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Contribution regarding the integration of photovoltaic power plants into the grid

Doctoral thesis – Summary

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CONTENTS

1. Introduction

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

The global energy sector is in a phase of profound transformation, characterized by an intense focus on increasing energy efficiency, expanding renewable energy production and implementing innovative solutions such as smart grids.

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

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

To address these challenges, Romania needs to:

- Invest in renewable energy: Developing wind, photovoltaic and hydropower parks can help reduce dependence on fossil fuels and increase the share of clean energy in the energy mix.
- Improve energy efficiency: Promoting energy efficiency measures in residential buildings, industry and transport can reduce energy consumption and costs.
- Modernize energy infrastructure: Investments in electricity, gas and district heating networks are essential to ensure efficient energy distribution and to integrate renewable sources.
- Diversify supply sources: Romania needs to explore new energy sources, such as Black Sea natural gas and nuclear power.

• Develop the internal energy market: Creating a competitive internal market can stimulate investment and innovation in the energy sector.

• Cooperate with European partners: Romania must collaborate with other EU member states to implement common energy policies and to address cross-border challenges.

In the planning process of the electricity distribution networks, the aim was to identify an optimal level of security of the National Energy System (SEN) 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.

The adoption of this criterion led over time to the realization of a safer distribution system, having the following advantages:

• High voltage networks generally adopt a loop configuration, which allows for power redundancy and increased system reliability. 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.

• Within high-voltage/medium-voltage (HV/MV) electrical transformer stations, it is generally practiced installing 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 configuration, 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. Thus, in the event of a failure at a high voltage/medium voltage (HV/MV) substation, power supply to consumers can be ensured through other adjacent medium voltage (MV) lines from neighboring substations.

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

In conclusion, the Romanian energy system is in a process of profound transformation, marked by significant challenges, but also by important opportunities. In order to ensure a sustainable energy future, a strategic and coordinated approach at national and European level is necessary in the long term.

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

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. Distribution Network

Distribution networks are divided into three voltage levels starting from the low voltage level through which household consumers and small industrial consumers are supplied, followed by the medium voltage network where rural transformer stations PTA and urban transformer stations PTAB are supplied. The high voltage network transports energy from the system operator OS stations to the distribution operator OD stations and in the opposite direction with the emergence of electricity producers from distributed sources.

2.1. Low voltage distribution networks

[[2] This section presents other types of networks that are sometimes encountered in practice and in which the short-circuit currents are supplied from different sources. The most common types of networks in the public and industrial sectors are radial networks. For these networks, the calculation of short-circuit currents is very simple. The medium and low voltage sides can be configured arbitrarily, according to the power supply requirements (figure 2.1).

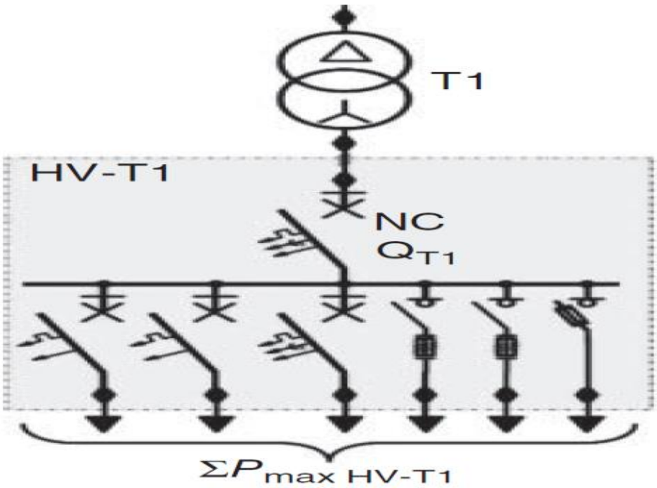

Figure 2.1. Simple radial networks with individual circuits and a transformer.

In industrial networks, the power supply of systems where the power supply must not be interrupted in the event of a failure, switching can take place from one transformer to another. (Figure 2.2). In order to be able to switch between the 2 transformers, an ATS type automation is used, which, when the voltage on the low-voltage bus disappears, brings the backup transformer into operation.

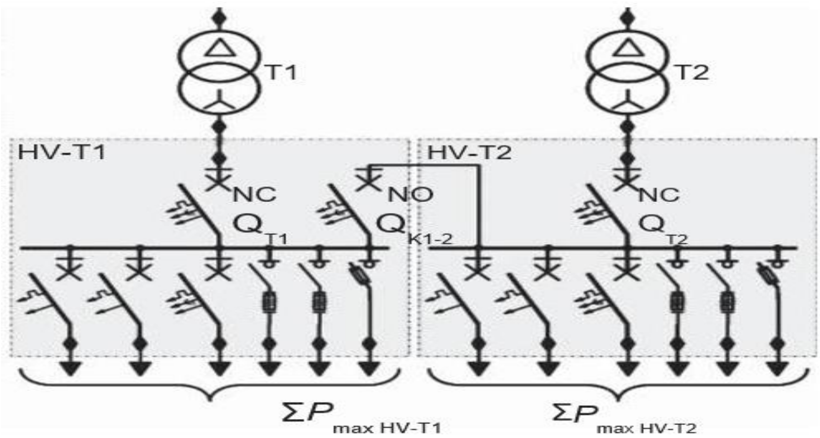

Figure 2.2. Simple radial networks with individual circuits and 2 transformers.

2.2. Medium voltage distribution network

Although regional transmission and distribution use distinct voltage levels, and the load requirements and specifications of substation transformer installations vary significantly, the term "medium voltage" has been adopted to designate voltages used in zonal distribution of electricity, which fall within the high voltage range, between 1 kV a.c. and 110 kV a.c. inclusive.

Most operating voltages in medium voltage systems are in the 6–20 kV a.c. range.

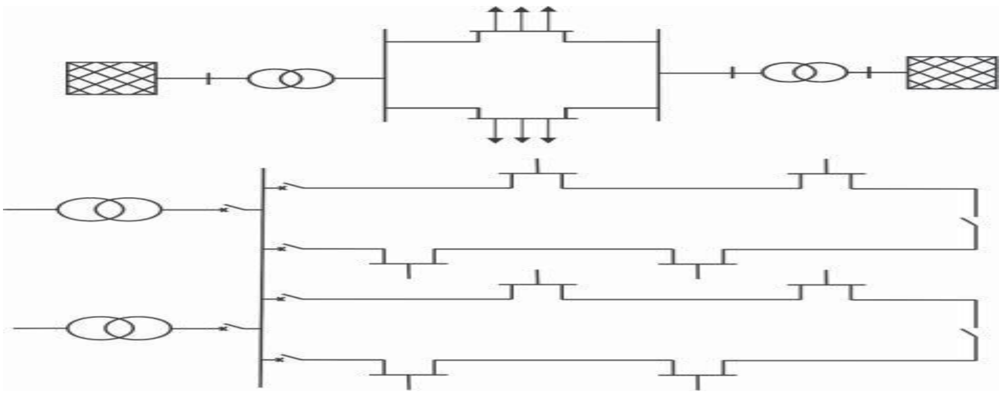

Figure 2.3. Distribution network operating in loop mode and loop-to-loop mode.

The loop network is usually powered from two sources, for example, an industrial network, figure 2.3. After eliminating the fault, the network can be put back into operation. Loop networks are networks that operate in a normal scheme with closed loops. At the time of a fault in the distribution network, all consumers remain unpowered; the fault is isolated by performing fault location maneuvers, after which consumers can be fully powered.

2.3. High voltage distribution network

High-voltage substations are points in the distribution system where power can be aggregated from generating sources, distributed, transformed, and delivered to points of consumption. Substations are interconnected with each other so that the power system becomes a looped network. [3] This increases the reliability of the power supply system by providing alternative paths for the flow of power to handle any situation so that the delivery of power to the loads is maintained and the generators do not face any interruption.

High voltage (110 kV) electrical networks can fulfil the following roles:

– distribute electrical energy in urban and rural areas;
– supply concentrated high-power consumers, individual or industrial;
– discharge energy from medium and high-power power plants;
– reserve for the electrical transmission network.

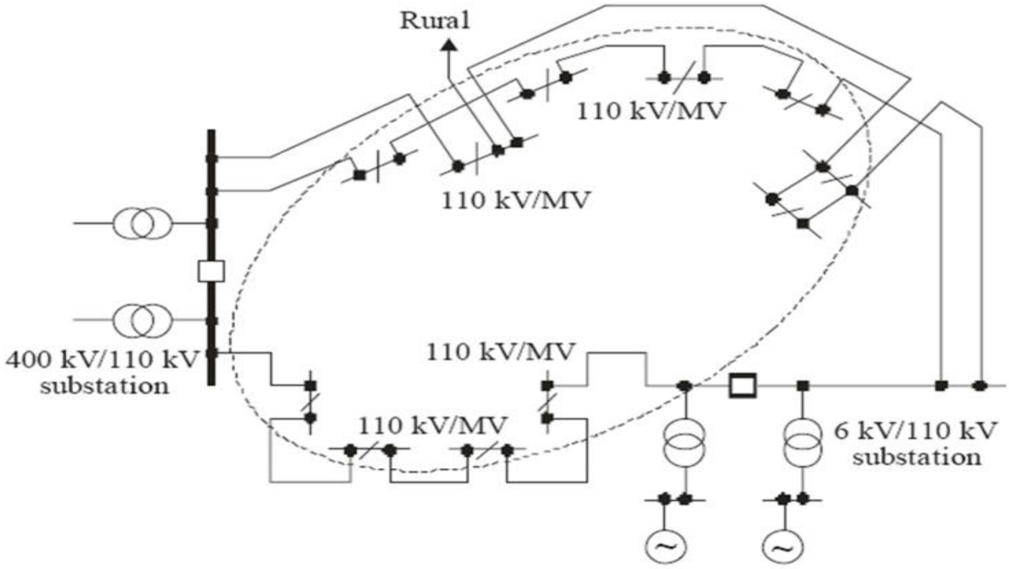

Figure 2.4. Urban high-voltage distribution network, urban/rural distribution.

Operating principle:

In the event of a fault on an overhead power line supplying distribution stations operated in a radial configuration, an interruption of their power supply is observed. In this context, the Open Loop Automatic Recloser (RABD) automation intervenes, after a longer pause period than that characteristic of the Fast Automatic Recloser (RAR) automation, by connecting the circuit breaker of the line in hot reserve of the distribution station where two energy sources from transmission stations converge.

3. The impact at the distribution level of photovoltaic plants

Traditionally, the distribution system has been designed to operate radially, with one-way flow from source to consumer. [4] Since the enactment of the Public Utilities Regulatory Policy Act in 2010, distributed generation (DG) of renewable electricity has begun to appear more frequently in the distribution system.[58] Recently, due to improved economic viability, and through the implementation of financing programs and economic incentives provided by EU member states for the development of new power generation capacity as an alternative to traditional circuit upgrades and state standards in the renewable energy portfolio, distributed photovoltaic (PV) systems have become more common.

Unlike traditional distribution network analysis, which is done at a few significant moments (e.g.: load void and load peak), the impact of PV energy producers should be investigated using a time-varying analysis, which captures the interactions between generation, consumption and control equipment that are difficult to predict using a single time-varying analysis. The time-varying analysis should include the behavior of fast-acting inverters, dynamic loads and automatic voltage control devices at the distribution station level.

This chapter documents the impact of photovoltaic power plants on the distribution system. In the context of this paper, it is found that photovoltaic power plants connected to the medium-voltage distribution network have an increased probability of generating deviations from voltage, current and/or protection criteria.

The production of electricity from photovoltaic sources is dependent on weather conditions, being intermittent and variable.

This variability can lead to voltage and power fluctuations in the distribution network, affecting the quality of electricity and the stability of the distribution system in the area.

Hidden charge

Hidden load is defined as the demand for electricity that is not visible to the grid operator due to its location in the grid. This load can come from various sources, such as:

- Distributed Generators (DG): DGs are small power plants installed near consumers. Since many forms of DG are not monitored and can be disconnected or absent for other reasons without prior notification to the grid operator, it is important to consider the total load when designing and operating electricity networks.

- Local consumption: Part of the electricity produced by a power plant may be consumed locally, without being recorded by the grid operator's electricity meters.
- Network losses: Some of the electrical energy is lost in the network as a result of electrical resistance and other factors.

Hidden load can have a significant impact on electrical networks, including:

- Overloads of power lines and transformers if the hidden load is not taken into account, power lines and transformers can be overloaded, which can lead to equipment damage and power outages;
- Grid stability issues, hidden load can affect the stability of the electrical grid, which can lead to increased frequency and voltage, which can damage equipment and cause power outages;
- Difficulties in grid planning and management, grid operators need accurate information about the total load on the grid to be able to plan and manage the grids effectively.

It is important that electricity grid operators take the necessary measures to estimate and manage hidden loads.

These measures may include:

- Installation of electricity meters at DG sources and local consumers;
- Development of models to estimate latent load;
- Implementation of demand management systems.

As DG deployment continues to grow, it is essential that grid operators take a proactive approach to managing hidden load and ensure that their grids can reliably and efficiently handle this new source of electricity.

Figure 3.1 shows the metered load, native load, and PV generation for a peak demand day. The natural load (grey line) of this circuit is significantly higher than the metered consumption (light blue line) on the circuit. This is because the metered circuit power is the sum of the natural load and the PV generation (dark blue line).

If grid design and operation decisions are based on measurements of power flows in the circuit instead of native load calculations, significant overloads of circuit elements can occur. This can happen if PV generation disconnects unexpectedly, as the metered circuit flow will drop sharply but the native load will remain unchanged.

This example illustrates the problem of not relying on measured load for electrical grid design and operation practices. Native load is a more accurate measure of total demand on the grid and should be used to make decisions that ensure the grid can reliably and efficiently handle total demand.

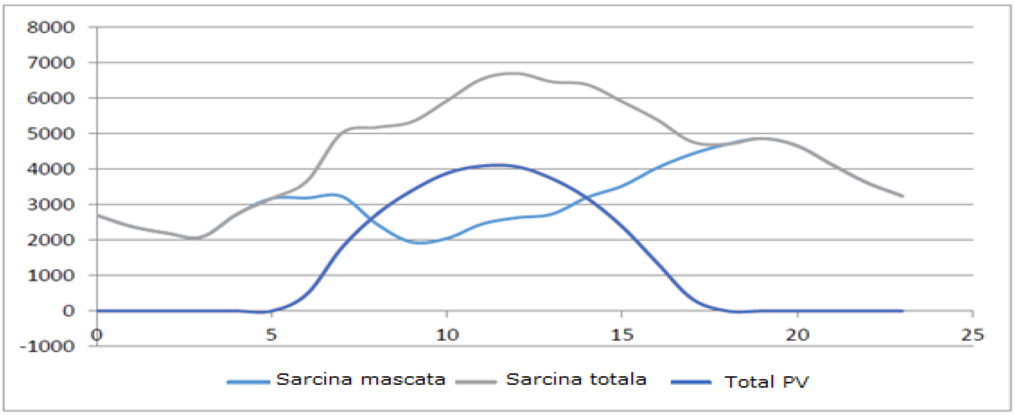

Figure 3.1. Load graph seen at the distribution station bars.

Figure 3.2 illustrates an example of the impact of solar PV on the voltage profile of a power line. In this example, the line voltage increases significantly during the day, when PV production is high. This increase in voltage can exceed the operating limits of electrical equipment and lead to power quality problems.

It is important for power grid operators to consider these factors when assessing the impact of PV on the grid voltage. Simulation models can be used to predict the voltage increase on specific lines and identify potential problem locations.

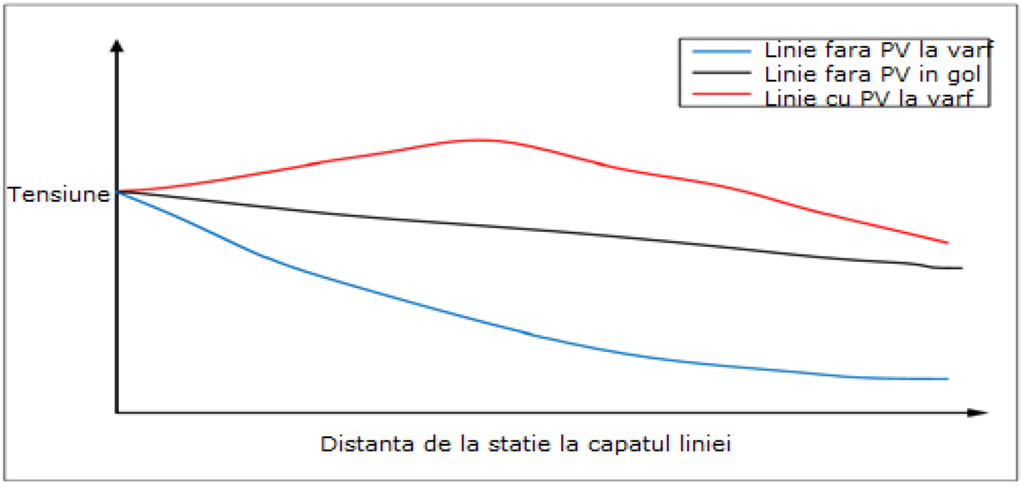

Figure 3.2. The impact of PV on the voltage profile on a distribution line.

Presentation of RAR break voltage waveforms in the presence of a fault in the near of the PV source

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.

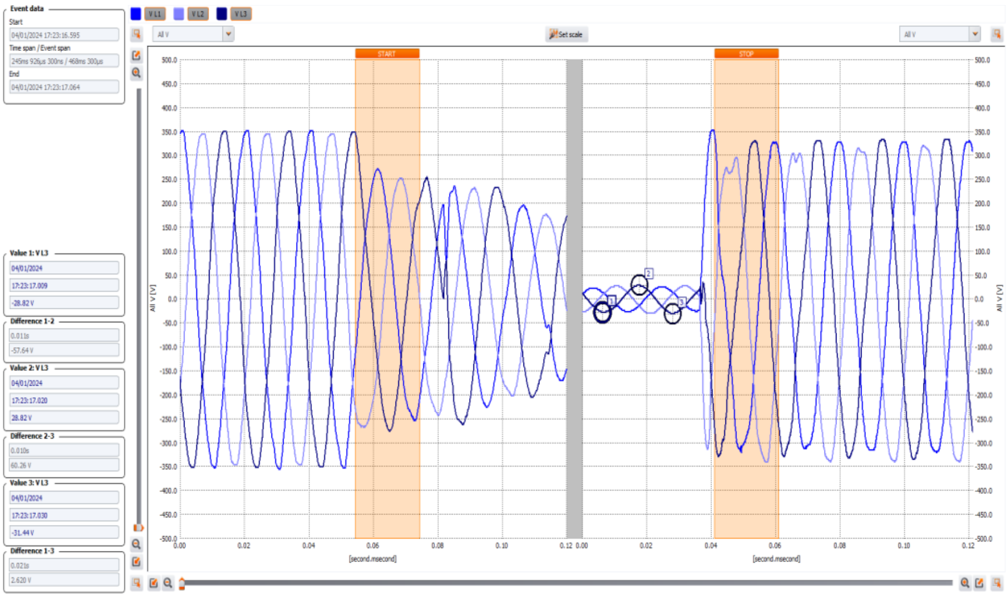

Figure 3.3. Presence of residual voltages in the RAR break on all 3 phases.

Figure 3.3 presents an overview of the phenomenon recorded by the analysers following a fault, in which the effect of harmonics that appear after the substation circuit breaker is reconnected and the line voltage is restored can also be observed. This visual analysis provides an important insight into how a near fault affects the electrical parameters of the network and can help understand the challenges related to the protection of power systems in the presence of distributed generation.

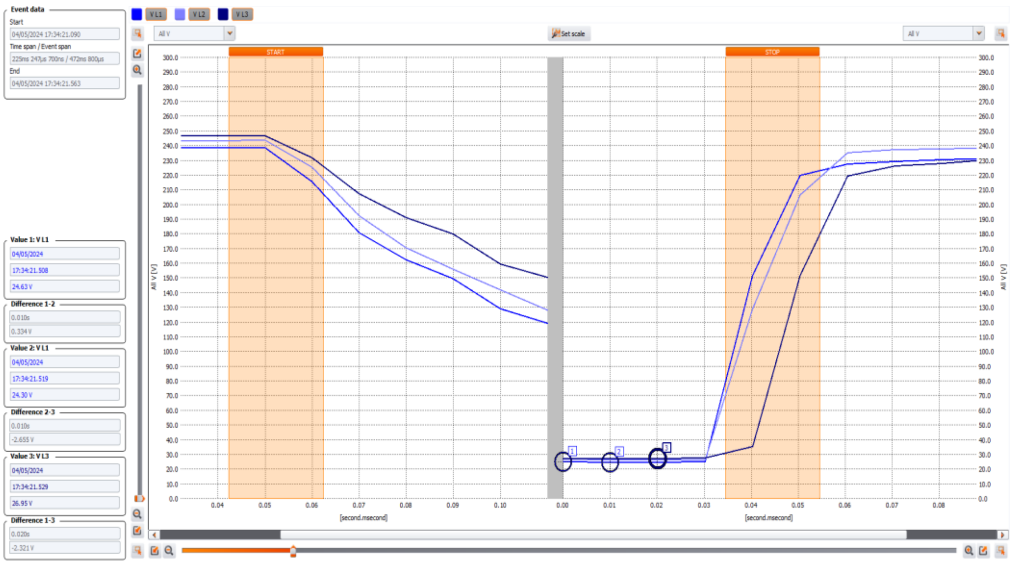

Figure 3.4. Voltage evolution on all 3 phases.

Presentation of the waveforms of the currents in the RAR break in the presence of a fault in the near of the PV source

It can be observed that in polyphase or three-phase faults near the PV electricity production 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 electricity production installation is present.

According to the observations in figure 3.5, the occurrence of a fault in the vicinity of the PV photovoltaic electricity source determines a significant variation in the current, accompanied by notable distortions of the waveform.

This current distortion has consequently 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.

It is essential that the design, installation and operation of photovoltaic systems take these aspects into account and implement adequate measures to ensure the safe and reliable operation of the electrical network.

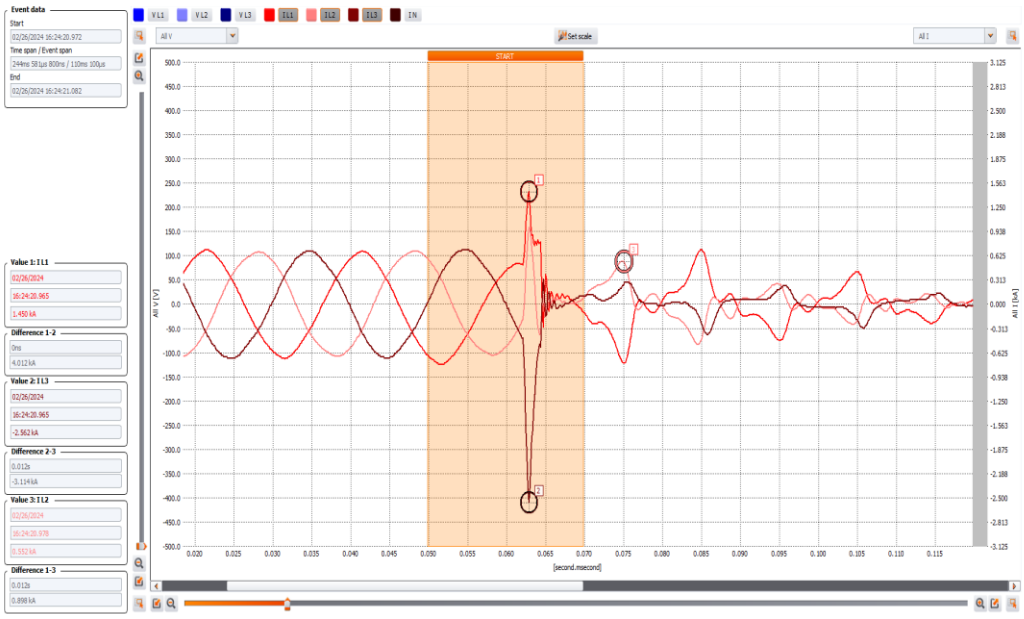

Figure 3.5. Presentation of the current waveform on L1, L2, L3.

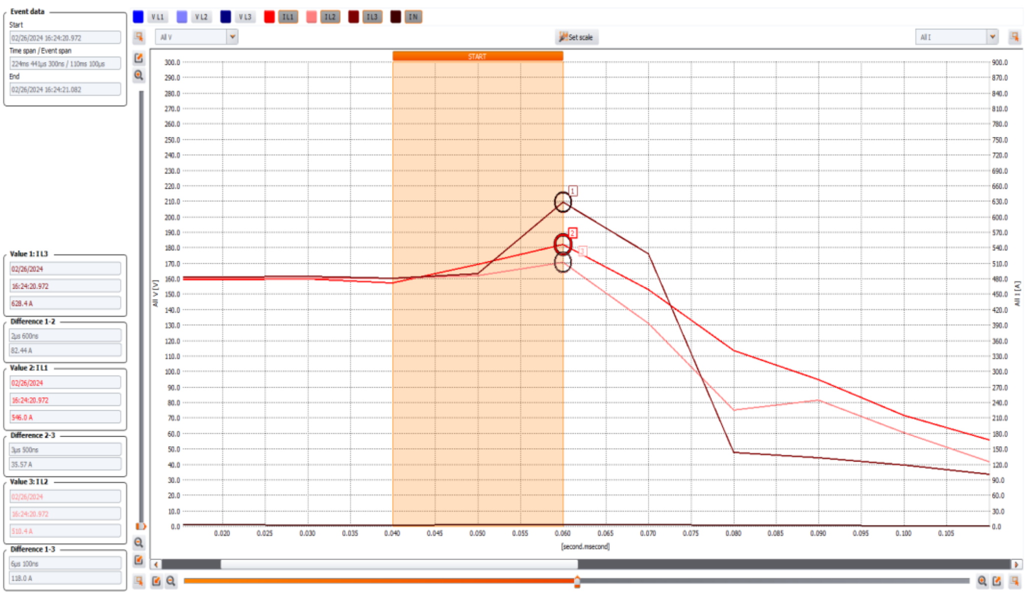

Figure 3.6. Evolution of currents on all 3 phases.

4.Modeling and simulation of the distribution system HV,MV,LV

The choice of the CEF integration mode in the SEN 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 the 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 RAR pause after which it automatically reconnects. 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.

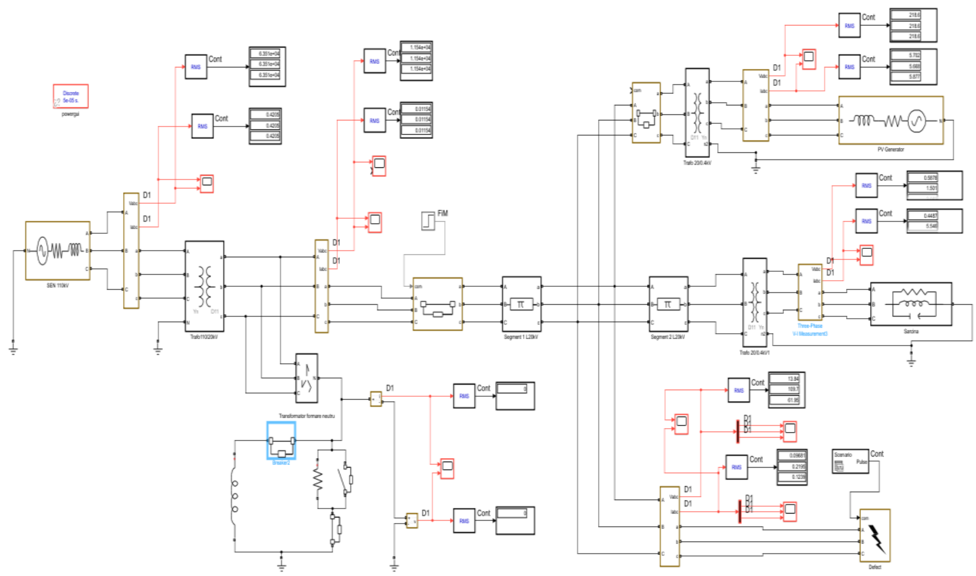

Figure 4.1. Distribution network modelling block diagram.

Presentation of voltages and currents at the fault location in the distribution line in the absence of the distributed generation source

Understanding the behaviour of voltage and currents at the fault location in a distribution line is crucial for protecting the electrical network and ensuring the continuity of the electrical power supply. The behaviour of voltage and currents at the fault location in a distribution line is complex and depends on several factors, such as the type of fault, the impedance at the fault location and the way in which the neutral of the network is treated.

In figure 4.2, the occurrence of a ground fault followed by the tripping of the line in the distribution station and the operation of the RAR automation was simulated, the fault disappearing after the completion of the first RAR cycle.

The presence of overvoltage's can be observed both at the tripping of the line and at its reconnection, this phenomenon is due to the reactance of the line and its load.

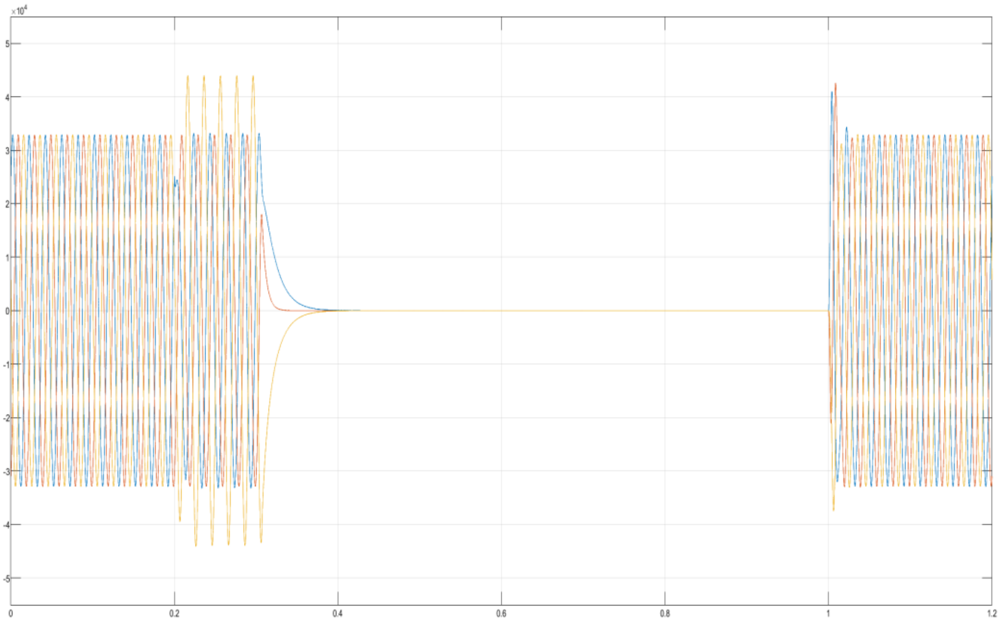

Figure 4.2. Presentation of voltages at the fault location in the distribution line

Presentation of voltages and currents at the fault location in the distribution line in the presence of the distributed generation source

The study of the behaviour of voltage and currents at the location of a fault in a distribution line is a fundamental aspect for ensuring the effective protection of the electrical network and maintaining continuity in the supply of electricity. Understanding these phenomena is essential, given their complexity and the multitude of factors that influence them.

According to the information provided in figure 4.3, the simulation of the event includes a grounding, followed by the tripping of the line in the station and the activation of the rapid automatic reclosing (RAR) function. It is mentioned that the fault disappears after the completion of the first RAR cycle. During this interval, the generator connected to the line continues to inject energy into the portion of the line affected by the fault. From this information provided, it is deduced that the fault is kept active by the generator in the distribution line until it detects the operation of the line in islanded mode and the modification of its parameters.

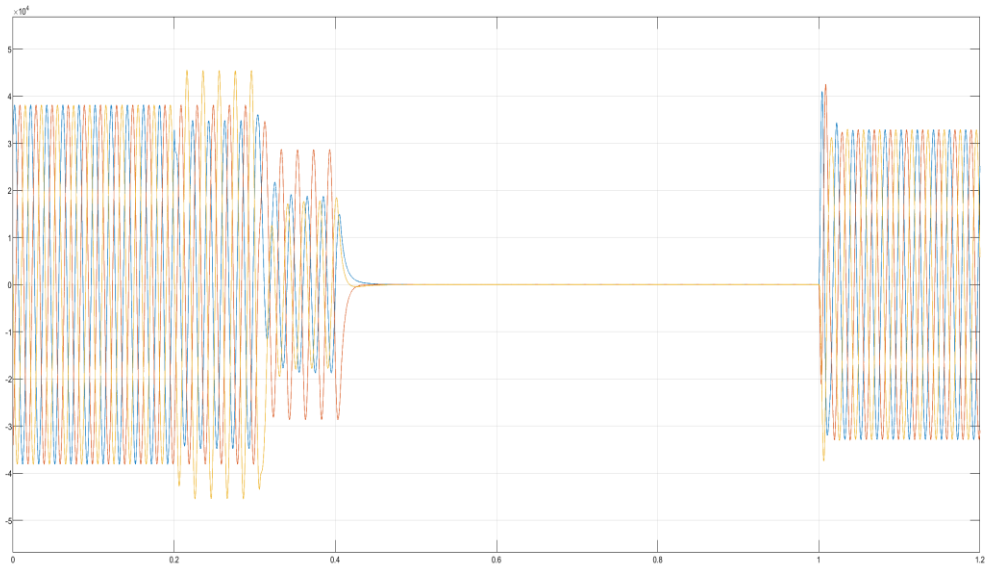

Figure 4.3. Presentation of voltages at the fault location in the distribution line.

5. Analysis of the types of faults that can occur in the medium voltage network

To summarize the analysis of the types of faults that can occur in medium voltage networks, it is necessary to classify the operating modes of distribution networks to ensure safe and reliable operation of the electrical system.

Understanding the causes, impact and methods of detecting faults allows network operators to take preventive measures and intervene quickly in the event of problems.

[5] Electrical faults are deviations from the normal operating conditions of an electrical system, generally caused by a significant decrease in the electrical resistance of the insulation. They can be classified into short circuits, which can be three-phase (involving all phase conductors) or single-phase (involving one phase conductor and earth).

Types of operating modes	Variation of three-phase electrical sizes	Nature of the regime
Normal	symmetric	normal
Short-term transient	symmetrical/ asymmetrical	normal/failure
failure	asymmetrical	failure

Table 5.1. Classification of operating modes of electrical networks.

[6] In the operation of electrical networks, several operating modes are distinguished, each characterized by specific electrical conditions. These modes are influenced by a multitude of factors, including the load level, the importance of consumers and the demands placed on network components. Among the most common modes are:

- **Normal operating mode:** Corresponds to operating conditions in which all network components operate within nominal parameters, and the electricity supply is ensured continuously and with satisfactory quality.
- **Short-term transient mode:** Represents an intermediate, short-term state that occurs following a system disturbance (e.g. a short circuit). In this mode, the values of electrical quantities (voltages, currents) can vary rapidly and significantly.
- **Fault mode:** Corresponds to a situation in which an electrical fault causes a significant interruption of the electricity supply, either for an individual consumer or for a wider area of the distribution network.

Highlighting defects occurring in the medium voltage network through the oscilloscope in the distribution station

[7] A disturbance recorder is a complex electronic device, usually integrated into a protection system, which is designed to monitor the electrical parameters of a network in real time. [8] It records and analyses disturbances that may occur in the system, such as short circuits, overvoltage's, undervoltage or frequency variations. Disturbance recorder "A Guardian of the Stability of the Electrical Network"

Disturbance recorder provides a series of information such as:

- Voltage and current waveforms: These waveforms allow the identification of the type of disturbance (symmetrical, asymmetrical short circuit, overvoltage, etc.).
- Time of occurrence of the disturbance: This information is essential to correlate the event with other relevant data, such as alarms generated by other equipment.
- Duration of the disturbance: Knowing the duration of the disturbance allows the assessment of its impact on the equipment.
- Energy dissipated during the disturbance: This information is useful for assessing the severity of the fault and for sizing the protective equipment.

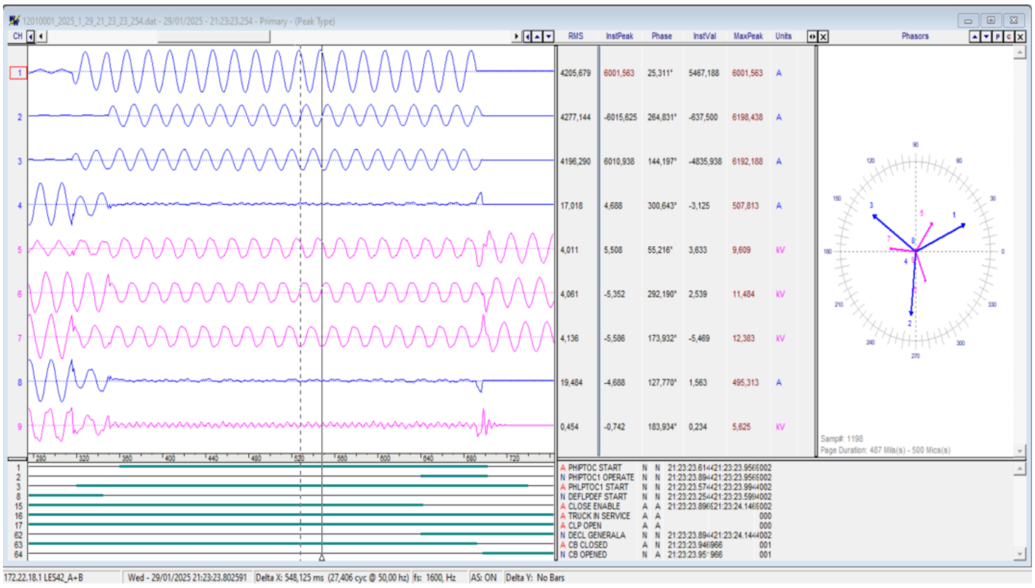

Figure 5.1. Presentation of the system in the presence of a three-phase 3FN short circuit and without the operation of the RAR automation.

Annexes

Figures 6.1 and 6.2 illustrate a specific phenomenon of damage to a medium voltage cable termination (CTI), namely its breakdown through the insulation. This phenomenon is caused by an overvoltage, which leads to an electrical discharge between the cable shield braid and the active conductor.

Figure 6.1. 20kV LES terminal end faulted in the 20kV L2-phase.

Figure 6.2. 20kV LES terminal end faulted in the 20kV L3-phase.

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