

Analysis of the Impact of Faults Occurring in the Vicinity of Photovoltaic Plants on the Distribution Network

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Abstract:

In the event of polyphase or three-phase faults in the vicinity of photovoltaic (PV) power sources, it is observed that the residual voltage can reach values that maintain the electric arc at the fault location, after the tripping of the circuit breaker in the distribution station on the distribution line where the renewable energy generation facility is located. This observation highlights an important challenge in the integration of photovoltaic systems into electrical distribution networks. Residual voltage, i.e., the voltage that persists after the tripping of the distribution line circuit breaker and the occurrence of a fault, can maintain a dangerous electric arc, with the potential to cause fires or damage equipment. This paper presents the simulation of the behavior of a distribution network upon a fault near a PV station, along with a series of specific measurements (THD, waveforms, voltage, current, and power values) obtained in a real situation.

Keywords:

Electric Faults; PV Plants; Distribution Networks.

1. Introduction

Modern power systems face a series of interconnected challenges, driven by rapid technological advances, the massive integration of renewable energy sources, the evolution of telecommunications infrastructure and power electronics, and the increasing physical vulnerability of power grids. These issues converge in a context marked by increased risks, generated by incidents such as equipment theft and cyberattacks.

The global energy sector is undergoing a profound transformation, marked by a strong focus on improving energy efficiency, expanding renewable energy production, and implementing innovative solutions such as smart grids [1]. These trends are driven by a series of interconnected factors, including the depletion of fossil fuels, increasing pressures to reduce greenhouse gas emissions, and the need to ensure a secure and sustainable energy supply.

The European power system is also in a period of profound transition, marked by a series of complex and interconnected challenges [2]. These challenges are driven by a combination of factors, including climate change, increasing energy demand, the depletion of fossil resources, and the need to ensure energy security.

1.1. The main challenges of the Romanian power system

The Romanian power system faces a series of complex challenges, like those encountered at the European level, but also with some specific to the national context [3]. These challenges are related to the energy transition, energy security, energy efficiency, and integration into the European energy market.

Some of these challenges may refer to:

- Dependence on fossil fuels: A large part of Romania's electricity and heat is produced from coal and natural gas, making the country vulnerable to price fluctuations on international markets and risks associated with the security of supply.
- Aging infrastructure: Electricity, gas, and district heating networks are old and require significant investments for modernization and expansion.
- Low energy efficiency: The residential and industrial sectors have significant potential for improving energy efficiency, which would lead to reduced energy consumption and lower costs.
- Integration of renewable sources: Although there is significant potential for the development of renewable energy (wind, solar, hydro), the integration of these sources into the national energy system requires investments in infrastructure and mechanisms to balance production and consumption.

- Energy security: Diversifying energy sources and reducing import dependency are essential to ensure Romania's energy security.
- Adapting to climate change: Extreme weather events, such as droughts and floods, can affect hydroelectric power production and increase energy demand for cooling or heating.
- Interconnections: Cross-border energy exchange capacity is restricted by low transmission capacity constraints, highlighting significant bottlenecks in optimizing international energy flows.
- Integration into the European energy market: Romania needs to align its legislation and regulations with those of the EU to fully participate in the common energy market and benefit from the opportunities it offers.

In the planning process of the electricity distribution networks, the aim was to identify an optimal level of security of the National Energy System (NES) that would balance the investment costs with the costs associated with interruptions in the supply of electricity.

To quantify this balance, the concept of the marginal cost of interruption was introduced, representing the economic value attributed to a quantity of energy not delivered due to a breakdown. By integrating this cost into the cost-benefit analyses, the assessment of the financial impact of different investment decisions in the distribution infrastructure was facilitated.

1.2. Technical solutions adopted on distribution networks in Romania

The Romanian energy system is in a process of profound transformation, marked by significant challenges but also by important opportunities [4]. To ensure a sustainable energy future, a strategic and coordinated approach at the national and European levels is necessary in the long term.

The development of wind farms, photovoltaics and hydroelectric power plants can contribute to reducing dependence on fossil fuels and increasing the share of clean energy in the energy mix.

- The adoption of this criterion of the marginal cost has led, over time, to the creation of a more secure distribution system, with the following advantages:
- High-voltage networks generally adopt a loop configuration, which allows for redundancy in the supply and an increase in system reliability [5]. Under normal operating conditions, the values of the currents that transit the high-voltage lines are significantly below the admissible thermal limit, being of the order of half the maximum allowed value.
- In high-voltage/medium-voltage (HV/MV) electrical transformer stations, it is generally practiced to install two power transformers, each with a nominal capacity of approximately 65% of the total load. This redundant configuration ensures high service availability, allowing continuous supply to consumers even in the event of a failure of one of the transformers.
- Although the typical configuration of medium-voltage (MV) networks is the loop one, their operation is based, in most cases, on the radial principle. This hybrid approach offers both the advantages of a redundant network, with multiple power supply paths for consumers, and the flexibility of a radial network, simplifying operations and improving system reliability [6]. Thus, in the event of a fault at a high voltage/medium voltage (HV/MV) substation, power to consumers can be ensured through other medium voltage (MV) lines coming from neighbouring substations.

The implementation of the telecontrol system in the distribution network facilitates the reduction of intervention times in the event of failures and, at the same time, limits the extension of the area affected by the fault.

This article is part of the current context of the global energy transition and the increased integration of renewable energy sources in distribution systems [7]. The paper aims to bring an original contribution to the optimization of the integration process of photovoltaic power plants into the national electricity grid, with a focus on real-time monitoring and optimization of the performance of overhead power lines.

The calibration and coordination of protections in integrated systems with photovoltaic power plants is a complex challenge, requiring a detailed analysis of the system characteristics and a multidisciplinary approach [8]. Through a correct design and implementation of the protection system, a safe and reliable operation of the photovoltaic power plant and the electrical grid can be ensured.

In conclusion, this research provides an opportunity to deepen the understanding of the interaction between photovoltaic power plants and medium voltage networks, contributing to the development of technical solutions to ensure a safe and efficient operation of the energy system [9].

The proposed research aims to improve the reliability and efficiency of the Romanian energy system in the context of the increasing share of solar photovoltaic energy in the energy mix.

2. Details regarding the monitored photovoltaic plant

Choosing the topology of a distribution network is a complex decision, which must take into account a multitude of factors, such as [10]:

- Consumer requirements: Reliability and quality of energy, cost.

- Geographical characteristics of the area: Population density, climatic conditions.
- Development of renewable sources: The need to integrate an increasing amount of renewable energy into the network.
- Network reinforcement works: in the area where the photovoltaic plant is connected, there is a need to carry out network re-conduction works.
- Economic considerations: Investment and operating costs.

We will present the situation of a photovoltaic power plant located near the town of Faget, in western Romania.

2.1. Main electrical connections

We will briefly present the main electrical schemas concerning the network connection of this photovoltaic plant, first to the 20 kV overhead lines.

Figure 1 shows the 20kV overhead line with all its switching elements, namely classic disconnectors and remote-controlled disconnectors (IMS). The connection point where the photovoltaic park feeds energy into the grid can be seen halfway down the line.

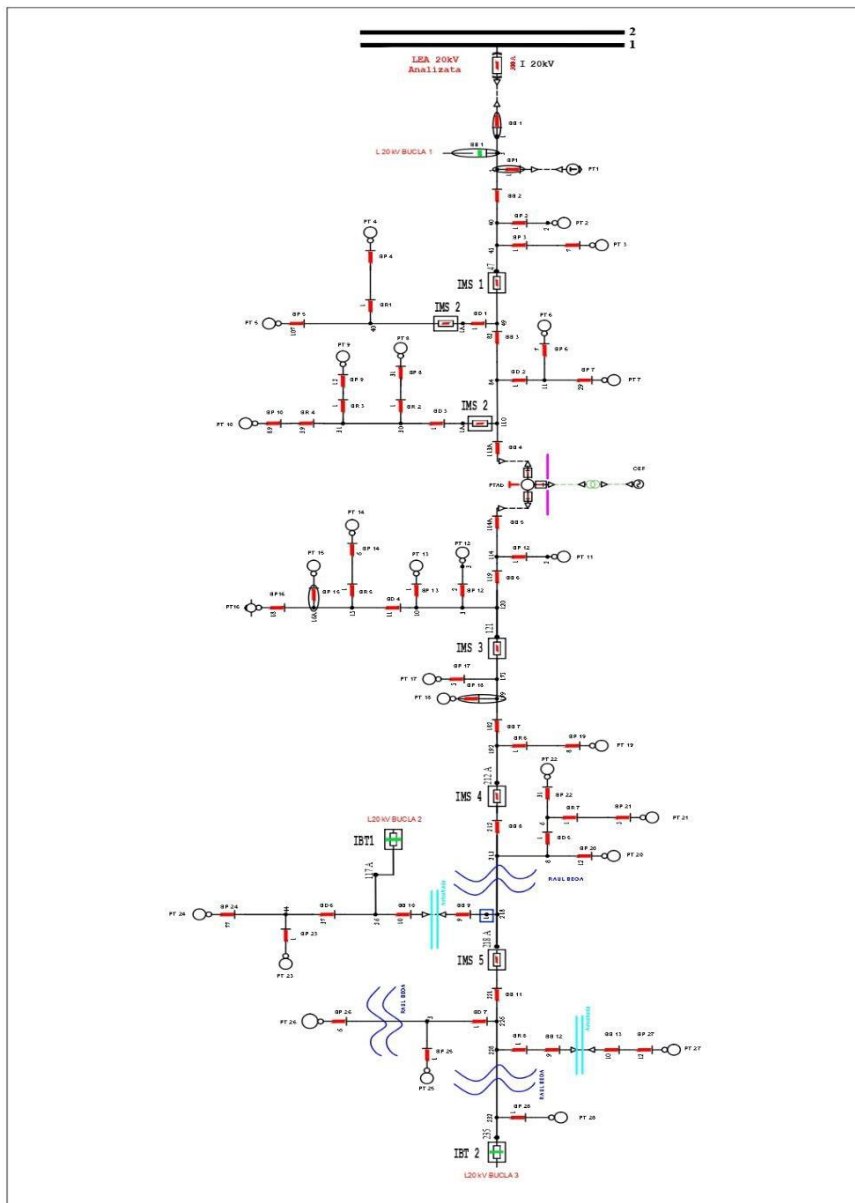


Figure 1. Schema of the 20 kV overhead line used for the PV plant connection.

The 110/20kV substation in the network area where the energy produced by the analysed photovoltaic plant is evacuated is a substation with a simple busbar system sectioned by a 20kV CL longitudinal coupler with 2 110/20kV 16MVA transformers, and the interconnection with the SEN is achieved through a 110kV line. The neutral treatment is achieved through TCN-BS-R.

The operating manoeuvres in the substation are carried out entirely through the telecontrol system by the local distribution dispatchers at the medium voltage and high voltage levels. The existing substations are periodically modernized to improve their efficiency, reliability, and operation [11].

At the same time, increased attention is paid to reducing the impact on the environment, including noise and electromagnetic fields.

Figure 2 will present the real topology of the monitored area.



Figure. 2. Schema of the 20 kV overhead line connection.

The pink 20kV overhead line represents the axis of the line where the energy produced by the PV plant is evacuated to the NES;

The yellow 20kV overhead line is the underground power line from the park to the demarcation point between the OD and the PV plant.

Square G represents the connection point where the metering cell is located, where the energy produced and delivered to the SEN by the PV plant is measured.

2.2. Measuring procedures

The distribution board includes a busbar to which the inverters are connected via power fuses intended to protect the inverters, followed by a general circuit breaker that protects the busbars and the transformer on the low-voltage side that connects the busbars to the transformer [12].

The secondary circuits are also part of the general distribution board, where a series of specific relays are found to protect the electrical transformer against internal faults, namely gases and overtemperatures. Also in the general distribution board are a series of automatic circuit breakers used in secondary circuits that supply a socket circuit, a lighting circuit, and a UPS circuit. This is the area where the measurement unit was positioned, according to Figure 3.



Figure. 3. General 0.4kV switchboard of the PV plant where the network analyser was installed

A power grid analyser is a specialized device or software that measures, analyzes, and records the electrical parameters of a power grid. It provides a detailed picture of the network's status, identifying potential problems and providing valuable data for optimizing energy consumption and improving power quality.

Resistant to all conditions, the Sonel PQM-700 power quality analyser is an efficient device for analysing and recording network parameters. Based on advanced technology, the Sonel PQM-700 power quality analyser is efficient for measuring, analysing, and recording power network parameters. All recorded parameters - including indicated events - can be easily read using the dedicated Sonel Analysis software.

3. Presentation of the voltage waveforms

In the event of polyphase or three-phase faults occurring in the vicinity of photovoltaic (PV) power sources, it is observed that the residual voltage can reach values that sustain the electric arc at the fault location, after the tripping of the circuit breaker in the distribution station on the distribution line where the renewable energy generation facility is located.

This observation highlights an important challenge in the integration of photovoltaic systems into electrical distribution networks. The residual voltage, i.e., the voltage that persists after the tripping of the distribution line circuit breaker and the occurrence of a fault, can maintain a dangerous electric arc, with the potential to cause fires or damage equipment [13].

Figures 4,5 and 6 show the waveforms recorded by the analyser on the voltages on phases L1 and L3 that occur in the immediate vicinity of the photovoltaic system. In these figures, you can see the delay in triggering its protections, which have the effect of maintaining the electric arc at the fault location in the line.

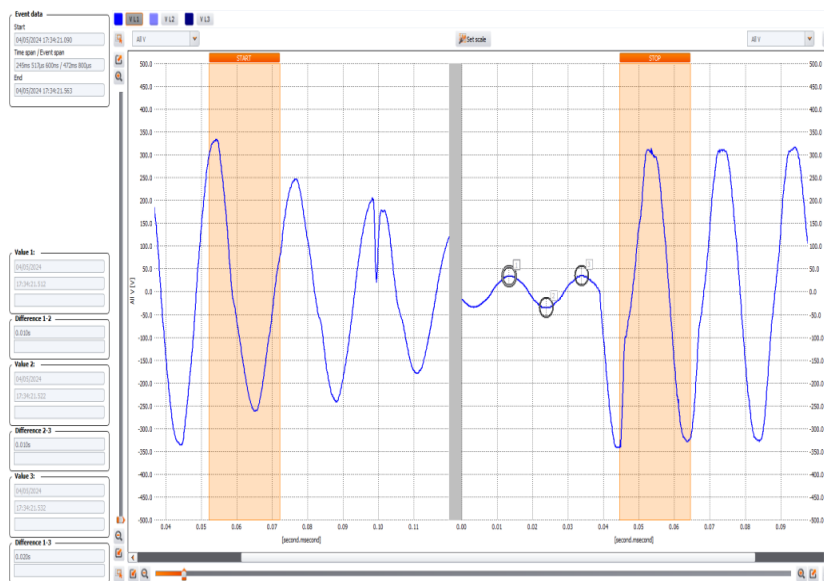


Figure 4. Presentation of the voltage waveform on L1

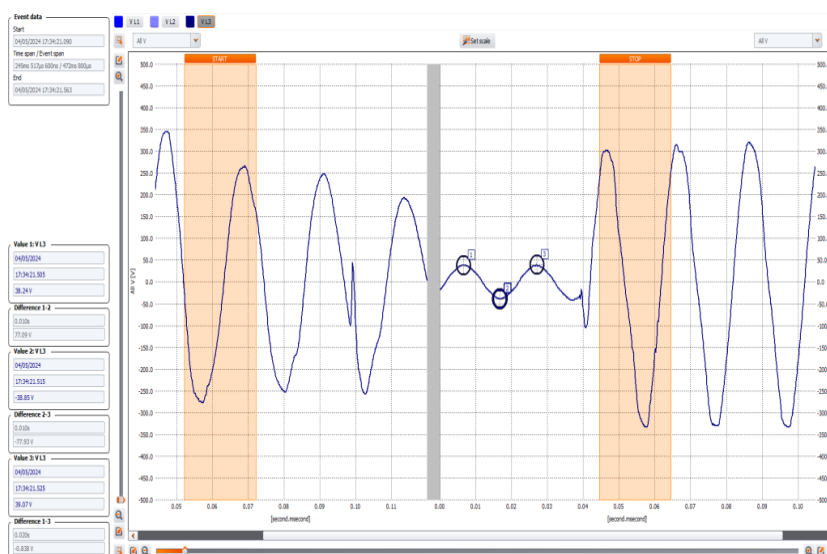


Figure 5. Presentation of the voltage waveform on L3

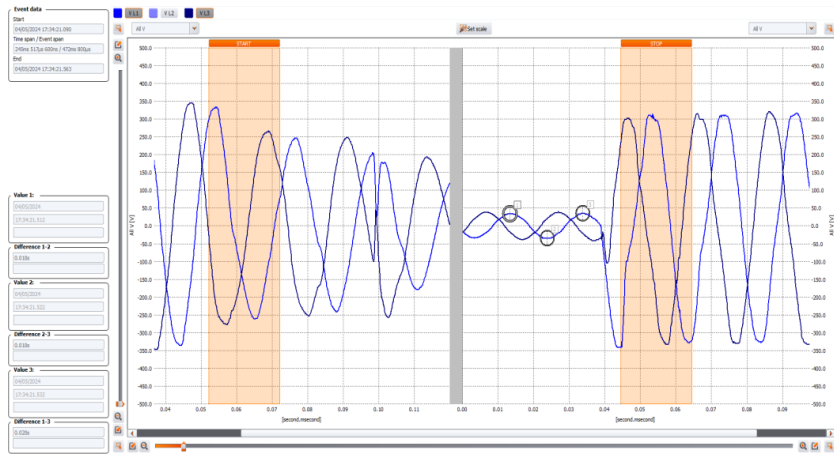


Figure 6. Presentation of the voltage waveform for a short-circuit between L1 and L3

From these figures, we can notice that for polyphase or three-phase faults near the PV power generation sources, the residual current has a value that does not reach 0, and that can maintain the electric arc at the fault location in the distribution line where the PV power generation installation is present.

Figure 7 presents an overall view of the phenomenon recorded by the analyser following the occurrence of a fault, in which the effect of harmonics that appear after the switch in the substation is reconnected and the voltage on the line is restored can also be observed. The voltage evolution on all 3 phases, after the rapid automatic reclosing, is shown in Figure 8.

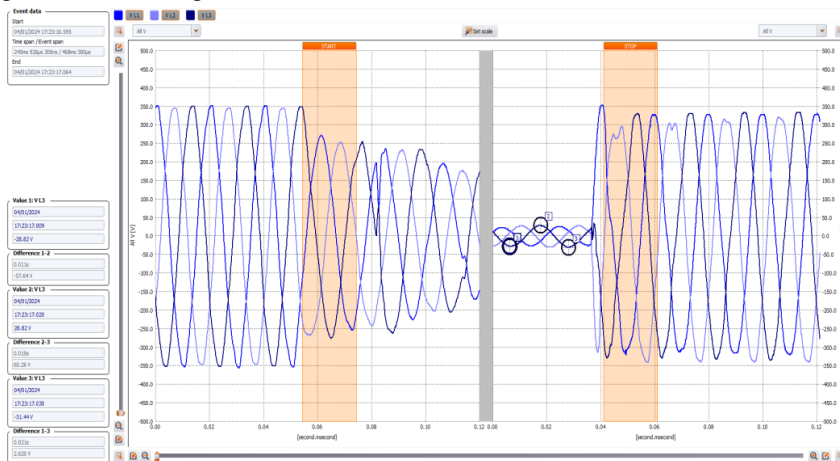


Figure 7. Presence of residual voltages during the rapid automatic reclosing pause on all 3 phases

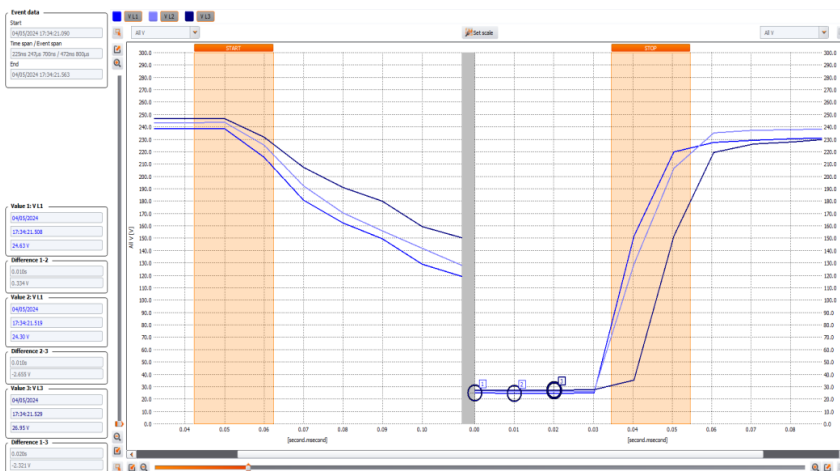


Figure 8. Voltage evolution on all 3 phases

According to the observations, the occurrence of a fault in the vicinity of the PV photovoltaic power source determines a significant variation in the current, accompanied by notable distortions of the waveform.

This current distortion has, as a consequence, the generation of harmonics, which can negatively affect the operation of the protections related to the general switch of the PV source, possibly leading to their desensitization.

A two-phase short circuit, i.e. a short circuit between two phases of a three-phase system, can generate a significant level of current THD. This is because the short circuit causes an imbalance in the system and can introduce current components with frequencies different from the fundamental.

The short circuit transient is the initial, very fast phase of a short circuit in an electrical system. It is characterized by rapid variations in current and voltage, before the system stabilizes in a transient and, eventually, permanent regime.

4. Distribution system modeling and simulation

The choice of the PV plant integration mode inside the NES involves a number of issues, such as the reliability of the electricity distribution system, relay protection, equipment isolation requirements, operating personnel safety, electromagnetic pollution, economic benefits, etc. Against the background of the continuous expansion of photovoltaic power plants and reliability requirements that must be continuously improved, the integration of photovoltaic power plants into the electrical distribution network can amplify the negative effects that occur during a breakdown in the distribution system.

The modelled electrical network was created in such a way as to be able to compare the case when a fault occurs on a distribution line, in which case the line protection in the distribution station detects the fault on the line and gives the command to trip the distribution line circuit breaker, followed by a reclosing pause after which it automatically reconnects [14]. For this, we used an ideal circuit breaker controlled from a signal generator block. The signal generator controls the moment when the single-phase or two-phase fault occurs on the distribution line.

Figure 9 presents the MATLAB-Simulink model for the distribution network with a PV plant.

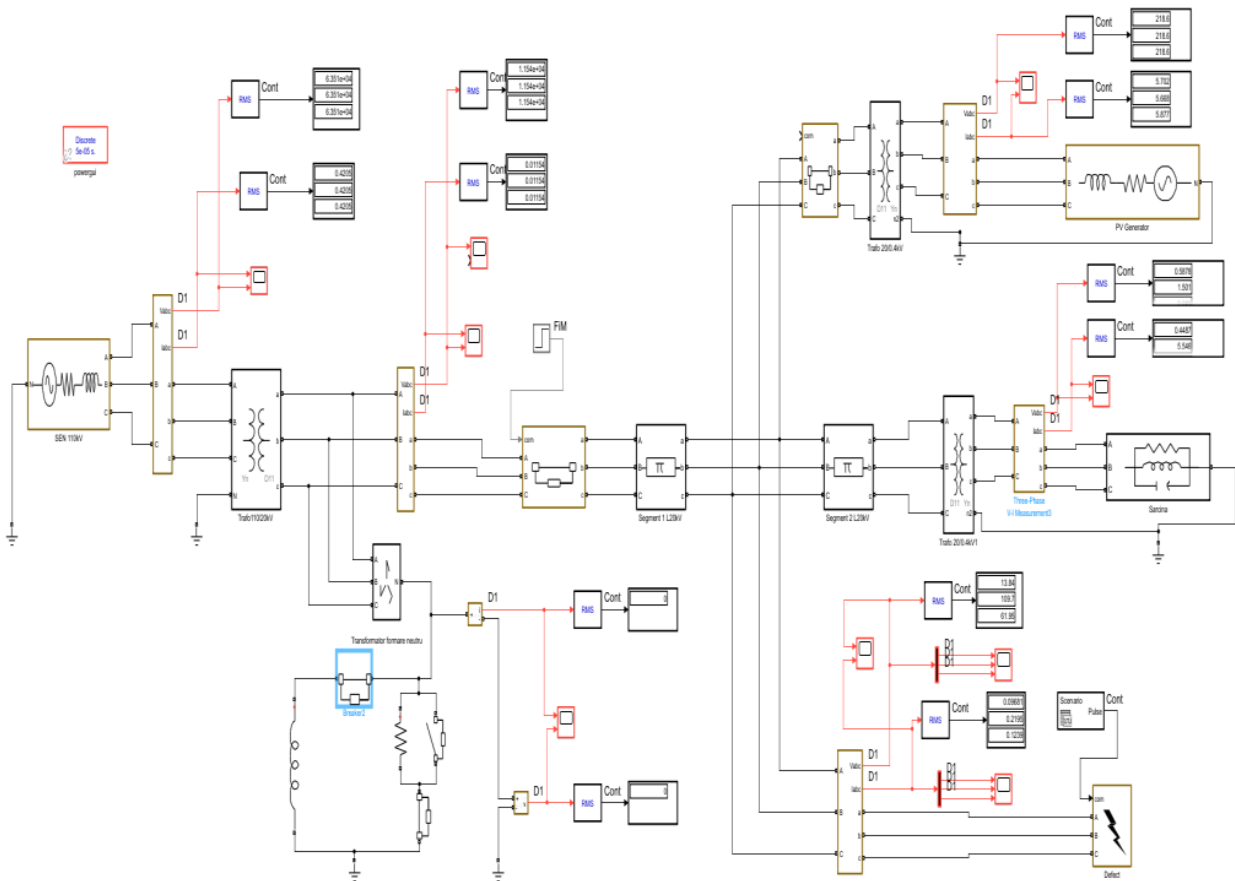


Figure 9. The Matlab-Simulink model for the distribution network.

The voltage generator is a relatively simple model, as close as possible to the SEN parameters, and has an output voltage of 110 kV. The transformer is connected to the SEN through a 110 kV busbar, and the distribution at the medium voltage level is done through a simple sectioned busbar system. To model the transformer, the SMath application was used in Simulink, an interface similar to Mathcad, which allows the representation of formulas as close as possible to mathematical notation.

In Figure 10, we can see the effects of the appearance of the PV electricity producer in the distribution line. Following the occurrence of a fault, the electrical line protection system, located in the power station, identifies the event and gives the command to trigger the circuit breaker for the affected line. According to the graph presented, it is found that, although the distribution line has been disconnected, the generator connected to it continues to inject energy into the portion of the line where the fault occurred, namely a simple grounding.

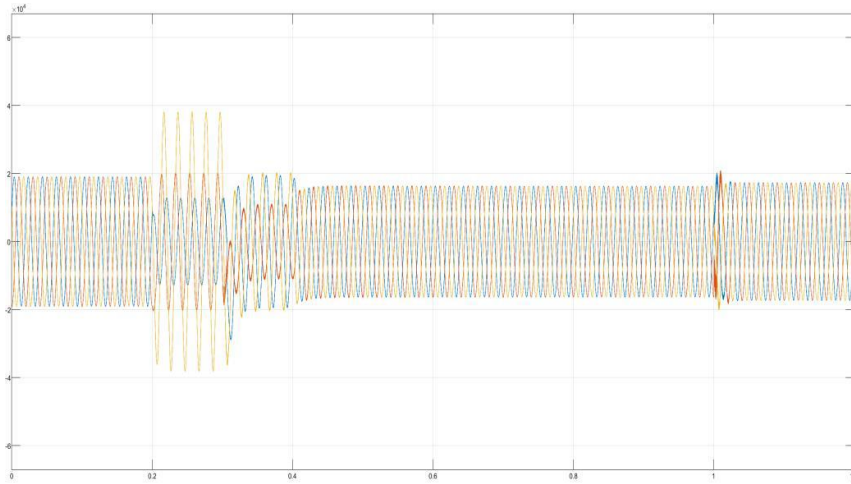


Figure 10. Voltage evolution for the 20kV busbars.

Also in Figure 10, the impact of the presence of voltage on the behaviour of the switching element, namely the circuit breaker, is highlighted, analysing the recorded graphic variations.

In Figure 11, it is noted that the blue signals, representing the phase voltage on the conductor affected by the simple grounding, register a significantly reduced value in the first graph. This decrease in voltage is an indicator of the occurrence of the fault. Subsequently, graphs 2 and 3 illustrate an increase in the voltage values on the other two phases. This increase in voltage can be attributed to the imbalance created in the three-phase system by the grounding.

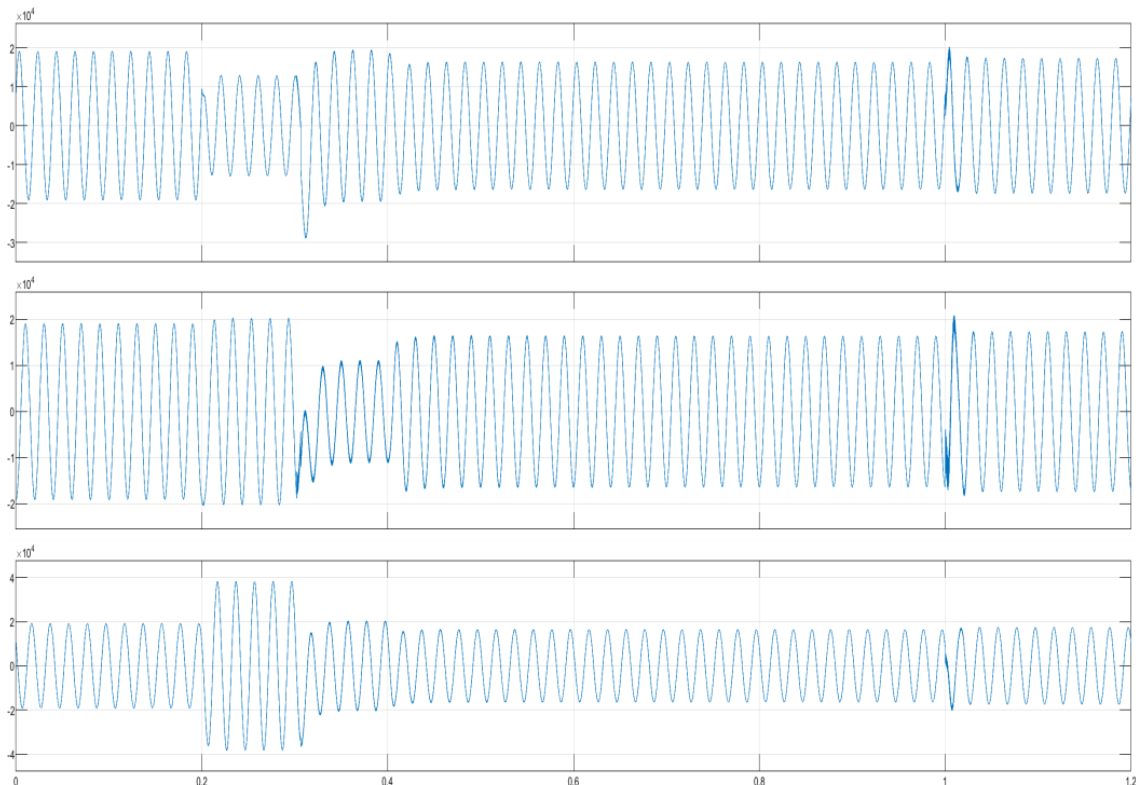


Figure 11. Voltage evolution on each phase.

An important aspect mentioned is the presence of residual voltage, generated by the generator connected to the distribution line. Residual voltage represents an electrical voltage that persists in the circuit even after the main power source has been disconnected. In the present case, the generator continues to inject energy into the distribution line, maintaining a dangerous residual voltage in the fault area.

According to the information provided in Figure 11, a transient overvoltage is observed upon line reconnection after the rapid automatic reclose (RAR) break. This overvoltage is an effect of the residual capacitive load present in the distribution line.

This situation highlights the need for effective coordination between the line protection system and the generator control system, in order to prevent the maintenance of the electricity supply in the faulty area. Otherwise, risks such as fire, damage to equipment, or even electrocution may occur.

5. Conclusions

In medium voltage networks, maintaining a stable voltage is important for the correct operation of electrical equipment and for ensuring the quality of electricity supplied to consumers.

A clear definition of transient phenomena was presented, as well as a classification of them according to their nature and duration (electromagnetic transients, thermal transients, etc.).

The masked load is defined as the demand for electricity that is not visible to the electricity network operator due to its position in the network.

Overvoltages represent a significant threat to the correct and long-term operation of photovoltaic inverters. These voltage transient phenomena can have various causes, such as lightning strikes, network switching, or even the internal operation of some equipment.

In this chapter, an original approach was presented to explore the interdependence between the operation of photovoltaic plants in the network and the occurrence of malfunctions in electrical networks. Through in-depth analysis of waveforms, the study aims to identify specific indicators that highlight a correlation

It is important to note that the aggregate contribution of faults from photovoltaic (PV) parks on a single circuit can significantly affect the fault current on other circuits fed from the same busbar. This additional contribution can significantly increase the fault current value, exceeding the breaking capacity of the upstream circuit breakers.

It is therefore essential to check the breaking capacities of the circuit breakers supplied from the same busbar to ensure that they can reliably handle the increased fault current. This also applies to the protective devices located on the respective circuits.

This significant increase in fault current may require the replacement of circuit breakers and protective devices to maintain safe grid operation. A detailed analysis of the impact of PV installations on the grid is essential to identify potential weak points and to take the necessary preventive measures. Said analysis may include simulating faults at various points in the grid with the PV installation in operation, as well as assessing its impact on fault currents and the short-circuit breaking capacity of the switching equipment. The implementation of appropriate grid protection strategies, such as differential relaying and arc flash protection systems, can help mitigate the risks associated with PV fault contributions and maintain the integrity of the distribution grid.

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