]	Us [V]	Ps [kW]
40	52	763	49	271	39.4	49	231.5	-34

The graphs illustrate the plant's operation in steady state (Fig. 5, Fig. 6) and with unity power factor, both at the inverter terminals (Fig. 7) and in the transformer secondary (Fig. 8).

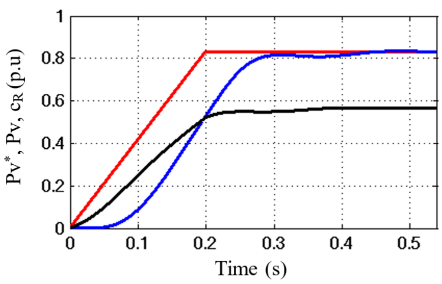

Fig. 5 – Time evolution of prescribed (Pv*– in red) and real (Pv – in blue) PP power and output of power controller (in black), in per-units.

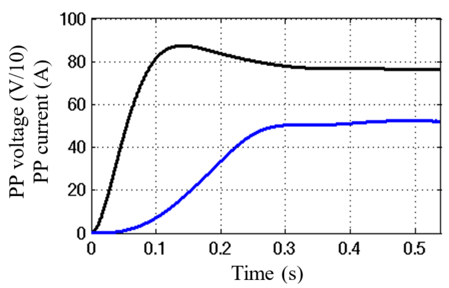

Fig. 6 – Time evolution of PP voltage (in black) and current (in blue).

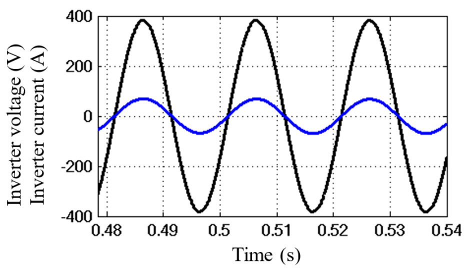

Fig. 7 – The wave shapes of inverter voltage (black) and current (blue).

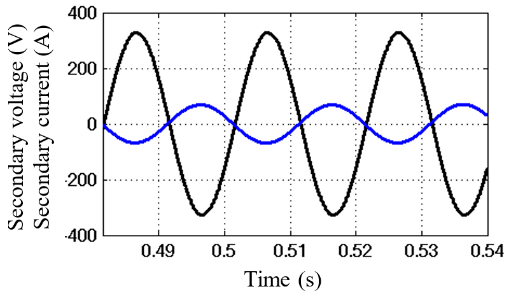

Fig. 8 –The wave shapes of voltage (in black) and current (in blue) in the transformer secondary.

4.2 CONTROL WITH INDUCTIVE POWER FACTOR EQUAL TO 0.8

The values in Table 2 show that the active power transfer is similar, but it occurs at higher current levels. Also, the voltage at the inverter terminals is 281 V, which represents an 11% excess over the allowed value and an increase of almost 4% compared to the unity-power-factor control.

The voltage and current waveforms at the inverter terminals (Fig. 9) and in the transformer secondary (Fig. 10) indicate inductive power-factor operation.

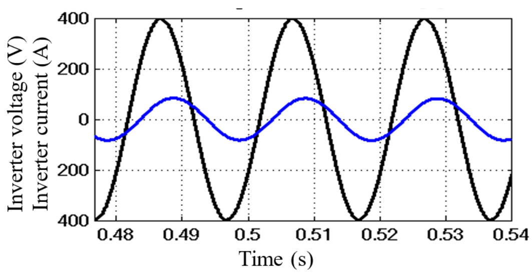

Fig. 9 –The wave shapes of inverter voltage and current in case of inductive power factor control.

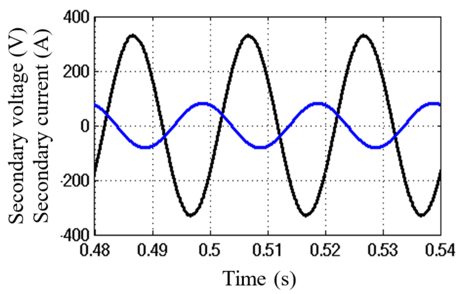

Fig. 10 –The wave shapes of voltage (in black) and current (in blue) in the transformer secondary in case of inductive power factor control.

Table 2

Numerical values of the quantities of interest in the case of inductive power factor control.

Pv [kW]	Iv [A]	Uv [V]	Iinv [A]	Uinv [V]	Pinv [kW]	Is [A]	Us [V]	Ps [kW]
40.4	52	765	58	281	40	57	233	-32

4.3 CONTROL WITH CAPACITIVE POWER FACTOR EQUAL TO 0.8

The values in Table 3 indicate that the active power transfer is similar, and the voltage at the inverter terminals is 253 V, which equals the maximum allowed value. At the same time, it is noted that power transfer occurs at even higher current levels.

The voltage and current waveforms at the inverter terminals (Fig. 11) and in the transformer secondary (Fig. 12) indicate inductive power-factor operation.

Table 3

Numerical values of the quantities of interest in the case of capacitive power factor control.

Pv [kW]	Iv [A]	Uv [V]	Iinv [A]	Uinv [V]	Pinv [kW]	Is [A]	Us [V]	Ps [kW]
40	52	763	66	253	39.7	67	229	-29.2

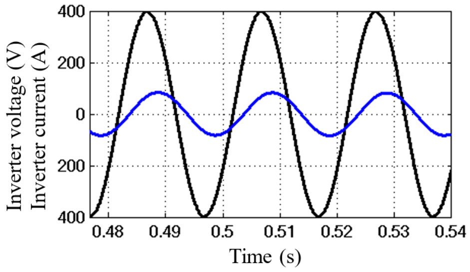

Fig. 11 – The wave shapes of inverter voltage and current in case of capacitive power factor control.

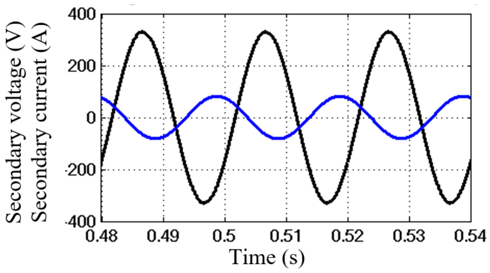

Fig. 12 –The wave shapes of voltage (in black) and current (in blue) in the transformer secondary in case of capacitive power factor control.

5. INFLUENCE OF THE ADDITIONAL PHOTOVOLTAIC POWER PLANT

In reality, except for isolated power plants serving a single consumer, the phase voltage at the inverter terminals is limited to 253 V (+10% compared to 230 V). In this way, the power transmitted to the grid is limited when the limiting voltage is approached.

To clearly highlight the influence of a second power plant connected 200 m from the connection point of the analyzed power plant, the quantities of interest were determined if the own load consumes 50% of the nominal power of the power plant and in two cases: without the additional power plant and with it operating at nominal power (40 kW) (Table 4). In addition to the quantities in the previous tables, the values of the phase current of the own load (*IL*) and the own load power (*PL*) are specified.

It is specified that both power plants are controlled at unity power factor, and the inverter phase voltages are limited to 250 V and 253 V (DPPP2), respectively.

It is found that, without DPPP2, the power plant operates at the limiting voltage and nominal power. Half of the generated power (19.5 kW) is consumed by its own load, and the other half is transferred to the transformer secondary (19.4 kW).

If DPPP2 is connected, the values of the quantities of interest (Table 5) reveal significantly different aspects:

- By limiting the voltage to the value of 250 V, the PP power is limited to 29.2 kW, although the prescribed value is 40 kW;
- The power transmitted by the inverter is also limited to 28.8 kW, of which 20.1 kW is taken up by its own load, and the difference is sent to the transformer secondary;
- DPPP2 operates at nominal power (40.3 kW), which is sent to the transformer secondary;
- After covering the losses on the connection line, 46.5 kW is transferred to the transformer secondary.

In Table 5, U_{DPPP2} is the phase voltage of DPPP2 and P_{DPPP2} is the active power of DPPP2.

6. EXPERIMENTAL VALIDATION

The verifications were carried out based on recordings from a photovoltaic power plant in the city of Tg. Jiu, on April 14, 2025, for a period of 24 hours.

The PPs provided sufficient energy for the power plant to operate; the voltage exceeded the minimum value (Fig. 4) in the time interval 7:15-18:15.

It is specified that the power plant is isolated, with power limitation from 265 V to 280 V.

The evolution of the quantities of interest allows highlighting the plant's operating mode.

- The power plant becomes active when the voltage exceeds the minimum value (Fig. 13).

Table 4

Numerical values of the quantities of interest in the case of unity power factor control and 20 kW own load, without DPPP2

Pv [kW]	Iv [A]	Uv [V]	Iinv [A]	Uinv [V]	Pinv [kW]	Is [A]	Us [V]	Ps [kW]	I_L [A]	P_L [kW]
40	52.3	764	53	250	39.3	29	243.3	-19.4	26	19.5

Table 5

Numerical values of the quantities of interest in the case of unity power factor control and 20 kW own load, with DPPP2

Pv [kW]	Iv [A]	Uv [V]	Iinv [A]	Uinv [V]	Pinv [kW]	Is [A]	Us [V]	Ps [kW]	P_L [kW]	U_{DPPP2} [V]	P_{DPPP2} [kW]
29.2	36.5	798	38.4	250	28.8	63.3	243.2	-46.5	20.1	253	40.3

- The maximum voltage is 271 V (Fig. 13), and the oscillations are determined by the variations of the own load, or those in the vicinity of the distribution transformer.
- The current through the connection line is also limited, with small variations determined by the same causes (Fig. 14).
- The inverter's active power is approximately 40.5 kW (Fig. 15), and the active power taken from the PP is 41 kW (Fig. 16).

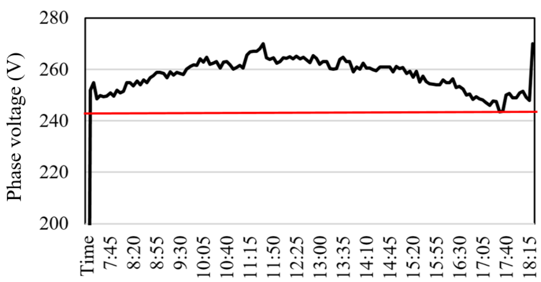

Fig. 13 – The recorded inverter phase RMS voltage.

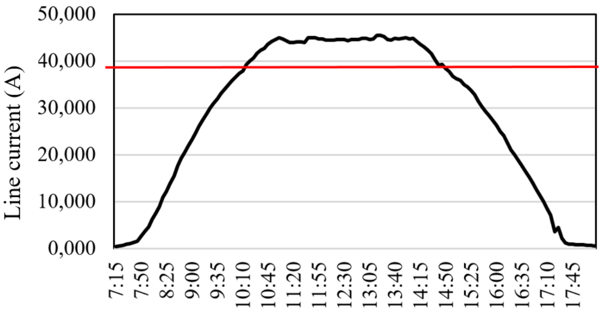

Fig. 14 – The recorded line RMS current.

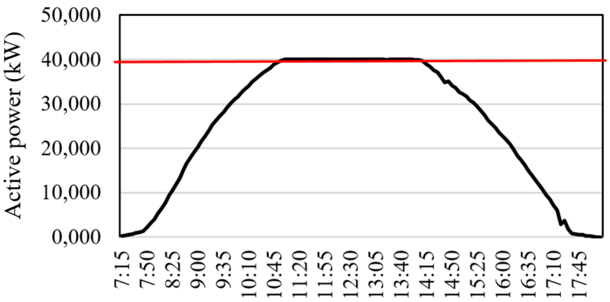

Fig. 15 – The recorded inverter active power.

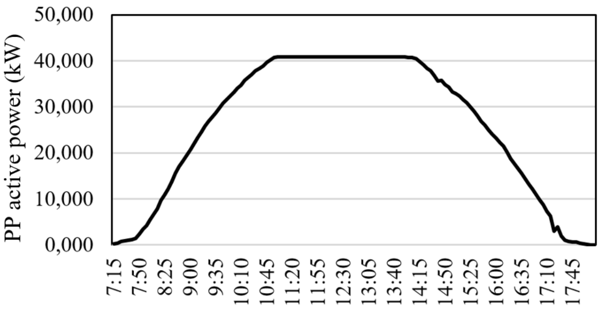

Fig. 16 – The recorded PP active power.

7. **CONCLUSIONS**

The research conducted in this paper led to the conclusions summarized below.

A. The causes that determine the increase in voltage at the inverter terminals when the plant sends the nominal active power to the network are:

- The length and specific impedance of the connection line to the distribution transformer;
- The absence of consumers in the immediate vicinity;
- The voltage level in the secondary of the distribution transformer.

B. Unity power factor control minimizes the current in the plant connection line.

C. Capacitive power factor control leads to a reduction in the voltage at the inverter output (at the same active power) but causes an increase in the current.

D. Inductive power factor control is the most disadvantageous with respect to the voltage at the inverter terminals.

E. Capacitive power factor control can be used to reduce the voltage at the inverter connection point, only if the permissible current limit is not exceeded.

F. The existence of several power plants connected in cascade to the same line may determine the limitation of the power supplied by the power plants located at greater distances from the distribution transformer.

G. Limiting the voltage at the inverter terminals leads to partial use of the power available in the PP.

H. Given that existing regulations limit the voltage at the inverter terminals, for the most complete use of the power available in the DPPP, the following means are identified:

- Strengthening the connection lines by reducing the specific impedance;
- Reducing the voltage in the secondary of the distribution transformer, without exceeding the minimum value provided for by the regulations;
- Correlating the limiting voltage for power plants connected in cascade to the same line, so that the associated values decrease with the approach to the distribution transformer.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

MIHAITA LINCA: conceptualization, methodology, investigation, results analysis, draft writing, review.

ALEXANDRU BITOLEANU: methodology, resources, investigation, simulation, results analysis, writing, review, editing.

MIHAELA POPESCU: methodology, investigation, results analysis, review, editing.

Received on 9 May 2026

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