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SUMMARY

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DOCTORAL THESIS (SUMMARY)

**TITLU (română): EFICIENTIZAREA PRIN AUTOMATIZĂRI ÎN REȚELELE
DE DISTRIBUȚIE A ENERGIEI ELECTRICE**

**TITLU (engleză): EFFICIENCY THROUGH AUTOMATION IN POWER
DISTRIBUTION NETWORKS**

Doctoral domain: ELECTRICAL ENGINEERING

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CONTENTS

1. INTRODUCTION.....	5
1.1. THE NECESSITY AND JUSTIFICATION OF THE THESIS	5
1.2. THE PURPOSE OF THE THESIS AND OBJECTIVES.....	6
1.3. RESEARCH METHODOLOGY.....	6
1.4. THE THESIS CONTENT	6
1.5. THE IMPORTANCE OF RESEARCH AND NEW DIRECTIONS	9
2. IMPROVING THE MONITORING OF OVERHEAD POWER DISTRIBUTION LINES.....	9
2.3. MAKING OVERHEAD LINE FAULT DETECTION SYSTEMS MORE EFFICIENT	9
2.3.1. The overcurrent protection of overhead power lines and the influence of ambient temperature on it's setting.....	9
2.3.2. Maximizing the protection of overhead power lines under the influence of temperature for the OI-AI 185/32 mm ² conductor (case study).....	12
2.3.3. Overhead powerlines pole integrity monitoring system.....	16
2.4. CONCLUSION	20
3. IMPROVING THE EFFICIENCY OF DEFECT DETECTION SYSTEMS FOR ELECTRICAL POWER DISTRIBUTION CABLES.....	22
3.3. CONTRIBUTIONS TO IMPROVING THE EFFICIENCY OF ELECTRICAL CABLE FAULT DETECTION SYSTEMS	22
3.3.1. Method for detecting electrical cable faults with inductive current sensors	22
3.3.2. Method for detecting faults in electrical cables with induction-powered loops.....	23
3.4. CONCLUSION	25
4. IMPROVING AUTOMATION SYSTEMS IN TRANSFORMER STATIONS.....	25
4.3. MAKING AUTOMATION MORE EFFICIENT IN ELECTRICAL TRANSFORMER STATIONS	25
4.3.1. C++ application for verifying the possibility for parallel operation of transformers	25
4.3.2. Method for detecting faults in medium-voltage electrical networks using Fuzzy techniques.....	26
4.4. CONCLUSION	30
5. VOLTAGE STABILITY IN POWER DISTRIBUTION NETWORKS	31
5.3. CONTRIBUTIONS THROUGH AUTOMATION FOR POWER DISTRIBUTION NETWORKS STABILITY	31
5.3.1. Method for power and voltage regulation in power distribution networks.....	31
5.3.2. Application for checking voltage stability in electrical distribution networks when connecting renewable production sources (case study).....	33
5.4. CONCLUSION	36
6. POWER DISTRIBUTION NETWORKS SUSTAINABILITY THROUGH AUTOMATION USING ARTIFICIAL INTELLIGENCE.....	38
6.3. STREAMLINING THE ELECTRICITY PRODUCTION PROCESS USING AUTOMATION.....	38



6.3.2. Electrical production efficiency from alternative energy sources with Fuzzy Technique.....	38
6.4. CONCLUSION	42
7. STEP VOLTAGE DETECTION SYSTEM IN POWER DISTRIBUTION NETWORKS	42
7.3. CONTRIBUTIONS IN STEP VOLTAGE FOR ELECTRICAL NETWORKS	42
7.3.1. Step voltage measuring sistem in electrical networks.....	43
7.4. CONCLUSION	44
8. CONCLUSION AND PERSONAL CONTRIBUTIONS.....	45
8.1. GENERAL CONCLUSIONS.....	45
8.2. PERSONAL THEORETICAL CONTRIBUTION	47
8.3. PERSONAL PRACTICAL CONTRIBUTION.....	49
8.3.1. Practical achievements.....	49
8.3.2. Participation in energy projects during doctoral.....	49
8.4. DESIGNATING THE RESULTS	50
8.5. FUTURE RESEARCH DIRECTIONS	50
SELECTED BIBLIOGRAPY.....	52
LIST OF PUBLISHED ARTICLES.....	53

1. INTRODUCTION

1.1. The necessity and justification of the thesis

The energy system is one of the important pillars of a society. Energy ensures the proper functioning of production systems, as well as life in residential areas. The supply of deficient electricity through frequent interruptions or in inappropriate parameters causes major losses to a society by reducing comfort, material losses, and in isolated cases even the loss of human lives.

In our country, the equipment within the SEN is at the end of its service life, with network operators in a continuous process of modernization to ensure the delivery of electricity to consumers in high quality conditions. Romania, part of the European Union since 01.01.2007, must comply with European Directive 2003/87/EC with subsequent amendments and additions ETS 2 – Directive 2023/959 regarding carbon dioxide (CO₂) emissions. Modernization is done slowly, through its own funds, by connecting new users (consumers and producers) and in recent years through the PNRR.

The process of modernizing the electricity grids is a long one, given the size of the grids, their importance and the avoidance of long-term interruptions. The above-mentioned directive on CO₂ emissions establishes clear limits on emissions in the electricity production process, so the national energy system (SEN) is in a state of continuous change, with many thermal power plants being decommissioned, with new generating units to take their place in the coming years. The main types of generators that will replace decommissioned thermal power plants are renewable energy sources: wind power plants (WPPs) and photovoltaic power plants (PVPs).

The new generators will not be located in the same location as the old generators, given that the installation of the new generators will be done considering their maximum efficiency. CEE will be located in the hilly area, areas suitable for this type of power plant being the area of Moldova, Dobrogea and the mountainous Banat. CEF will generally be located in flat areas, preferably plains, areas suitable for this type of power plant being the plain Banat, Oltenia, Muntenia, Dobrogea, but also the Transylvania area.

In general, high energy consumption is in the metropolitan areas of the largest cities in Romania: Bucharest, Cluj Napoca, Constanța, Timisoara, Iași, Braşov, Sibiu. If the generators are located in areas further away from those of consumers, a current circulation will appear on the power lines, losses will increase and the lines will reach in certain scenarios the upper limit represented by the maximum protection setting. Currently, there are solutions for operational limitation of generators to reduce the power transmitted on the power lines in case of unfavorable scenarios.

The SMARTGRID system is being implemented, by installing smart meter networks, the level of automation increasing exponentially in this network concept.

The author's research in the field of energy automation fits perfectly with the evolutionary direction of the power networks in Romania to make the process of electricity transmission and distribution more efficient.

1.2. The purpose of the thesis and objectives

The purpose of the doctoral thesis is to make electrical networks more efficient through automation, specifically for electrical power distribution networks by achieving the **following specific objectives**:

1. Improving the protection and monitoring systems of overhead and underground power lines by developing applications and studies regarding maximum current protection and monitoring of faults and integrity of power lines;
2. Developing automation in transformer stations by carrying out studies and applications for paralleling transformers with different characteristics and analyzing voltage stability when connecting renewable sources of electricity production;
3. Introducing artificial intelligence systems in making electrical networks more efficient for detecting faults in medium voltage electrical networks, regulating voltage and power in electrical distribution networks and making electricity production more efficient;
4. Development of a step voltage monitoring system capable of ensuring fast, efficient, safe and accurate measurement of the step voltage value in the vicinity of electrical installations without the use of an auxiliary source.

1.3. Research methodology

The mixed research approach, both qualitative - analysis of experiences gained during professional development, through completed projects, and quantitative - through the collection of statistical data following the preparation of case studies, provides this work with information for conducting the research.

The research methodology was based on the following stages: identifying the research object, designing the research (qualitative or quantitative), collecting data and applying the chosen instruments, analyzing and interpreting the data, and respecting confidentiality and consent norms.

1.4. The thesis content

This paper proposes the efficiency of the operation of electrical distribution networks through automation, given the slow process of their modernization and the connection of renewable energy sources together with the challenges that this process brings:

- **Chapter 1** entitled "**Introduction**" includes the framing and justification of the topic that constitutes the subject of the doctoral thesis, in the context of the current stage of the evolution of electrical energy systems and of the concerns existing globally and locally in the country and a brief presentation of the content of each chapter of the thesis. It highlights both the way of capitalizing on the research carried out (publications, case studies, software simulators), and the perspectives regarding further research directions.
- **In chapter 2** entitled "**Effective monitoring of overhead power distribution lines**", solutions were developed to optimize the operation of overhead power lines by setting a maximum dynamic protection that takes into account the ambient temperature in which the conductor is located, allowing the modification of the line protection settings in accordance with the external temperature and the extension of the protection range for the same section of a conductor. Systems for monitoring overhead lines and the integrity of concrete support poles are analyzed by analyzing the dynamics at their top and controlling the triggering of power switches in the event of movement beyond a predetermined interval - the system triggers the line before the pole tilts dangerously much and the conductors touch the ground, avoiding the occurrence of step voltage in the area of the power line failure. The monitoring system was also analyzed in the autonomous version, being able to operate without power from auxiliary energy sources.
- **Chapter 3** entitled "**Effectiveness of fault detection systems for power distribution cables**" analyzes electrical cable monitoring systems that allow for the fastest possible identification of the fault and the narrowing of the search area as much as possible by identifying signals in the field using electrical induction loops. The induction loops allow signaling to the control room of the electrical cable status without consuming energy from auxiliary sources. The voltage induced in the loops in the electrical cable is rectified using dedicated schemes, used to signal the failure of the portion of the electrical cable that is monitored.
- **Chapter 4** entitled "**Improving automation systems in transformer stations**" analyzes in detail the automations implemented at the transformer stations. The programs developed in the C++ programming language for the main automations are described. The application developed by the author regarding the verification of the possibility of paralleling transformers according to their technical characteristics is presented. To automate the detection of faults in medium voltage networks, a comparative study is carried out between the admittance and current injection method and the detection method using Fuzzy techniques developed by the author. The simulations for the proposed method were performed in the Fuzzy application within the Matlab program.

- **Chapter 5** entitled **"Voltage stability in electricity distribution networks"** studies the evolution of the voltage of an electrical network in the case of connecting renewable power plants to it, the concept of voltage stability and the known analysis methods are analyzed and defined: bifurcation theory, active power - voltage and reactive power - voltage curves. The analysis includes a case study on an industrial park in which conditions of maximum consumption and maximum production were simulated, as well as the evolution of the voltages in the network in the two scenarios. The voltage stability analysis was carried out in the NEPLAN program, the results indicating the weak points of the electrical network and the place where electricity producers can be connected.
- **Chapter 6** entitled **"Sustainability of electricity distribution networks through automation using artificial intelligence"** presents the evolution of the energy system from its establishment to the achievement of the SMARTGRID concept. The SMARTGRID concept has begun to be implemented in Romania, the process being a laborious and long-term one. An automation using artificial intelligence through Fuzzy concepts is analyzed for choosing the types of generators to operate in the electrical grid as well as when to use accumulator batteries to streamline the process of distributing electricity in future smart grids. The simulations are performed using the FuzzyApp application in the Matlab computing program.
- **Chapter 7** entitled **"Step voltage detection system in distribution networks"** integrates the preventive maintenance systems used in electrical networks, the measurements to be made, their periodicity and the way in which they must be performed for concrete results. A mobile system proposed by the author for detecting step voltage using an Arduino board, LEDs, a haptic warning bracelet and a horn is presented. Depending on the level of detected step voltage, there are 3 warning levels: within parameters, at the limit and dangerous level, so that the operator can draw conclusions from the measurements regarding places with dangerous step voltage and take measures.
- **Chapter 8** entitled **"Conclusions and personal contributions"** highlights the research results of this doctoral thesis, the articles in which they were developed, detailed and concluded, as well as their usefulness in the framework of future modernized distribution networks.

The doctoral thesis includes four annexes with computer programs that can be developed for the implementation of automation in transformer stations. With each automation implemented in electricity distribution networks, reliability is increased and the time of interruptions in the supply of electricity to users is reduced.

1.5. The importance of research and new directions

Smart grids are the concept towards which the energy system is moving. Small steps are being taken, sustained every day, with each modernization of a substation or electrical network the trend is towards a more reliable distribution system and with a greater degree of autonomy.

Of course, research has its place in this process, elements resulting from research are used in the national energy system. Inventions that were part of energy studies and research in the past are now used for protection and automation in electrical networks.

Research areas such as the method of transmitting wireless energy over small areas where electrical cables cannot be used are directions to be taken into account in further research.

Part of the results obtained within the thesis were published in prestigious journals and in the volumes of recognized scientific events from abroad or in the country: 3 articles published in renowned journals at national level and 3 articles published in internationally recognized conferences.

The author's research demonstrates that the steps taken in the automation of electrical energy distribution networks increase their efficiency.

The theoretical and practical analyses carried out within the doctoral thesis, as well as the results obtained, open a series of perspectives and directions for further continuation and deepening of research in the field:

- **Implementation of the SMARTGRID concept with the tendency to increase the autonomy of electrical networks through automation implemented at key points**
- **Increasing cyber security at the level of electrical distribution networks.**

2. IMPROVING THE MONITORING OF OVERHEAD POWER DISTRIBUTION LINES

2.3. Making overhead line fault detection systems more efficient

This subchapter describes how maximum protection can be improved using ambient temperature monitoring along the power line route and proposed automations for monitoring the integrity of poles, these contributions leading to a safer distribution network and improving the level of electricity supply to network users.

2.3.1. The overcurrent protection of overhead power lines and the influence of ambient temperature on it's setting

Currently, the distribution and transmission networks are sized at the level of the 1960-1980s when they were built. During the period 1960-1980, Romania was a predominantly energy-consuming country, given the industry distributed in each region. During that period, production was ensured by thermogenerators and hydrogenerators, later in 1996, reactor

no. 1 was put into operation and later in 2007 reactor no. 2 at the Cernavoda nuclear power plant. The current requirements for the national energy system are less for consumption and more for the connection of new producers of renewable sources: photovoltaic and wind, but also of storage facilities. Currently, the energy system is overloaded and for the connection of new producers, automatic operational limitation (ALO) are required to avoid overloading the power lines.

The proposed dynamic protection takes into account the protection of the power line at its real transmission capacity, by modifying the tripping threshold of the line circuit breaker depending on the temperature monitored in the conductor area - figure 2.1. [1]

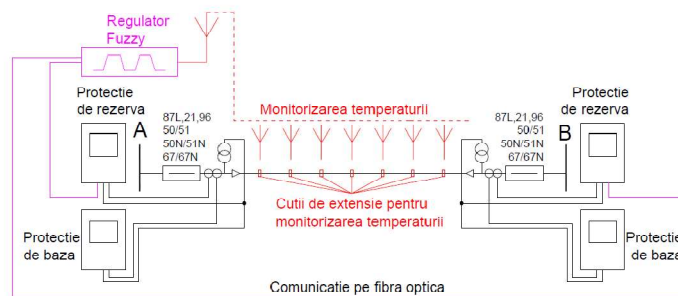


Fig 2. 1. The dynamic overcurrent protection in high voltage networks[1].

The tripping curve will be calculated according to the temperature measured by the system using a simple algorithm for choosing the maximum temperature among the temperatures read instantaneously at different points of the electrical line. This step is essential because the line having a considerable length and being located in different geographical and climatic areas, the highest conductor temperature recorded at a given time must be taken into account.

The frequency of temperature reading should be done four times per hour at 15 minute intervals, and if there are notable temperature differences, it will command the change of the protection setting to align with the temperature around the conductor. The temperature information read from the field will be processed by a central unit that will use Fuzzy logic to set the maximum conductor protection according to the temperature information according to the closed-loop block diagram in figure 2.2[1].

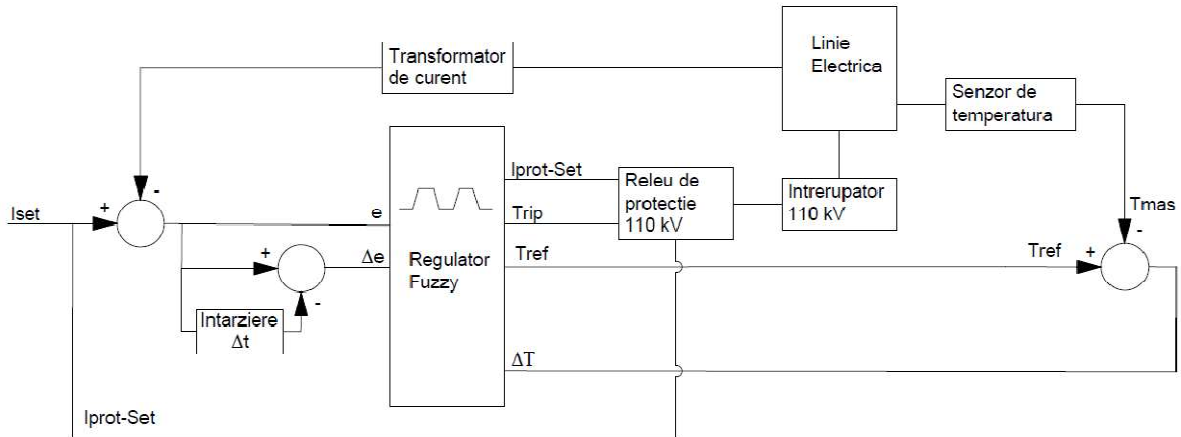


Fig 2. 2. Block diagram for temperature monitoring

The controller will read the conductor temperature and use the maximum of the measured temperatures, the current recorded on the line measured with the help of current transformers and using Fuzzy logic will create the protection tripping curve, but will also set after each iteration a new current protection adjustment threshold in the protection relay. Considering that protection relays have processors, the Fuzzy controller can be included directly in the protection relay through a software upgrade.

To implement the Fuzzy controller will be used:

- Rules defined by the user
- Each rule correspondes to an output partial set
- $e = T_{set} - T_{mas}$ – temperature error
- $\Delta e = e(t) - e(t-1)$ – temperature error variation
- ΔI_{prot} – overcurrent protecton error variation

Fuzzy rules impemented :

- 1.If e is (N)negative and Δe is (N)negative, then ΔI_{prot} is (N)negative.
- 2.If e is (N)negative and Δe is (ZE)zero, then ΔI_{prot} is (N)negative.
- 3.If e is (N)negative and Δe is (P)positive, then ΔI_{prot} is (ZE)zero.
- 4.If e is (ZE)zero and Δe is (N)negative, then ΔI_{prot} is (N)negative.
- 5.If e is (ZE)zero and Δe is (ZE)zero, then ΔI_{prot} is (ZE)zero.
- 6.If e is (ZE)zero and Δe is (P)positive, then ΔI_{prot} is (P)positive.
- 7.If e is (P)positive and Δe is (N)negative, then ΔI_{prot} is (ZE)zero.
- 8.If e is (P)positive and Δe is (ZE)zero, then ΔI_{prot} is (P)positive.
- 9.If e is (P)positive and Δe is (P)positive, then ΔI_{prot} is (P)positive.

Table 2.1 below presents the Fuzzy rules for temperature monitoring and the values that the maximum current protection variation can take, and Figure 2.3 presents the input functions of the Fuzzy controller.

Table 2. 1. – Overcurrent variation ΔI_{prot} with e and Δe

$e \backslash \Delta e$	N	ZE	P
N	N	N	O
ZE	N	O	P
P	O	P	P

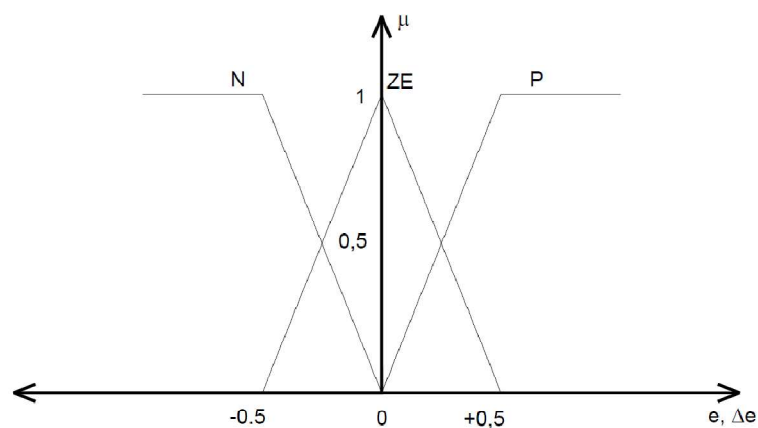


Fig 2. 3. The temperature monitoring Fuzzy System input/output functions

The calculation values for the output function based on which the dynamic protection is calculated have in relative units values between 0 and 1. To calculate the real values, inverse scaling is required, meaning that 0 corresponds to the temperature value of 0°C and 1 corresponds to the temperature of 40°C. The other temperatures will be calculated proportionally.

2.3.2. Maximizing the protection of overhead power lines under the influence of temperature for the OI-Al 185/32 mm² conductor (case study)

A case study is presented below for the OI-Al 185/32 mm² bimetallic conductor, the conductor with which most 110 kV power lines are equipped.

The usual method of protecting power lines against overload is performed with fixed thresholds. The method proposed in this subchapter is a protection terminal that monitors the line on-line and is able to set the power line protection in accordance with the temperature information that is read and processed at a given time.

Thus, the protection threshold if reported in time will become a protection curve similar to the conductor capability curve, but having a smaller amplitude than this. For any temperature between 0°C and 40°C , the maximum value of the current that the ACSR 185/32 mmp conductor can conduct in normal operating mode is calculated using the formula of dependence of the electrical resistance of the conductor and the ambient temperature in which it is installed.

It is proposed to install sensors at each pole of the overhead line, so that the Fuzzy controller acquires temperature values of the different areas through which the electrical line is installed, established in advance between the thresholds of 0°C and 40°C .

For any temperature between 0°C and 40°C , the maximum value of the current that the ACSR 185/32 mmp conductor can conduct in normal operation is calculated.

The temperature monitored on the electrical line will be processed by a Fuzzy controller installed in the end transformer station. The Fuzzy controller will exchange data with the data acquisition unit that reads data from the temperature sensors that will be placed along the electrical line. The Fuzzy controller receives from the temperature monitoring system, at each set time interval, the maximum instantaneous temperature in the conductor area, processes it and transmits to the protection relay the new current threshold corresponding to the measured temperature.

The Fuzzy controller communicates both with the relay in the station where it is mounted, and with the relay at the opposite end using the fiber optic infrastructure. The protection relays receive the new protection setting in current value from the Fuzzy controller and thus the conductor is protected according to the measured temperature.

The communication between the extension box and the Fuzzy controller can be achieved via fiber optic or GPRS technology, thus being able to monitor long lengths of overhead lines.

2.3.2.1. Calculations performed in the case of overcurrent protection with fixed threshold

Following the calculations, the capability graph for the OI-Al 185/32 mm^2 conductor can be seen in Figure 2.4 with a solid line. The dotted line represents the set value of the maximum protection with a fixed threshold.

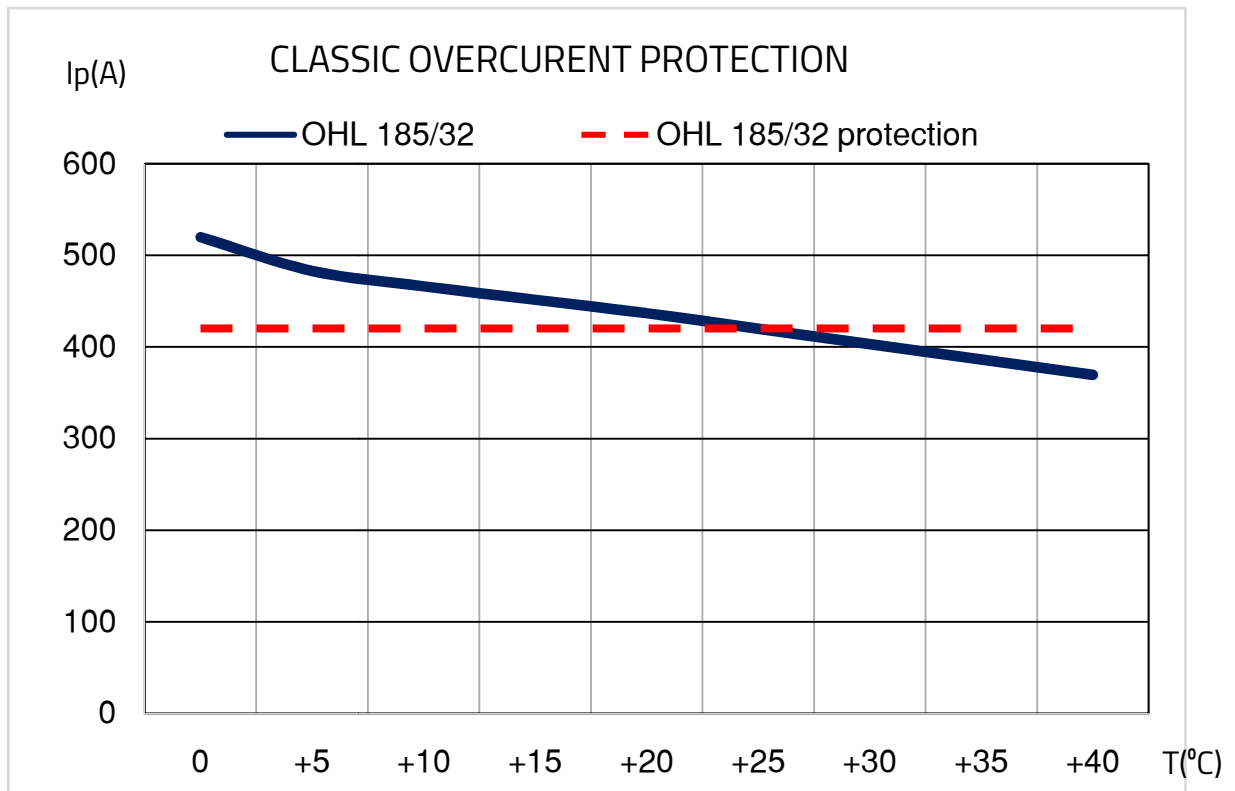


Fig 2. 4. The protection curve for the classic overcurrent protection[1]

This is calculated using conductor catalogs that list the conductors' conduction capacity at a given outdoor temperature. If we look at the tables for the 185/32 mm² ACSR conductor, it can conduct a maximum current of 717A at 20°C. This value is reduced by a coefficient for multiple circuits on the pole, depending on the ambient temperature.

$$I_c = K_1 \cdot K_2 \cdot I_{max} \quad (2.1)$$

$$I_c = 0,56 \cdot I_{max} = 401A \text{ for } 185 \text{ mm}^2 \text{ bimetallic conductor} \quad (2.2)$$

The value of the timed maximum protection is set between 100% and 120% of the calculated current for the conductor.

$$I_p = 1,0 \dots 1,2 \cdot I_c \quad (2.3)$$

$$I_p = 401 \dots 481A \text{ for } 185 \text{ mm}^2 \text{ bimetallic conductor} \quad (2.4)$$

It can be seen that in case of ambient temperature below 25°C, the set value is too low considering the conductor capability.

Also, in the case of ambient temperature above 25°C, the value set for protection exceeds the capability of the conductor.

2.3.2.2. Calculations in the case of maximum current protection with variable threshold depending on temperature

The resistance of the conductor varies with temperature. The parameter that varies with temperature that enters the resistance calculation formula is the resistivity – see relation 2.5.

$$R = \frac{\Delta P}{I^2} = K \cdot \rho \frac{l}{s} [\Omega] \quad (2.5)$$

Where:

- ΔP are the power losses
- I is the conductor current
- K represents the constant for solid conductors or rope conductors, for solid conductors $K=1$, respectively for rope conductors, due to the twist, they have a length greater than the length of the rope by a percentage between 2% and 4% and respectively K can take values between 1.02 and 1.04.
- ρ is the material resistivity

The resistivity of materials varies with temperature according to the formula below:

$$\rho_{\theta} = \rho_{20} \cdot [1 + \alpha(\theta - 20) + \beta(\theta - 20)^2] \quad (2.6)$$

Where:

- α, β are coefficients of variation of resistivity with temperature
 - $\alpha_{Al} = 0,0387 \text{ } ^\circ\text{C}^{-1}$
 - $\beta_{Al} = 1,10 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-2}$
 - $\rho_{Al} = 2,82 \cdot 10^{-8} [\Omega\text{mm}^2/\text{m}]$ for ambient temperature of 20°C
- l is the conductor length
- s is the conductor cross section[6].

The dynamic protection status is achieved by calculating the conductor resistance at any temperature using the above formula for the variation of resistivity with temperature.

Tabel 2. 2. – The conductor ampacity variation with temperature

$\theta(^{\circ}\text{C})$	0	5	10	15	20	25	30	35	40
Fuzzy	0	0,125	0,25	0,375	0,5	0,625	0,75	0,875	1
$I_c(\text{A})$	500	480	465	450	435	420	405	390	375
$I_p(\text{A})$	450	430	415	400	385	370	355	340	325

Following the measurements, the capability graph for the OI-Al 185/32 mm² conductor can be seen in Figure 2.5 with a solid line. The dotted line represents the set value of the

maximum dynamic protection that takes into account the ambient temperature. The protection value can be set 50A below the maximum value that the conductor can carry at a certain time interval depending on the temperature.

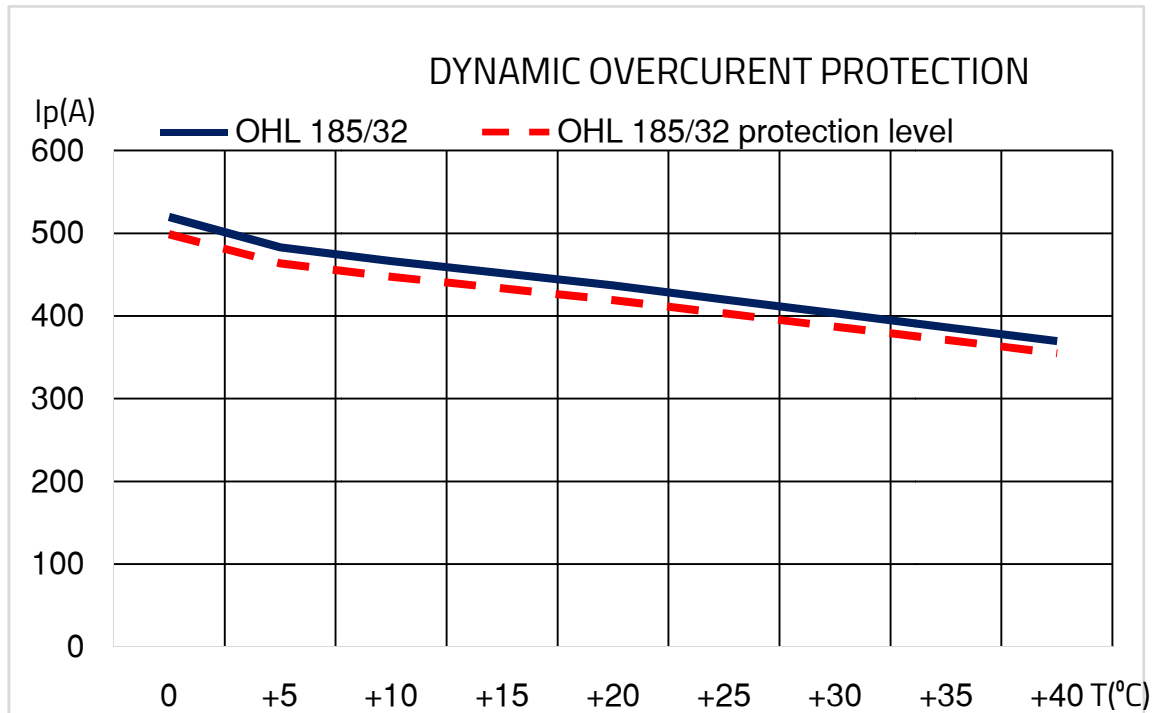


Fig 2. 5. The protection curve for the dynamic overcurrent protection[1]

It can be seen that throughout the temperature range, the protection set value is below the maximum that the conductor can conduct. In this way, the capacity of the electrical line will be used with maximum efficiency.

2.3.3. Overhead powerlines pole integrity monitoring system

By analyzing the current solutions for protecting electrical networks against potential risks, solutions can be identified that help to improve the risks identified in subchapter 2.1.2.

The adverse effects of phenomena occurring on electrical lines can be reduced by measuring the verticality of the poles and the angle of deviation at the top from the vertical.

A normalized deviation from the vertical, which can be concluded that the position of the pole is incompatible with the normal operation of the electrical line, can be measured and transmitted in less than a second to the protection equipment located in the end stations, so that it can command the tripping of the electrical line before the pole and implicitly the wires fall to the ground. This system reduces the risk in the event of accidents and vandalism, especially for people and animals in the affected area[2,12].

Figure 2.6 shows the block diagram of the system for monitoring electrical line poles against vandalism and accidents. The data transmission infrastructure will be fiber optic, but for

wireless data transmission, an opportunity to transmit via ultrasound was analyzed, with energy being obtained from the power line through induction.

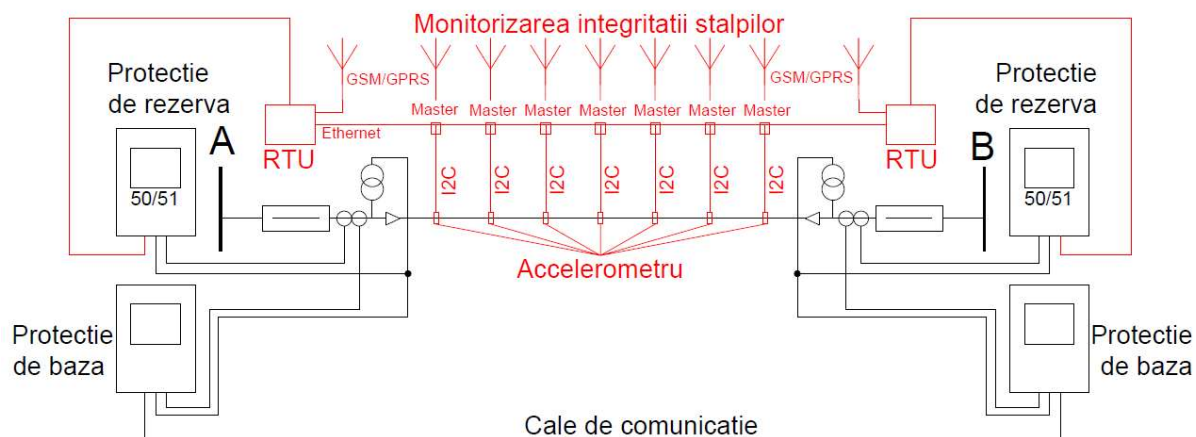


Fig 2. 6. Block diagram for pole integrity monitoring system[2]

The proposed system, which incorporates an accelerometer, will detect a displacement of the pole's posture greater than 5° from the vertical position in a short time interval and will command the tripping of the power line if movement is detected.

In this way, a fall of a pole can be detected as a result of acts of vandalism or accidents as long as the detection device is not affected in the early phase and the line can be tripped so that there are no victims as a result of the live wires touching the ground through the step voltage.

Compared to a normal situation that does not use this system, loss of human life can be avoided, as those in the vicinity of the fallen pole are protected. At the same time, the homopolar protection of the line that would trigger in the event of the live wires touching the ground, would be doubled by a protection that detects the displacement at the top of the supporting poles of the power line.

The operation of this new proposed system eliminates the small but significant probability that the homopolar protection will not work and the line conductor will be affected as a result of the short-circuit current passing through it, a current accepted for a very short time. Figure 2.7, 2.8 shows a comparison of the system currently in use and the proposed system. The difference between the fault detection time of the proposed system and the fault detection time for the existing protection system is a few seconds, during which some people in danger can be saved by the new proposed system.

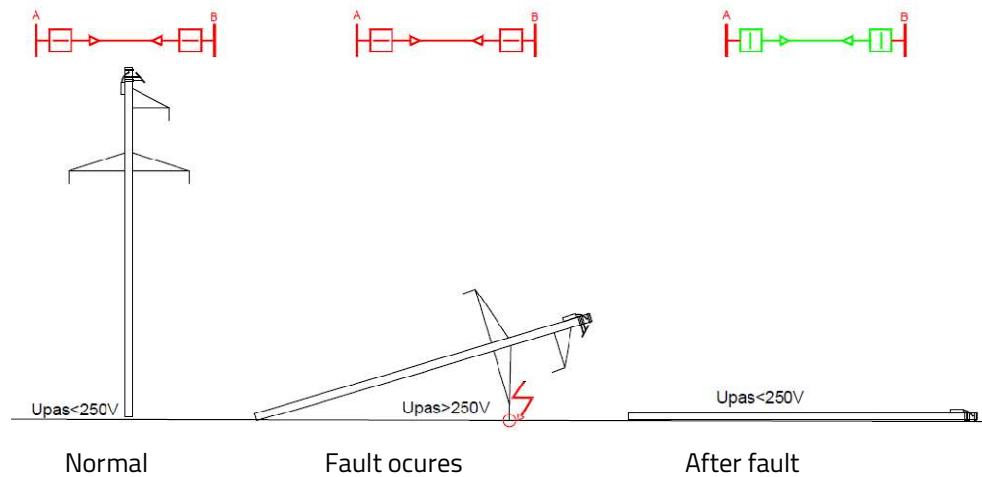


Fig 2. 7. The existing system for fault detection

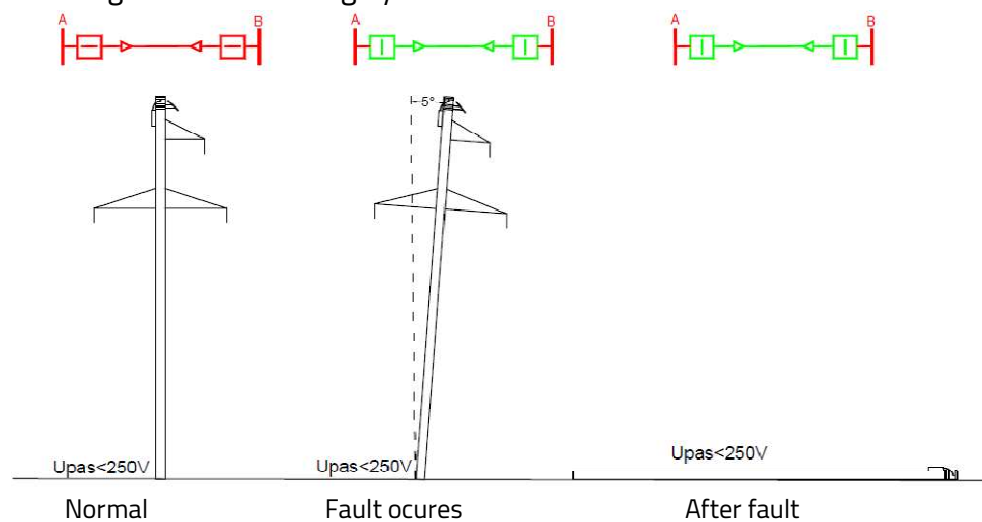


Fig 2.8. The proposed system for fault detection[2]

2.3.3.2 The power supply for pole integrity detection monitoring system with PV panels

The system for detecting the tilt or breakage of the poles, being made with electronic circuits, needs an electrical power supply. Each pole of the overhead lines for which monitoring will be provided must be equipped with equipment that detects the tilt or breakage of the poles by means of the technique of measuring the acceleration at the top. The electrical power required for the electronic circuits of each pole is not significant, being of the order of tens of watts. Photovoltaic panel systems with storage can be used to power the system. These systems are marketed by several manufacturers, being used to power the night beaconing of the poles.

In Romania, the photovoltaic panel power supply system is produced by the Electromax company and can be successfully used to power the system proposed in this chapter. The power supply voltage will be 12V DC, a 120 W source with a 130Ah battery[12], being

sufficient to power the electronic circuits of the pole tilt detection system. The power supply system is shown in figure 2.9.

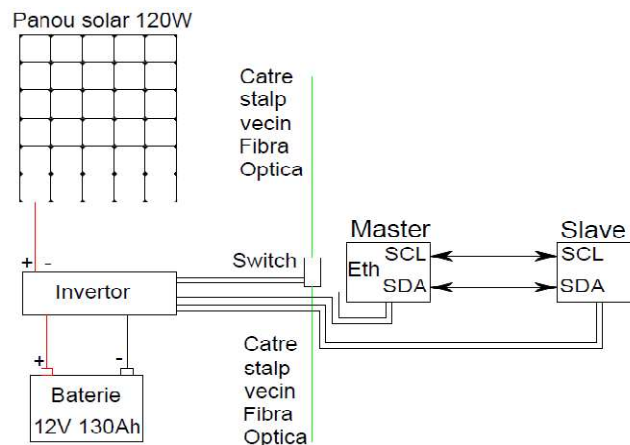


Fig 2. 9. Tilt monitoring power supply with PV panels

2.3.3.3 The power supply for pole integrity detection monitoring system with energy from the power line

The principle diagram of this system is presented in figure 2.10 where the energy captured from the distribution network using a toroidal transformer is used to ensure the functionality of the pole tilt detection system. The system uses the energy produced from the distribution network through the phenomenon of electromagnetic induction. The voltage in the secondary of the toroidal transformer varies depending on the load on the overhead distribution line between 5 and 10V. The signal can be finely transformed and rectified so that it can be used by an oscillator (e.g. MPU-6050), commonly used in the construction of mobile phones which has an operating voltage of 3.3-5V and which can be successfully used in the pole tilt detection system. The diagram in fig. 2.10 must be implemented for each pole that is to be monitored.

The transmission to the end station that supplies the line for the triggering command will be done by radio using the ultrashort wave band with modulation in the frequency of 87.8 - 108 MHz or GSM / GPRS using a card for each monitored point.

For the autonomy of the system in the absence of voltage on the electrical line, a 3.7V 5000 mAh battery is provided.

The system thus composed is an innovative and cheap system from the point of view of implementation, and by installing it in the electrical distribution networks it brings added value by protecting the distribution network, but especially the people in the area of the poles in case of tilting of the poles in short periods of time.

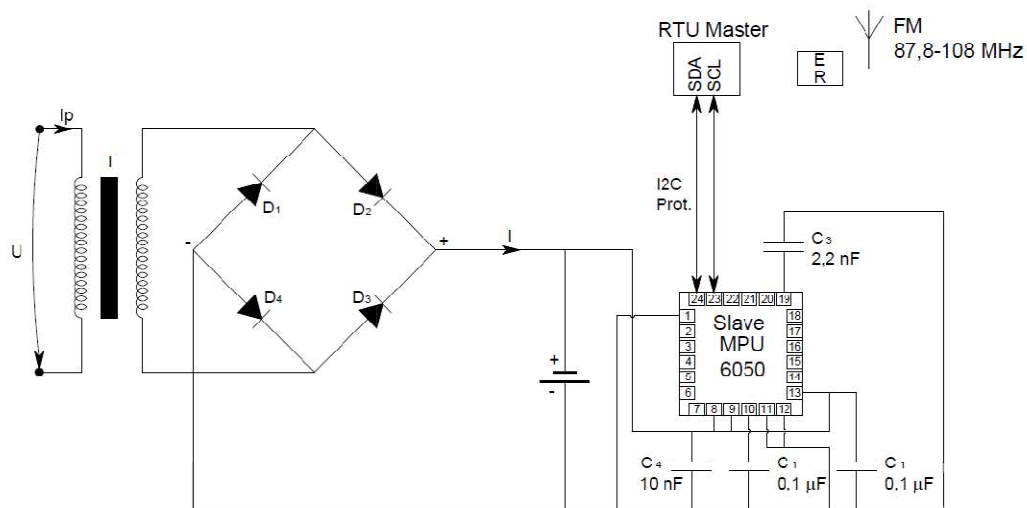


Fig 2. 10. Tilt monitoring power supply with energy from the line

2.4. Conclusion

The overcurrent protection is present in electrical networks, at all voltage levels. Its set values protect electrical lines both in case of overload and in case of short circuits.

It is the protection that triggers first if the current recorded on the line exceeds the value calculated as a threshold.

Advantages of using dynamic maximum protection compared to classic overcurrent protection in the current solution using a fixed threshold:

- Real-time protection of the electrical line according to the capability curve
- Ensures the maintenance of lines that under certain given conditions would be triggered by setting a fixed threshold, thereby avoiding the interruption of some consumers/producers.
- Rapid identification of line defects considering the detection of the maximum temperature on the electrical line.
- Avoids overloading the conductor at high temperatures by protecting it proportionally to the capability curve.
- Avoiding the start of re-conduction works or the construction of new power lines by using the maximum conduction capacity of existing lines.

The operating services within the distribution operators express their concern regarding the concrete supporting poles of the 110 kV overhead lines built between 1950 and 1980. The concrete from which these poles are built begins to deteriorate with the passage of time, weakening the resistance of the pole and in the case of certain limit conditions: maximum wind, simultaneous wind with frost deposits can constitute sources of damage by breaking

them. These constructions are at the end of their lifespan, but must be permanently monitored until the necessary funds are available to replace them.

With the connection requirements of renewable energy producers, additional loads appear on the poles of these electrical networks due to the demands for installing fiber optics for the communication of the power plant with the dispatch centers and for the implementation of longitudinal differential protection on the electrical distribution lines, a current requirement for electrical lines shorter than 20 km.

The fiber optic conductor can replace the protective conductor mounted on the tops of the poles or can be mounted in the middle of the pole, under the lower console.

The above hypotheses gave rise to the author's idea of monitoring the poles of electrical networks by installing an accelerometer system, which in the case of early detection of a change in the position of the pole as a result of violent impacts or the aging of the material from which it is made, ensures the transmission of the tripping command to the line end switches.

In the risk analysis carried out, three risks were identified, which, if they occur, bring about loss of human life and destruction of the network. This chapter dealt with innovative solutions to minimize the risks identified using automation techniques.

In this way, the risks that act on people and animals in the vicinity of the faulty pole are avoided and the line tripping is no longer produced by homopolar protection (detection of contact with the ground of the energized conductor), but is produced more quickly by the new type of protection that uses the accelerometer and that trips the line before it touches the ground. In the case of a line in operation, when a pole falls and the energized conductors touch the ground, a step voltage peak is produced that can affect life in the surrounding area until the electrical fault current disperses into the ground.

The transmission of the tripping impulse in the analyzed system can be done through the fiber optic system, radio waves or GSM/GPRS. The energy required for the system to operate was analyzed in two variants: by direct current supply from a battery charged by photovoltaic panels or from a battery charged from the mains current.

By implementing the proposed system, the risks identified in the risk analysis are reduced to an acceptable level, without affecting life at the site of the defect.

Advantages of using the pole tilt detection system:

- Prevents accidents resulting in death or injury in the event of a defect
- Identification of any change in the pole tilt, offering the possibility of preventive maintenance action.
- Ensures cost reduction by monitoring poles, eliminating the need to replace them – especially concrete poles on high-voltage lines.
- It constitutes a precedent and a basis for future developments in the physical monitoring of overhead power lines with minimal costs.

3. IMPROVING THE EFFICIENCY OF DEFECT DETECTION SYSTEMS FOR ELECTRICAL POWER DISTRIBUTION CABLES

3.3. Contributions to improving the efficiency of electrical cable fault detection systems

Electrical cable networks are gaining ground at the expense of overhead power lines in Romania and worldwide, given the massive urbanization and population migration from villages to cities. Thus, large cities are becoming metropolises with crowded buildings where the need for underground networks is a necessity due to the narrow space left free between buildings, space that electrical networks must share with the rest of the utilities: water, gas, sewage, internet, lighting, etc.

Cable monitoring systems can be improved by creating fiber optic networks in parallel with the electrical cables to constitute the communication infrastructure between the sensors mounted on the electrical cable, including at voltages lower than 110 kV, especially if the cable section is very important: for example, the connection of a hospital, the medium voltage connection between two electrical stations, the supply of a fire station, etc.

The author's proposal is to divide the cable section into smaller sections that can be monitored individually and bring more information from the field to operational personnel who, in the event of a defect, can narrow the search area, quickly identify and repair the defect, and resume the electricity supply as soon as possible, information detailed in detail in subchapters 3.3.1 and 3.3.2.

3.3.1. Method for detecting electrical cable faults with inductive current sensors

Section monitoring is an idea that provides for monitoring the homopolar current on the cable under study at several points. Having several measurements made at the same time, in the event of a fault, they can be analyzed and, depending on the level of the homopolar current, the protection relay in the end station can estimate the length from the relay where the fault occurred.

The technology of the sensors placed on the electric cable will be inductive, they can measure the current on the cable by electromagnetic induction. There are inductive sensors with direct transmission of information via optical fiber – figure 3.1.

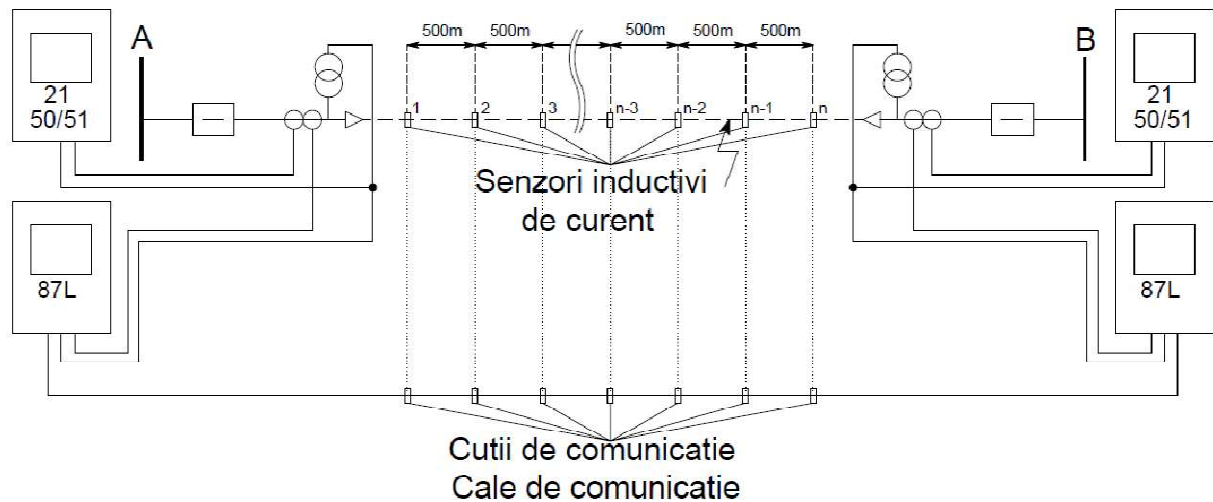


Fig 3. 1. Power cables monitoring system with inductive sensors

Each system that will monitor the cable will use a pair of optical fibers, so that in the transformer station from which the cable is powered, information will be collected from each monitored point of the electrical cable according to figure 3.1.

The monitored point that indicates the highest current will indicate the closest location to the fault. The monitoring points can be installed at 500m or 1000m depending on the needs and budget. The optical fiber pairs through which the electrical cable is monitored are different from the optical fiber pair on which the communication for the differential protection on the cable is carried out, if it is implemented.

3.3.2. Method for detecting faults in electrical cables with induction-powered loops

This monitoring system analyzes the information acquired from the sections, but the information transmission is carried out using an induction loop for each cable section. The information is converted for transmission on the fiber optic infrastructure with the help of LEDs that are powered by the voltage induced in the power conductor, by mounting this system at distances of about 0.5-1km along the cable route, the information being centralized in the station that feeds the electric cable.

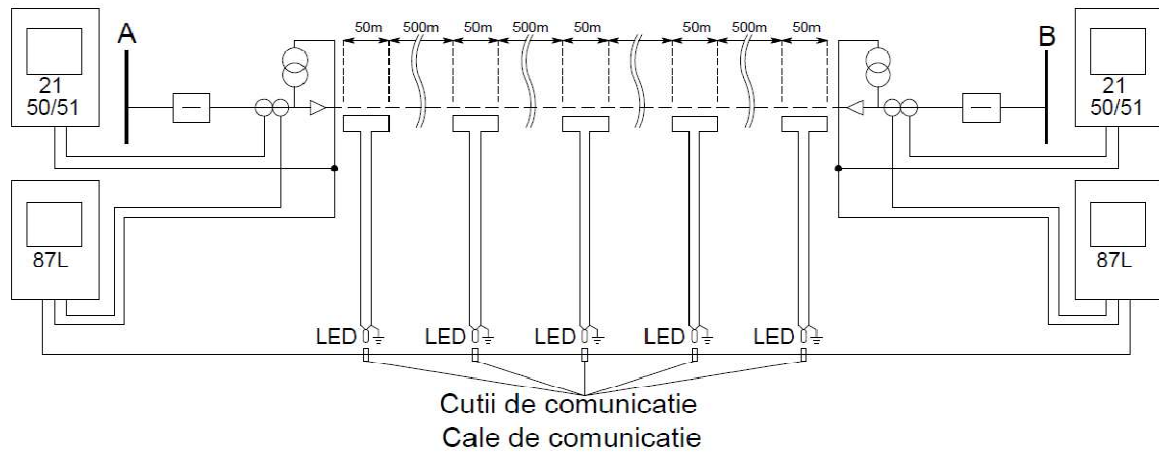


Fig 3. 2. Power cables monitoring with induction loops

The schematic diagram of this system is presented in Figure 3.10 where you can see the induction loops that are placed parallel to the electric cable over a distance of 50 m. According to specialized regulations, the current induced by the electric cable on a telecommunications cable is calculated with the following formula[20].

$$E = Z_c \cdot L \cdot K_c \cdot K_i \cdot I_c [V] \quad (3.13)$$

Where:

Z_c – is the mutual impedance between the power cable and the pilot cable – cca 250 mΩ/km.

L – the length for the parallel disposal. It has been considered 50 m.

K_c – reduction factor for power cable. Usual is used 1.

K_i – reduction factor for pilot cable. Usual is used 1.

I_c – the current in the power cable – between 0 and 250A.

The electromotive voltage induced in the signaling cable is directly proportional to the current flowing through the electrical cable. The mutual impedance was calculated based on the soil resistivity and the distance between the two cables according to SR 832/2008. The induced voltage is an alternating voltage, so in order to be able to signal with the LED on the fiber optic channel, it must be rectified according to the diagram in figure 3.3.

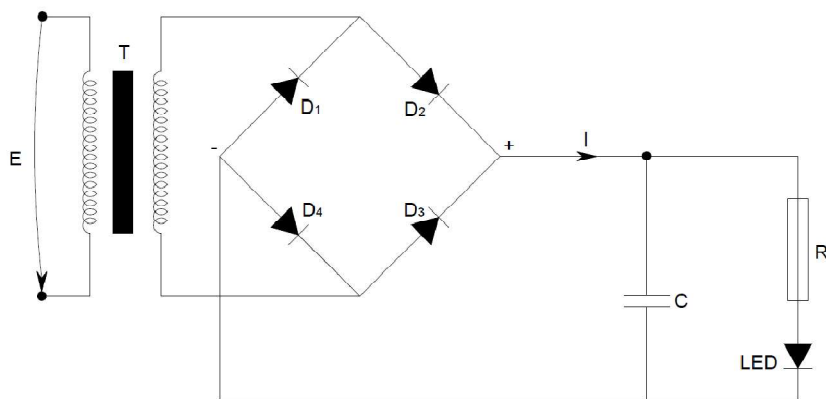


Fig 3. 3. The signaling diagram for overcurrent detection

At the fault location, the short-circuit current will have values of the order of thousands of amperes. The value of the single-phase and two-phase short-circuit current to earth are known to the operator of the electric cable. For example, for 6 kA, the induced voltage is 75 V. Thus, the value of the transformer and the resistor can be calculated so that the voltage applied to the LED is around 3V and can signal to the end station the existence of a fault on the monitored cable route.

3.4. Conclusion

Cables are increasingly gaining ground to replace overhead distribution networks in large cities to the detriment of overhead lines, which in congested areas can become a real danger and have a much larger safety zone[21].

They have advantages due to the small space occupied in the field and the small safety zone imposed for their protection, but they also have disadvantages due to the higher capacitive current than an overhead line introduced into the network, the lower conduction capacity at the same section and the more difficult detection of defects.

Cables are usually installed in areas with congested utility networks and must be monitored to be detected by subsequent investments after their installation.

For cable networks, there are route monitoring systems with electronic markers, also presented in this documentation. There are defectoscopy systems that detect the step voltage at the ground surface level in the area where the defect occurred, but it is necessary to power the defect, which creates the possibility of the defect expanding or affecting the functional phases.

This documentation proposes the creation of easier detection systems for defects in electrical cables, from the moment of production, transmitting information to the control room to help operational personnel narrow down the area to search for the defect. In order to reduce the risk of defects on cables due to weakened insulation or damage to the outer sheath during installation, it is recommended to perform preventive maintenance on electrical cables, through annual testing according to specialized regulations.

4. IMPROVING AUTOMATION SYSTEMS IN TRANSFORMER STATIONS

4.3. Making automation more efficient in electrical transformer stations

4.3.1. C++ application for verifying the possibility for parallel operation of transformers

Following the presentation in subchapters 4.3.1.1. and 4.3.1.2., table no. 4.1 can be drawn up, which summarizes the characteristics and consequences of paralleling transformers

depending on the differences between the nominal parameters: apparent power, transformation ratio and short-circuit voltage.[26]

Tabel 4. 1 – Parallel operation of transformers

Parallel operation		Result			Parallel operation Decision
		Equal load	Overloads	Equalizing current	
$K_{Ta} = K_{Tb}$ $u_{sca} = u_{sca}$	$S_a = S_b$	Yes	No	No	Yes
	$S_a \neq S_b$	No	No	No	Yes
$K_{Ta} = K_{Tb}$ $u_{sca} \neq u_{sca}$	$S_a = S_b$	Yes	Yes	No	Yes
	$S_a \neq S_b$	Yes	Yes	No	Yes
$K_{Ta} \neq K_{Tb}$ $u_{sca} \neq u_{sca}$	$S_a = S_b$	Yes	Yes	Yes	No
	$S_a \neq S_b$	Yes	Yes	Yes	No

Using the data in table no. 4.1, a program can be created in the C++ programming language that checks the conditions for paralleling transformers and returns a conclusion immediately after entering the input data of the transformers.

4.3.2. Method for detecting faults in medium-voltage electrical networks using Fuzzy techniques

The expert system that will use Fuzzy logic, as artificial intelligence for the detection of ground faults on the bars of a transformer station, consists of several sets of rules and variables for different quantities that intervene in the operation of an electrical line - presented in table no. 4.2. The current variables must be defined for each line separately.

Tabel 4. 2 – The inputs/outputs for Fuzzy System

Rules	Input variables								Output variables
	I_1	I_2	I_3	I_0	V_1	V_2	V_3	V_0	State
1.	N	N	N	N	N	N	N	N	FN
2.	H	N	N	H	L	H	H	H	L1-G
3.	N	H	N	H	H	L	H	H	L2-G
4.	N	N	H	H	H	H	L	H	L3-G
5.	H	H	N	H	L	L	H	H	L1,2-G
6.	H	N	H	H	L	H	L	H	L1,3-G
7.	N	H	H	H	H	L	L	H	L2,3-G
8.	H	H	N	H	L	L	N	H	L1,2
9.	H	N	H	H	L	N	L	H	L1,3
10.	N	H	H	H	N	L	L	H	L2,3
11.	H	H	H	H	L	L	L	L	L1,2,3

Unde N – Normal

L – Low

H – High

I_1 – Phase L1 current

I_2 – Phase L2 current

I_3 – Phase L3 current

I_0 – Homopolar current

V_1 – Line voltage L1

V_2 – Line voltage L2

V_3 – Line voltage L3

V_0 – Homopolar voltage

FN – Normal functioning

L1 – G – Phase L1 to ground

L2 – G – Phase L2 to ground

L3 – G – Phase L3 to ground

L1,2 – G – Phases L1,L2 to ground

L1,3 – G – Phases L1,L3 to ground

L2,3 – G – Phases L2,L3 to ground

L1,2 – Phases L1 to L2 fault

L1,3 – Phases L1 to L3 fault

L2,3 – Phases L2 to L3 fault

L1,2,3 – Triphasic fault

The definition of the membership functions will be determined for each variable separately. It will be defined using the Mamdani system for both input and output variables. The input variables are the current on each phase, the homopolar current, the line voltages and the homopolar voltage. For all these inputs, three levels of approximation are defined.[29,30]

L – Low – $[-0,5 \ 0 \ 0,5]$

N – Normal – $[0 \ 0,5 \ 1]$

H – High – $[0,5 \ 1 \ 1,5]$

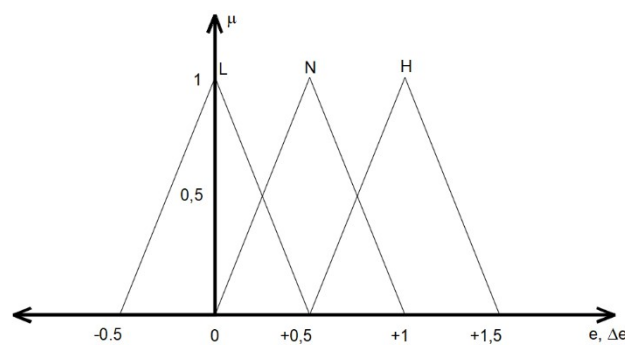


Fig 4. 1. Input variations for Fuzzy System

The output variables are the types of faults of the electrical line for which the following intervals are defined for the membership functions and according to figure no. 4.2:

L1-G – Phase L1 to ground $[-0,125 \ 0 \ 0,125]$

L2-G – Phase L2 to ground $[0 \ 0,125 \ 0,25]$

L3-G – Phase L3 to ground $[0,125 \ 0,25 \ 0,375]$

L1,2-G – Phases L1,L2 to ground [0,25 0,375 0,5]
 L1,3-G – Phases L1,L3 to ground [0,375 0,5 0,625]
 L2,3-G – Phases L2,L3 to ground [0,5 0,625 0,75]
 L1,2 – Phase L1 to L2 fault [0,625 0,75 0,875]
 L1,3 – Phase L1 to L3 fault [0,75 0,875 1]
 L2,3 – Phase L2 to L3 fault [0,875 1 1,125]
 L1,2,3 – Threephase fault [1 1,125 1,25]

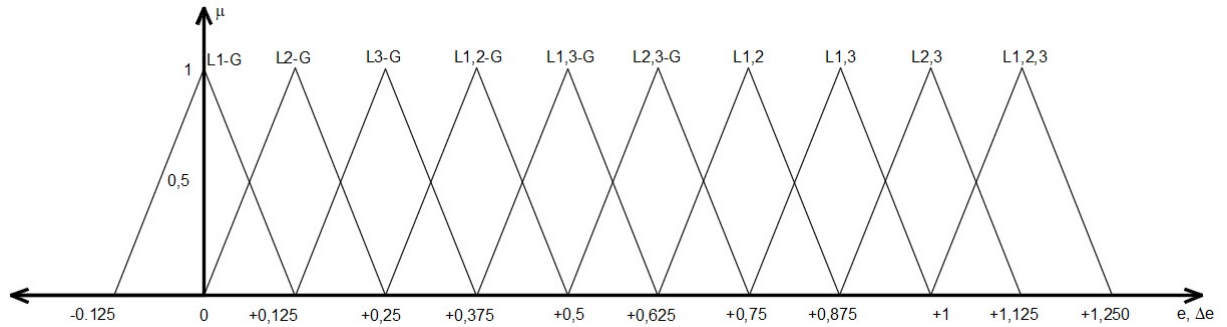


Fig 4. 2. Output variation for the Fuzzy System

The proposed system for detecting ground faults in electrical distribution networks was successfully simulated in the Matlab/Simulink program using the block diagram in figure 4.3. [27].

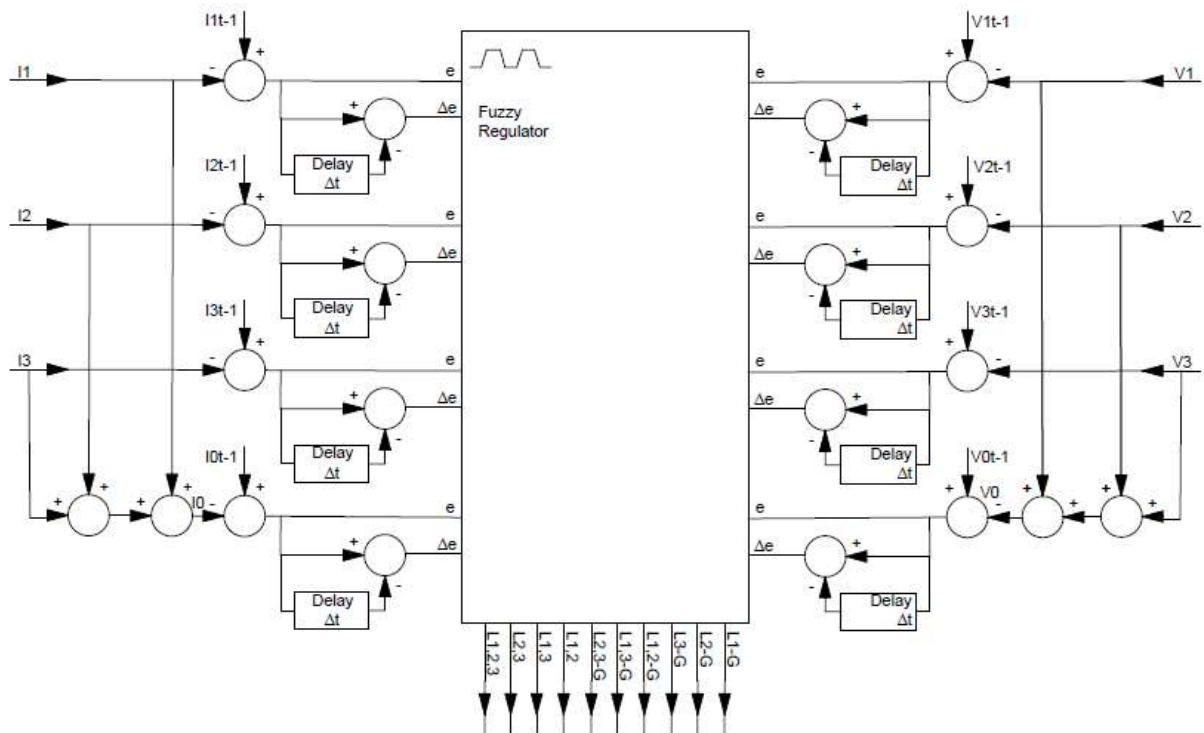


Fig 4. 3. Block diagram for Earth fault detection Fuzzy System

From the Simulink library, Fuzzy Logic Toolbox and Fuzzy Logic Controller were used, and to design the ground fault detection system using Fuzzy logic for a distribution line, the Matlab Fuzzy Logic Design App application was used (fig.4.4).[28]

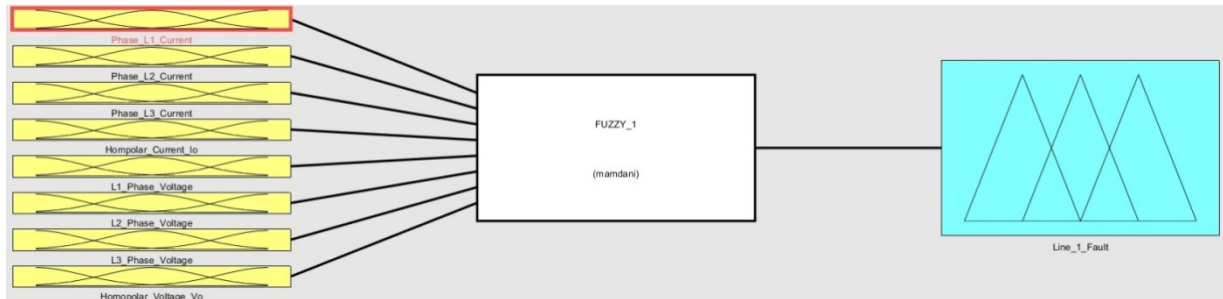


Fig 4. 4. Fuzzy App implementation for the Fuzzy System

8 input functions corresponding to currents, voltages, current and homopolar voltage were declared. For the input values, rules were created for the Fuzzy system to activate the output functions that are represented by the type of fault identified.

The rules implemented in the case of system simulation in the Simulink program for an electric line are the following:

1. *If I_1 is „H” and I_2 is „N” and I_3 is „N” and I_0 is „H” and V_1 is „L” and V_2 is „H” and V_3 is „H” and V_0 is „H” then the fault is L1-G.*
2. *If I_1 is „N” and I_2 is „H” and I_3 is „N” and I_0 is „H” and V_1 is „H” and V_2 is „L” and V_3 is „H” and V_0 is „H” then the fault is L2-G.*
3. *If I_1 is „N” and I_2 is „N” and I_3 is „H” and I_0 is „H” and V_1 is „H” and V_2 is „H” and V_3 is „L” and V_0 is „H” then the fault is L3-G.*
4. *If I_1 is „H” and I_2 is „H” and I_3 is „N” and I_0 is „H” and V_1 is „L” and V_2 is „L” and V_3 is „H” and V_0 is „H” then the fault is L1,2-G.*
5. *If I_1 is „H” and I_2 is „N” and I_3 is „H” and I_0 is „H” and V_1 is „L” and V_2 is „H” and V_3 is „L” and V_0 is „H” then the fault is L1,3-G.*
6. *If I_1 is „N” and I_2 is „H” and I_3 is „H” and I_0 is „H” and V_1 is „H” and V_2 is „L” and V_3 is „L” and V_0 is „H” then the fault is L2,3-G.*
7. *If I_1 is „H” and I_2 is „H” and I_3 is „N” and I_0 is „H” and V_1 is „L” and V_2 is „L” and V_3 is „N” and V_0 is „H” then the fault is L1,2.*
8. *If I_1 is „H” and I_2 is „N” and I_3 is „H” and I_0 is „H” and V_1 is „L” and V_2 is „N” and V_3 is „L” and V_0 is „H” then the fault is L1,3.*
9. *If I_1 is „N” and I_2 is „H” and I_3 is „H” and I_0 is „H” and V_1 is „N” and V_2 is „L” and V_3 is „L” and V_0 is „H” then the fault is L2,3.*
10. *If I_1 is „H” and I_2 is „H” and I_3 is „H” and I_0 is „H” and V_1 is „L” and V_2 is „L” and V_3 is „L” and V_0 is „L” then the fault is L1,2,3.*

In the event of a fault on the medium voltage bus of the power station, the Fuzzy system can analyze the currents and voltages on each line, identifying the faulty line in a very short time. From the set of rules detailed above and applied in the Simulink calculation program in all the scenarios presented in table no. 4.2, the results being successful, the identification result for a single-phase fault (rule 2) on a line on the median phase is presented in figure 4.5[27,28].

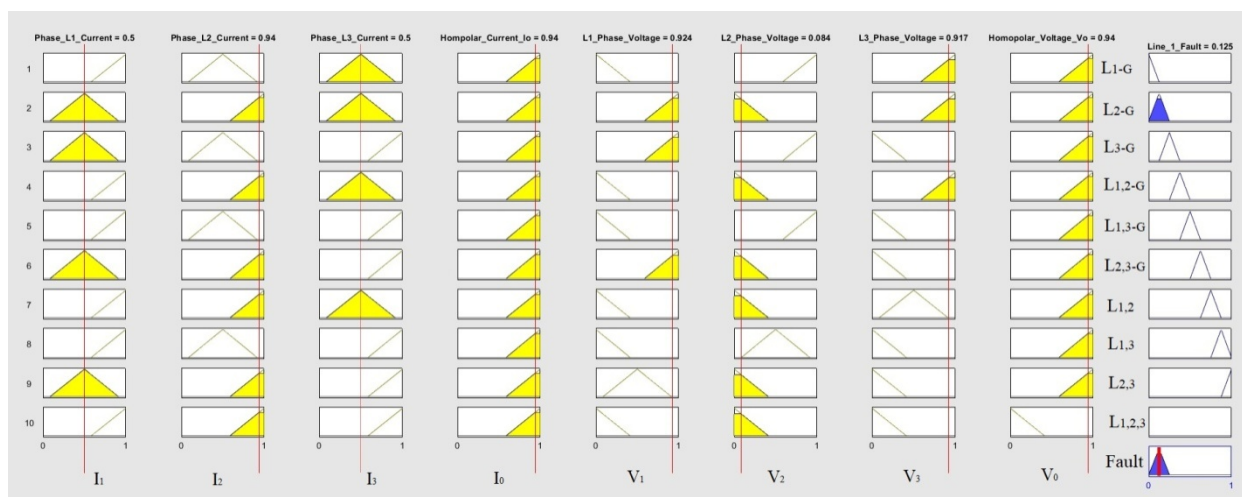


Fig 4. 5. Simulation results for L2 to ground fault

4.4. Conclusion

The admittance and current injection method for detecting ground faults in medium voltage networks treated with an extinguishing coil has very good results when the current and voltage measurements are made accurately.

If the measurements are inaccurate, the system will not work, because in the case of a large error due to the small ground fault current in electrical networks treated with an extinguishing coil. An example of an inaccurate measurement can be recorded with a Holmgreen filter having a high nominal current in relation to the fault current, in other words, an incorrectly sized homopolar transformer.

The Fuzzy system does not have this drawback, because the detection is performed in several steps by approximating the input values, so the detection is done accurately, without allowing erroneous trips.

Intelligent Fuzzy systems can be successfully used in this case with superior results to the classic detection method (the admittance and current injection method), because, by using ambiguous values measured by small, large, medium approximations for the voltages and currents in the system, decisions similar to those of a human operator who is present in the station in the event of a fault can be made, but in a much shorter time.

5. VOLTAGE STABILITY IN POWER DISTRIBUTION NETWORKS

5.3. Contributions through automation for power distribution networks stability

Analyzing in the previous subchapter how the voltage stability in the nodes of an electrical network is determined and the need to regulate the voltage in the nodes to maintain the stable state of the electrical network, in this subchapter the author wishes to contribute to the regulation of the voltage in the nodes using control loops and the study of the voltage stability in a distribution network to which producers have been connected through a case study.

5.3.1. Method for power and voltage regulation in power distribution networks

The automatic voltage and power regulation system in electricity distribution networks will use Fuzzy logic to control a generator mounted at a point in the network to generate or absorb active or reactive power.

The control block diagram implemented in the Simulink program is shown below in Fig. 5.1 and represents in principle the regulation mode of voltage and reactive power in the network.

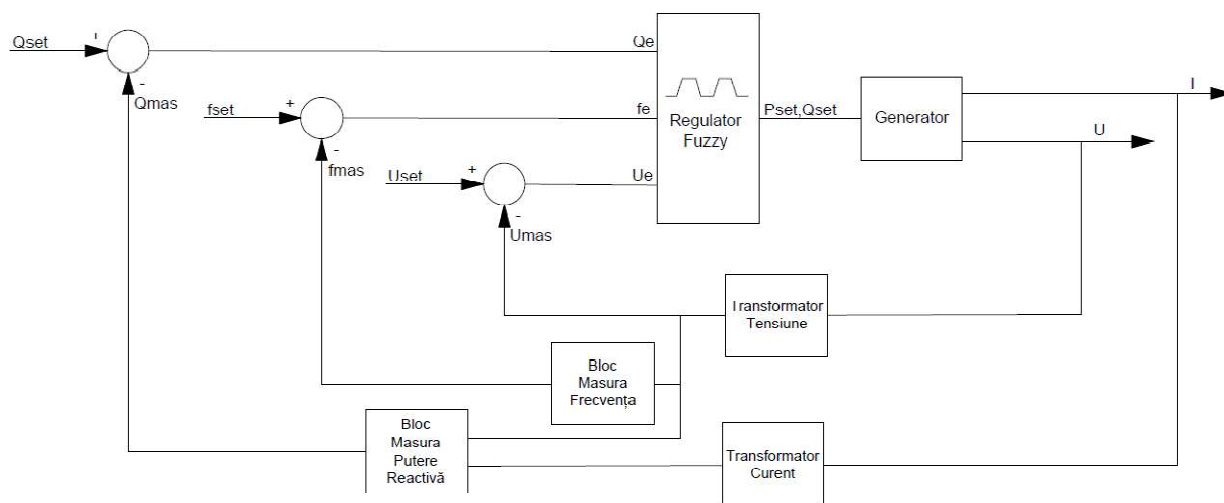


Fig 5. 1. Block diagram for power and voltage regulation with Fuzzy

The voltage regulator uses Fuzzy logic to maintain the voltage value around a value set by the operator (setpoint) based on measured values from the energy system, from the node where it will be installed.

In the Fuzzy system, input variables can take values between 0 and 1 and, based on the rules created, the output values can be determined using approximations of the input values.

For each input, 3 levels have been set: "L" - Low, "N" - Normal, "H" - High in order to be able to approximate them and to be able to apply the rules highlighted in the table below.

Tabel 5. 1 – Fuzzy rules for power and voltage regulation

Rules	Input variables			States – Output variables
	f	Q	U	
1.	L	L	L	Active power injection (P) and reactive power injection (Qcap)
2.	L	L	N	Active power injection (P)
3.	L	L	H	Active power injection (P) and reactive absorbtion (Qind)
4.	L	N	L	Active power injection (P) and reactive power injection (Qcap)
5.	L	N	N	Active power injection (P)
6.	L	N	H	Active power injection (P) and reactive absorbtion (Qind)
7.	L	H	L	Active power injection (P) and reactive injection (Qcap)
8.	L	H	N	Active power injection (P)
9.	L	H	H	Active power injection (P) and reactive absorbtion (Qind)
10.	N	L	L	Reactive power injection (Qcap)
11.	N	L	N	Normal functioning
12.	N	L	H	Reactive power absorbtion (Qind)
13.	N	N	L	Reactive power injection (Qcap)
14.	N	N	N	Normal functioning
15.	N	N	H	Reactive power absorbtion (Qind)
16.	N	H	L	Reactive power injection (Qcap)
17.	N	H	N	Normal functioning
18.	N	H	H	Reactive power absorbtion (Qind)
19.	H	L	L	Active power absorbtion (P) and reactive injection (Qcap)
20.	H	L	N	Active power absorbtion (P)
21.	H	L	H	Active power absorbtion (P) and reactive absorbtion (Qind)
22.	H	N	L	Active power absorbtion (P) and reactive injection (Qcap)
23.	H	N	N	Active power absorbtion (P)
24.	H	N	H	Active power absorbtion (P) and reactive absorbtion (Qind)
25.	H	H	L	Active power absorbtion (P) and reactive injection (Qcap)
26.	H	H	N	Active power absorbtion (P)
27.	H	H	H	Active power absorbtion (P) and reactive absorbtion (Qind)

The definition of the membership functions will be determined for each variable separately. It will be defined using the Mamdani system for both input and output variables. The input variables are frequency, reactive power and voltage. For all these input variables, three levels of approximation are defined.[29,30]

L – Low – $[-0,5 \ 0 \ 0,5]$

N – Normal – $[0 \ 0,5 \ 1]$

H – High – $[0,5 \ 1 \ 1,5]$

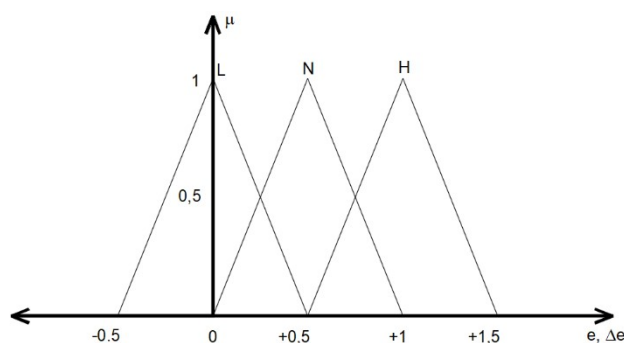


Fig 5. 2. Input variables for Fuzzy System

The output variables are the commands for increasing/decreasing active power, respectively increasing/decreasing reactive power, for which the following intervals are defined for the membership functions and according to figure 5.3:

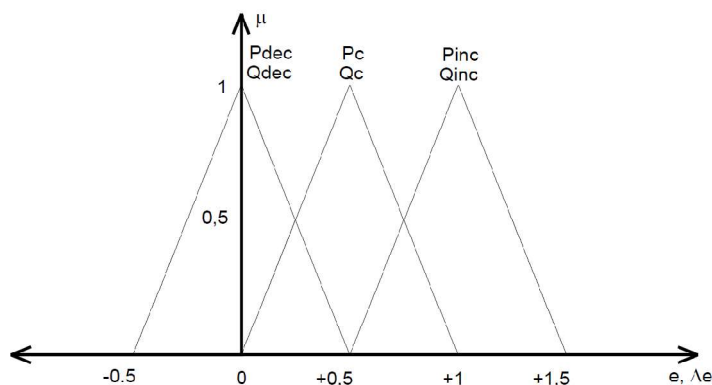


Fig 5. 3. Output variables for Fuzzy System

5.3.2. Application for checking voltage stability in electrical distribution networks when connecting renewable production sources (case study)

The network chosen for this case study is an electrical distribution network in the Braşov area of an industrial park. It is composed of 10 20/0.4 kV transformer stations with powers between 1000 and 1600 kVA according to the scheme in fig. 5.4. The power supply of the power network is carried out through a looped network with radial operation from two 110/20 kV transformer stations.

For a distribution operator, who manages this network and is obliged by the energy law no. 123/2012 to grant access to users (producers or consumers) to the distribution network, it is important to know the network and its distribution capacity as well as the stability of the network voltage in order not to give access to users whose operation can bring the network to collapse[52].

Three scenarios were analyzed, the existing situation under conditions of minimum consumption, one in which the consumption demand is maximum and the second in which there is demand for maximum production as a result of the installation of renewable energy sources.



Tabel 5. 2– Installed power in transformers

Nr.	Node	Installed P	Nr.	Node	Installed P
crt.	Name	kVA	crt.	Name	kVA
1	PT1 	1x1600	8	PT6 	1x1250
2	PT2 	1x1600	9	PT7 	1x1000
3	PT3 	1x1600	10	PT8 	2x1000
4	PT4 	1x1600	11	PT9 	1x1000
5	PT5 	1x1600	12	PT10 	1x1250

This scenario corresponds to a hypothetical situation of the network when renewable energy producers will be installed and the production from the substations will be maximum. The loads on the transformer substations are shown in the table below[51].

Tabel 5. 3 – Load flow when maximum produced power is reached

Nr.	Nod	U	u	Unghi U	P Consum	Q Consum	P Generat	Q Generat
crt.	Nume	kV	%	°	MW	MVAr	MW	MVAr
1	Statie 1 20 kV	21	100	0	7,229	1,854	0	0
2	PT1 	21,413	101,96	0,5	0,928	0,477	1,4	0,46
3	PT2 	21,242	101,15	0,3	0,576	0,296	1,4	0,46
4	PT3 	21,344	101,64	0,4	0,64	0,329	1,4	0,46
5	PT4 	21,408	101,94	0,5	0,256	0,131	1,4	0,46
6	PT5 	21,417	101,98	0,5	0,256	0,131	1,4	0,46
7	PT6 	21,399	101,9	0,5	0,32	0,164	1	0,329
8	PT7 	21,277	101,32	0,4	0,288	0,148	0,9	0,296
9	PT8 	21,294	101,4	0,4	0,384	0,197	0,9	0,296
10	PT9 	21,376	101,79	0,5	0,32	0,164	0,9	0,296
11	PT10 	21,354	101,69	0,4	0,384	0,197	1	0,329

The sensitivity analysis of the transformer substation bars to the variation of the reactive power in the electrical network was performed. The results are represented in the graph in Fig. 5.5.

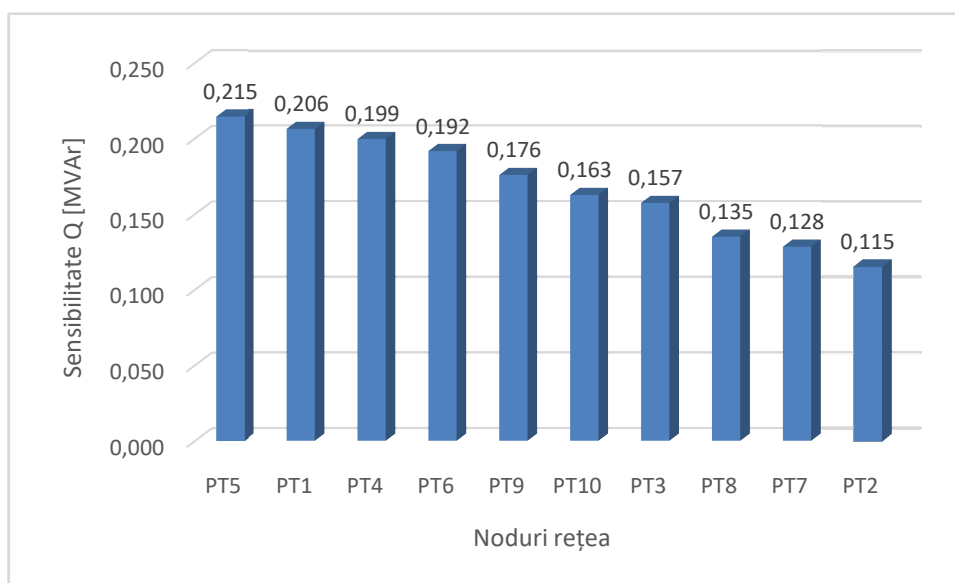


Fig 5. 5. Nods sensibility in maximum power produced regime

The factors involved in the regulation of reactive power and voltage in the system are represented in the table below.

Table 5. 4 – Participation factors for nodes in maximum produced power regime

Nr.	Participation factors for nodes in maximum produced power regime											
Crt	0,618		9,451		32,742		83,786		113,232		164,763	
1	PT5	0,127	PT2	0,197	PT10	PT9	PT9	0,273	PT2	0,435	PT9	0,496
2	PT1	0,126	PT7	0,191	PT3	PT4	PT4	0,260	PT8	0,300	PT4	0,142
3	PT4	0,123	PT8	0,163	PT2	PT3	PT3	0,112	PT7	0,095	PT3	0,129
4	PT6	0,120	PT5	0,139	PT9	PT5	PT5	0,112			PT5	0,125
5	PT9	0,110	PT1	0,116	PT5	0,104	PT2	0,091				
6	PT10	0,100	PT4	0,087	PT7	0,074	PT4	0,061				
7	PT3	0,095	PT6	0,046	PT1	0,052						
8	PT8	0,075	PT3	0,041								
9	PT7	0,069										
10	PT2	0,056										

The voltage - reactive power (U-Q) diagrams and the active power - voltage (P-U) diagram for the maximum production scenario are represented in the figures below.

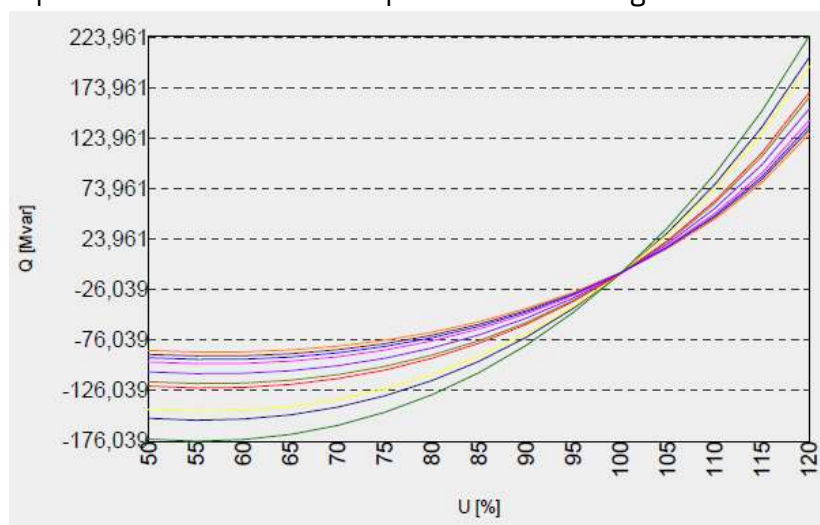


Fig 5. 6. U-Q diagram for maximum produced power

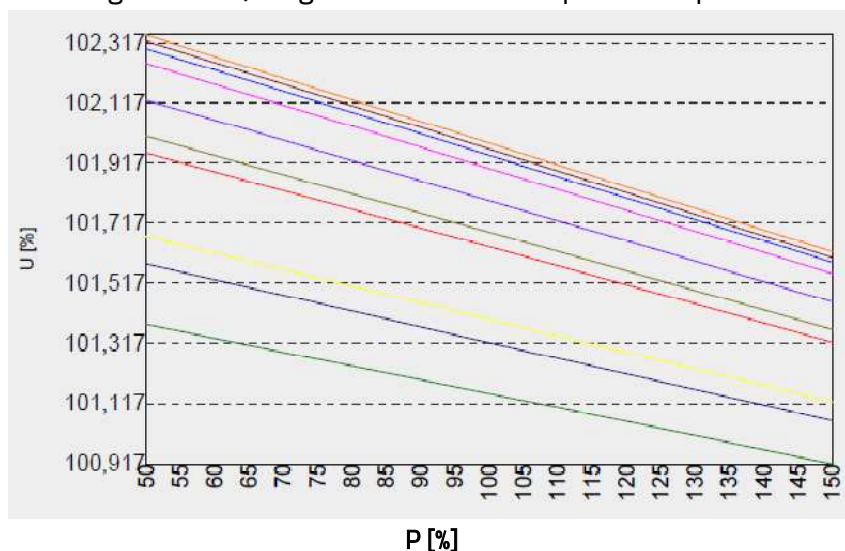


Fig 5. 7. P-U diagram for maximum produced power

5.4. Conclusion

Voltage stability in electrical networks is a very important factor for the security of supply to consumers. The effective values of the voltage averaged over 10 minutes must be within the

range of $+5\%/-10\%$ of the nominal voltage for 95% of the values and within the range of $+10\%/-15\%$ of the nominal voltage for all effective voltage values according to the performance standard in the field of electricity distribution[23].

Simulations were carried out in specialized programs starting from the current consumption records, but taking into account both development scenarios of the industrial park, namely: predominantly consumer by developing the production hall system and adding new consumers until reaching maximum consumption or predominantly producer of electricity by adding generators from renewable sources of electricity, especially photovoltaic panels.

The simulations revealed that the variation of voltages in the nodes, regardless of the simulated scenario, oscillates in the range of $+2\%/-3\%$, so that the values are within the parameters required by the performance standard in the field of electricity distribution. Given that the power of the generators supporting the energy system in the industrial park area is much higher than the power of renewable generators that could be installed in the area, the impact on the distribution network is minimal. The weakest node is the useful transformer station in the open distribution loop, namely PT5, it is most affected by voltage variations, but the percentage is around 20%, which is acceptable. The simulations showed that the 20 kV network is prepared for both a maximum consumption of about 8 MW and a maximum production of about 7 MW. When determining these values, the installed power in the transformers and the distribution capacity of the connecting cables between the transformer stations through which the 20 kV internal distribution is made were taken into account.

It is advisable for users within the industrial park to install generators from renewable sources because it ensures energy savings firstly by ensuring local production for consumption and secondly to deliver it to the distribution network.

The present analysis of voltage stability in this chapter can constitute a precedent for studying smart grids in another chapter of this work in which to analyze how the voltage can be automatically regulated in distribution networks, and the results of the simulations in this chapter to represent inputs of an automatic voltage and reactive power regulation system in the network.

The Fuzzy system for voltage regulation can be successfully used in electrical distribution networks because it does not need precise measurements for the input quantities in order to activate the outputs that are calculated with the same dose of uncertainty with which the inputs are measured. The system can be used in smartgrid applications because the system self-adapts and self-improves in relation to the input quantities.

6. POWER DISTRIBUTION NETWORKS SUSTAINABILITY THROUGH AUTOMATION USING ARTIFICIAL INTELLIGENCE

6.3. Streamlining the electricity production process using automation

The SMARTGRID concept is still in its infancy in Romania, being at the stage of future projection in which investments are made to optimize the power flow and reduce electricity consumption, and thereby the level of carbon emissions resulting from the electricity production process.

By installing automation in electricity distribution networks, the aim is to make them more efficient and increase the security of supply to consumers.

The author proposes two automations for the operation of future smart networks in Romania (SMARTGRID) that use information transmitted through existing SCADA systems within transformer stations.

6.3.2. Electrical production efficiency from alternative energy sources with Fuzzy Technique

We are in the process of replacing fossil fuel generators (coal-based) in the energy system with generators from renewable energy sources. However, this change comes with two main disadvantages: the replacement is not made at the same point in the network where the fossil fuel generator stopped and the low inertia especially of photovoltaic generators.

The first disadvantage is the distance created between the producer and the consumer, which causes active energy losses proportional to the distance between the producer and the consumer and reactive energy losses consumed for the transport of energy through the electrical networks.

Fossil fuel-based generators have a major advantage, namely that they can produce energy in the band, the power being maintained constant by constantly loading the combustion chamber or in the case of gas generators by maintaining a constant gas flow for the internal combustion engine, while renewable generators do not have this quality, production being inconsistent and unpredictable depending on weather conditions, especially photovoltaic generators. Photovoltaic generators can halve their efficiency on a cloudy day compared to a clear day. Wind generators have evolved a lot, currently there are wind turbines with powers up to 7 MW and which can produce maximum power for a wind speed of about 10 m/s.

The disadvantage of renewable voltage sources compared to fossil fuel-based generators is the inertia of the generator. In other words, fossil fuel-based generators are much larger and have higher rotation speeds than wind generators, ensuring a constant frequency even in the event of a trip until the rotation speed begins to decrease. The frequency of rotary generators is directly proportional to the rotation speed of the generator and the number of poles.

$$f = \frac{N \cdot p}{60} \quad (6.1)$$

Where:

f - frequency

N – rotor speed

p – poles number

Photovoltaic generators have no inertia at all, which means that it is more difficult to adjust the frequency in the event of a power plant trip, especially if it has considerable power.

A mass desynchronization of photovoltaic generators serving an area can turn into a huge power outage. Therefore, it is recommended that in each area there is a diversification of production sources and that a sufficient number of rotating generators (hydro, biomass, biogas, wind, fossil) be maintained so that the inertia of the system is ensured.

Given these shortcomings and the need for on-line production of electricity, renewable sources began after 2020 to be equipped with storage batteries with a capacity similar to the power plant in order to store energy and deliver it on-line. Of course, having control over the battery charging/discharging time, energy can be sold on the market at more favorable times when its price is higher.

The following proposes the study and implementation of a Fuzzy logic system that will streamline the production of electricity and make the most of the capacity of the batteries installed in the energy system depending on the consumption needs in that area.

The input variables of the system will be the power requirement that can be estimated by the intelligent measurement system and the inertia of the energy system that will be represented by the frequency variation rate (df/dt). A small frequency variation provides information about the system that there are enough functional rotary generators. A large frequency variation means low system stability and the need to start rotary generators that ensure a constant frequency and increased stability. For the output variables, the active power generated and the type of generator used, including storage batteries, were chosen.

In the Fuzzy system, the input variables can take values between 0 and 1 and, based on the rules created, the output values can be determined using approximations of the input values. For each entry, 3 levels were selected: "L" - Low, "N" - Normal, "H" - High in order to approximate their level and to apply the rules highlighted in the table below.

Tabel 6. 1 – Rules for energy efficiency Fuzzy system

Rules	Input variables		Output variables			System states
	df/dt	ΔP	P _G	P _R	P _B	
1.	L	L	L	L	L	Active power absorbtion in batteries
2.	L	N	N	L	N	Active power injection from renewable sources
3.	L	H	H	L	H	Active power injection from generators and baterries
4.	N	L	L	N	L	Active power absorbtion in batteries and active power injection from renewable
5.	N	N	N	N	N	Active power injection from renewable and generators
6.	N	H	H	N	H	Active power injection from generators and baterries
7.	H	L	L	H	L	Active power absorbtion in batteries and active power injection from generators
8.	H	N	N	H	N	Active power injection from generators
9.	H	H	H	H	H	Active power injection from generators and baterries

Where :

N – Normal

L – Low

H – High

df/dt – Frequency variation

ΔP – Active power necessity

P_G – Active power injection from renewable

P_R – Active power injection from generators (rotary)

P_B – Active power injection from batteries (L-Load/H – Injection)

The definition of the membership functions will be determined for each variable separately. It will be defined using the Mamdani system for both input and output variables. The input variables are the frequency variation and the active power requirement. For all these input variables, three levels of approximation are defined.[29,30]

L – Low – $[-0,5 \ 0 \ 0,5]$

N – Normal – $[0 \ 0,5 \ 1]$

H – High – $[0,5 \ 1 \ 1,5]$

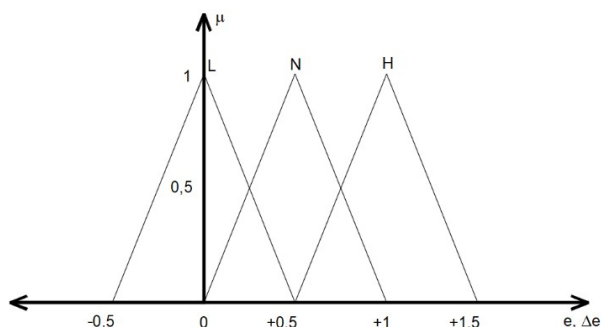


Fig 6. 1. Input variables for Fuzzy System

The output variables are the commands for increasing/decreasing the active power, respectively starting the different types of generators for which the following intervals are defined for the membership functions and according to figure 6.2:

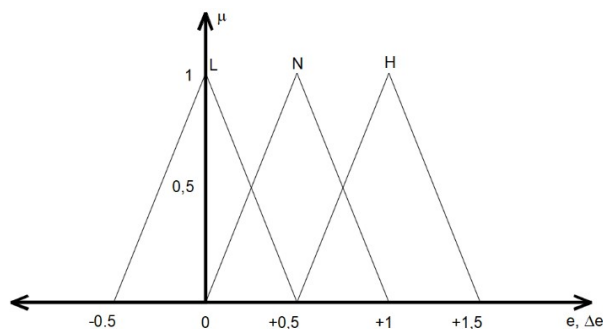


Fig 6. 2. Output variables for Fuzzy System

The Fuzzy system for making the electricity distribution system more efficient in terms of energy sources works according to the following rules.

1. If df/dt is „L” and ΔP is „L”, then P_G is „L” and P_R is „L” and P_B is „L”
2. If df/dt is „L” and ΔP is „N”, then P_G is „N” and P_R is „L” and P_B is „N”
3. If df/dt is „L” and ΔP is „H”, then P_G is „H” and P_R is „L” and P_B is „H”
4. If df/dt is „N” and ΔP is „L”, then P_G is „L” and P_R is „N” and P_B is „L”
5. If df/dt is „N” and ΔP is „N”, then P_G is „N” and P_R is „N” and P_B is „N”
6. If df/dt is „N” and ΔP is „H”, then P_G is „H” and P_R is „N” and P_B is „H”
7. If df/dt is „H” and ΔP is „L”, then P_G is „L” and P_R is „H” and P_B is „L”
8. If df/dt is „H” and ΔP is „N”, then P_G is „N” and P_R is „H” and P_B is „N”
9. If df/dt is „H” and ΔP is „H”, then P_G is „H” and P_R is „H” and P_B is „H”

Figure 6.3 represents the response of the Fuzzy system proposed for the efficiency of production sources based on environmental criteria, but also on voltage stability in the electricity distribution network. The state in which the frequency variation is high was taken into account, meaning that there is a state of instability in the system and the active power requirement is minimal. Then the system will choose to control the generators with high inertia, that is, the rotating ones, the minimum production from renewable sources is observed, the maximum production from generators with high inertia and the surplus energy that enters the network as a result of the need to stabilize the system, will charge the accumulator batteries.

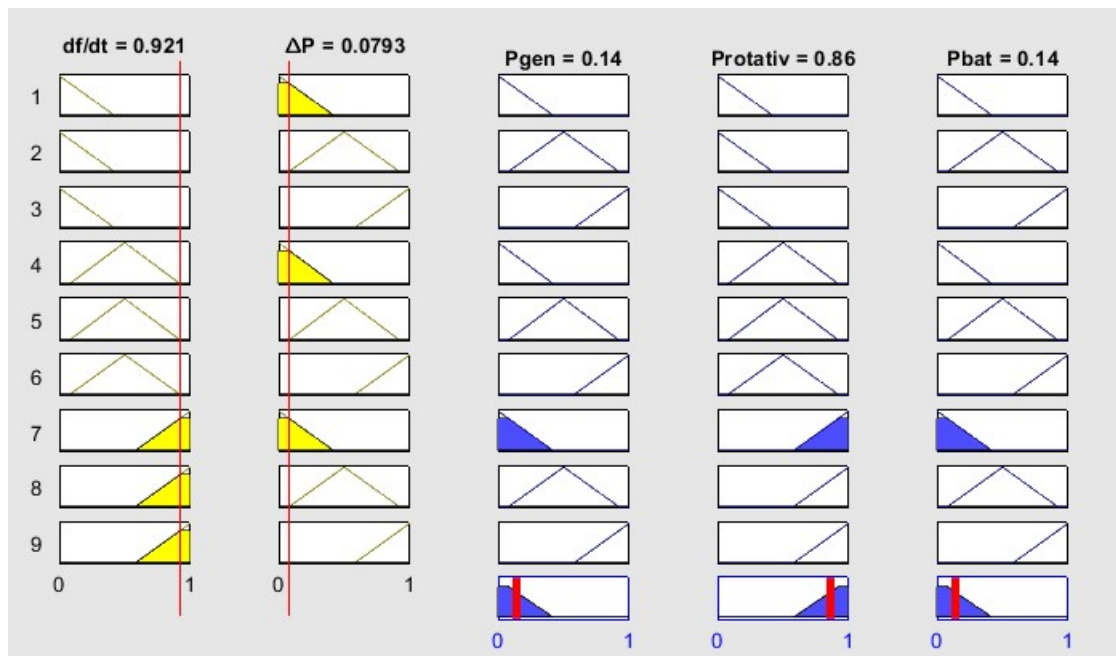


Fig 6. 3. The Fuzzy system response at df/dt High and ΔP Low

6.4. Conclusion

Electrical networks must keep up with technology and the needs of its users. This means that electrical network nodes must be ready at any time to receive or release energy, to supply producers or consumers, without the need to first turn off the voltage to make settings for a new operating mode.

The optimization targeted by this chapter is to ensure local production for each place of consumption, but especially for large places of consumption and to equalize production with consumption as much as possible, so that the transit of electricity through the distribution networks is reduced to a minimum and thus losses are reduced.

This vision can be extrapolated to a high level so that for each large consumer in an area an electricity production group is installed, preferably from unconventional sources that provide the ability to produce electricity for the consumer in the amount consumed by him at a certain point in time.

In the future, SMARTGRID systems will be able to control electricity production in relation to consumption in an area, store energy in batteries when consumption is lower than production, and have the ability to select generating sources based on efficiency and pollution criteria.

7. STEP VOLTAGE DETECTION SYSTEM IN POWER DISTRIBUTION NETWORKS

7.3. Contributions in step voltage for electrical networks

Additional protection of electrical installations is represented by the earthing. The earthing consists of horizontal and vertical electrodes made of good electrical conductive material, which in the event of a fault ensures the leakage of the fault current into the ground, protecting people in the installation area. Depending on the dispersion resistance of the earthing, the protection is also achieved. An earthing with a low dispersion resistance leads to the rapid dispersion of the fault current and implicitly ensures increased protection.

Step voltage appears at the time of faults in electrical installations, in their proximity. During the fault, the fault current will disperse through the earthing. Depending on how good its dispersion resistance is and its coverage, during the leakage of the fault current to the ground a potential difference will appear on the surface of the earthing and in the immediate vicinity, the greater it is, the more dangerous it is. [60]

7.3.1. Step voltage measuring sistem in electrical networks

The proposed method, currently in the research stage of the doctoral thesis, aims to create a portable device for measuring step voltage, so that measurements can be made quickly and accurately, involving a single operator.

The portable device would help operational personnel who perform maintenance work or interventions on electrical distribution installations to be warned in advance in the event of entering a dangerous area, with step voltage above the value imposed by the regulations, thus maintaining the safety of operational personnel throughout the work in the area of electrical installations.

The proposed device will be used by the operator himself, to whom we attach to the protective equipment (electrically insulating boots) some plates with very low resistance to facilitate the circulation of electric current.

The voltage measured by these plates will be used by the electronic circuit that we propose in 3 variants: acoustic warning, optical warning and haptic warning. By making the installation in this way, we will perform direct measurement of the step voltage with the help of an operator, practically performing real-time measurements from the areas we want to monitor. The connections to the resistance will be made with cables with 1 kV insulation so as not to affect the operator during the measurements. Optical and acoustic signaling can be performed in case of exceeding a preset level of the step voltage according to the diagram in fig. 7.1.

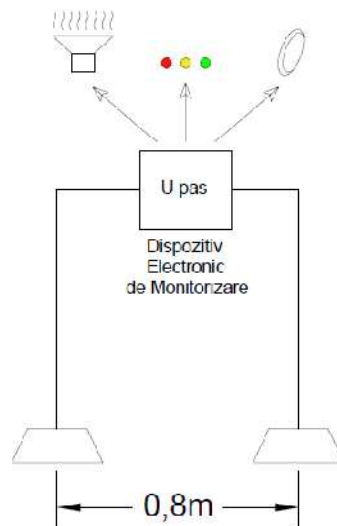


Fig 7. 1. Scheme for step voltage measuring

Step voltage is an important parameter in terms of safety when working in the area of an electrical installation or simply being in its vicinity. Whether authorized personnel are in the area of electrical installations or if the personnel are not trained, they must be safe regardless of the state the electrical installation is in: normal operation or failure mode operation - as an example we can list: single-phase or two-phase short circuits to earth.

The portable step voltage measuring device will optically, acoustically and haptically alarm the operator if the reference step voltage has been exceeded.

7.3.1.1. Portable transducer for acoustic warning

It will use a DC circuit with adjustable resistance. The measured step voltage will be rectified with a rectifier bridge and will be applied to the scheme, resulting in an acoustic alarm depending on its level.

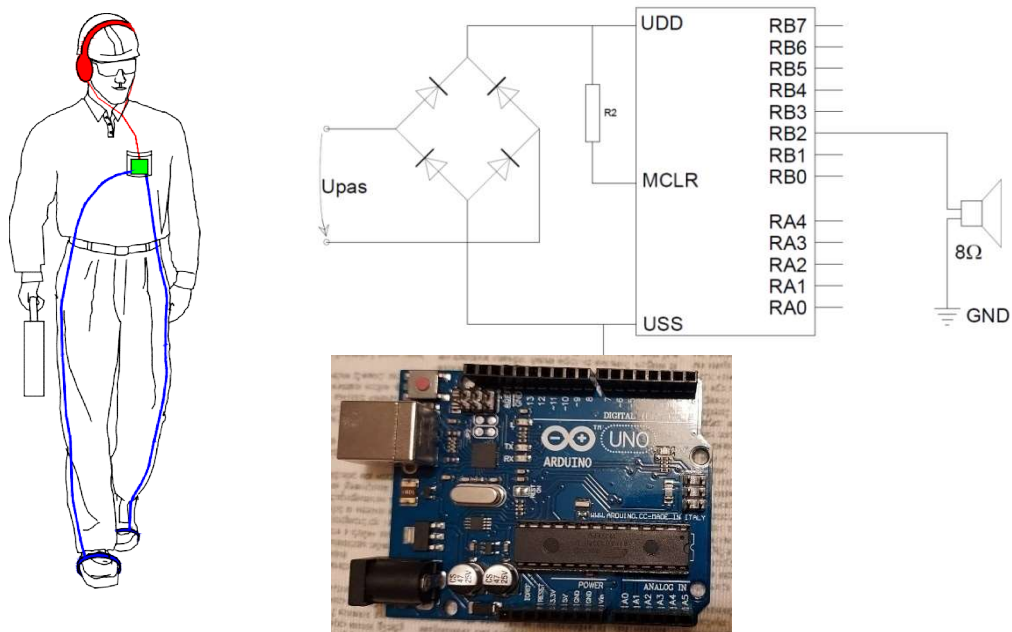


Fig 7. 2. Portable transducer for acoustic warning

The operator will be properly equipped with overalls, helmet and electrically insulating shoes. Two electrodes connected to the acoustic alarm scheme will be applied to the shoes as in fig. 7.2 where the electrodes and 1kV cables that will power the monitoring device, positioned in the pocket of the overalls, have been depicted in blue. The measured voltage will be an alternating voltage that will be rectified with a rectifier bridge and then applied to the designed circuit. Depending on the level of the measured voltage, the sound intensity will also be.

7.4. Conclusion

Preventive maintenance is the way to ensure that electrical installations operate with as few unscheduled interruptions as possible. Periodic electrical measurements, together with observation of the installation, its cleaning and cold functional testing, bring operational safety, production planning and a business plan that is not affected by unforeseen incidents, providing predictability to both company managers and electrical department personnel who will thus know the installation very well and will be able to propose equipment/material replacements if necessary. The methods studied in this chapter can become methods used in

preventive maintenance of electrical networks, and research directions can be deepened to carry out this action robotically under the command of an RTU in the future, integrating perfectly into the SMARTGRID concept, a national and international trend.

8. CONCLUSION AND PERSONAL CONTRIBUTIONS

This chapter summarizes the author's key contributions regarding the optimization of distribution networks—measures detailed throughout the preceding chapters of this work. It highlights major innovations at both theoretical and practical levels, the dissemination of results, and future research directions in the field.

8.1. General Conclusions

Through this work, the author conducted research into the automation of distribution systems, contributing positively to network operations by improving existing methods or proposing new automation techniques for electrical distribution networks, ultimately enhancing the efficiency of the national electricity distribution process.

- **In chapter 2, the overcurrent protection for overhead power lines** that takes into account the external temperature was analyzed, the case study highlighted a series of advantages:
 - Making the existing maximum protection more efficient by protecting the conductor according to the capability curve at the temperature level and not just a fixed threshold.
 - Ensuring an increased protection range by following the capability curve, thus avoiding line trips without reaching limit thresholds, considering the setting of a fixed threshold that does not take into account the conductor temperature.
 - Avoids overloading the conductor at high temperatures by protecting it proportionally to the capability curve.
 - Avoiding the start of extensive re-conduction works or the construction of new power lines by using the maximum conduction capacity of existing lines, a maximum capacity that is currently not exploited.
- **In chapter 2, the integrity detection system for overhead power line poles** was analyzed. By determining the acceleration at the top of the poles and controlling the line tripping at the end stations when a fault is detected, the system has the following advantages:
 - Prevents accidents resulting in death or injury in the event of a fault
 - Identification of any change in the inclination of the poles, offering the possibility of preventive maintenance action.
 - Ensures cost reduction by monitoring the poles, not requiring their replacement – especially concrete poles on high voltage lines.

- It constitutes a precedent and a basis for future developments in the physical monitoring of overhead power lines with minimal costs.
- **Chapter 3 analyzed electrical cable monitoring systems** that allow for the fastest possible identification of the fault and the narrowing of the search area as much as possible by identifying signals in the field using electrical induction loops. The induction loop system was highlighted, which allows signaling to the control room of the electrical cable status without consuming energy from auxiliary sources. The voltage induced in the loops in the electrical cable is rectified using dedicated schemes, used to signal the failure of the portion of the electrical cable that is monitored.
- **Chapter 4 synthesizes in detail the automations performed at the level of transformer stations**, the author developed programs in the C++ programming language for the main automations. The author developed and implemented an application to verify the possibility of paralleling transformers depending on their technical characteristics. For the automation of fault detection in medium voltage networks, a comparative study was conducted between the admittance and current injection method and the detection method using Fuzzy techniques developed by the author. The simulations were performed in the Matlab program using Fuzzy App. The Fuzzy system is not influenced by measurement errors, because the detection is performed in several steps by approximating the input values, so that the detection is done precisely, without allowing erroneous trips. Intelligent Fuzzy systems can be successfully used in this case with superior results to the admittance and current injection method, because, by using ambiguous values measured by small, large, medium approximations for the voltages and currents in the system, decisions similar to those of a human operator who is present in the station in the event of a fault can be made.
- **Chapter 5 analyzed the impact of renewable energy producers on the electrical distribution network** of an industrial park by synthesizing the results in a case study using the NEPLAN calculation program and proposing a voltage and reactive power regulation system with Fuzzy techniques by measuring frequency, voltage and reactive power.
- **Chapter 6 described the evolution of the energy system from its establishment to the achievement of the SMARTGRID concept.** The SMARTGRID concept began to be implemented in Romania, the process being a laborious and long-term one. The author developed an application using artificial intelligence with Fuzzy concepts for choosing the sources of electrical energy production: conventional or renewable and the moment when to use accumulator batteries to streamline the process of electrical energy distribution in future smart networks. The simulations were performed using the Fuzzy application in the Matlab calculation program. This

automation aims to use renewable sources as frequently as possible, provided that the energy system operates within the set parameters.

- **In Chapter 7, the author created a mobile step voltage detection system** without the help of an auxiliary source using an Arduino board, LEDs, a haptic warning bracelet and a horn. Depending on the level of the detected step voltage, there are 3 warning levels: within parameters, at the limit and dangerous level, so that the operator can draw conclusions from the measurements regarding places with dangerous step voltage and take measures. The system stands out for the ease with which the measurements are made and the number of them in a very short time.

8.2. Personal theoretical contribution

The research conducted in this paper is both theoretical and applied. The theoretical results can be a subject for future practical research and the development of prototypes that can ultimately be transformed into long-term adopted solutions for distribution networks. The following are the personal contributions made to solving the automation problem in the field of electrical distribution lines in the national energy system:

1. **Contributions to the improvement of protection and monitoring systems for overhead and underground power lines:**
 - **Design and development of an application regarding overcurrent protection** that can be set to different values depending on the external temperature measured in the vicinity of the overhead power lines. The dynamic maximum protection tripping curve was promoted through this research stage, replacing the classic protection threshold. The goal was achieved, the protection tripping curve following the conductor capability curve and especially during seasons with low temperatures, being able to record an increase in distribution capacity by changing the protection threshold depending on the temperature.
 - **Design and development of a system for monitoring the integrity of overhead power line poles** by monitoring the inclination and acceleration at the top, especially of concrete support poles which are a vulnerability of overhead power networks. The automatic monitoring system controls the tripping of the power line in case of detection of values incompatible with normal operation, thus avoiding accidents.
 - **Proposing a method for detecting faults in electrical cables** by measuring the indirect current on the sections and identifying the fault location as precisely as possible, induction monitoring being an alternative solution to current monitoring systems.

2. Contributions to the development of automation in transformer stations:

- **Design and development of an application for detecting the possibility of paralleling transformers with different technical characteristics**, very common in the process of re-engineering electrical transformer stations or designing new ones by immediately detecting the compatibility of the transformer units in order to be paralleled.
- **Analysis of voltage stability when connecting renewable sources of electricity production**. The connection of prosumers and renewable sources has become a challenge for voltage stability in distribution networks due to their dependence on the surrounding climate. Analysis in medium-voltage distribution networks that are affected by the growth of prosumers can provide information to the dispatcher to take measures before the electrical parameters of the network require the disconnection of energy production sources or power lines.

3. Contributions to the efficiency of electrical networks using artificial intelligence:

- **Design and implementation of a Fuzzy logic application for voltage and power regulation** in electrical distribution networks that highlighted the following advantages:
 - Very short response time
 - Low voltage shocks considering the working mode of Fuzzy applications with sensitive changes in output functions in close intervals.
- **Design and implementation of a Fuzzy logic application for detecting faults in medium voltage networks** that brings the following advantages:
 - Fast system – fault identification is done at the ms level
 - Efficient system – 100% fault identification percentage
 - Does not require exact measurements of input quantities
- **Design and implementation of a Fuzzy logic application for streamlining electricity production** that presents the following advantages:
 - Prioritizing production sources depending on frequency variation
 - Charging accumulator batteries with the surplus energy from the system
 - Contribution to a cleaner environment with lower CO₂ emissions by prioritizing renewable sources under stable conditions of the electricity grid

4. Contributions to the system of testing and verification of electrical networks

- **Design and development of a method for monitoring step voltage in the vicinity of electrical networks** that presents the following advantages:
 - simple and compact monitoring mechanism, no complex measurement equipment required.
 - Immediate results without auxiliary current injection sources

The objectives proposed for this work have been fully met.

The present research is a precedent for the analyses not to be stopped at this point and to be continued in other works considering the crucial importance of distribution networks for the normal conduct of daily life, detailed in subchapter 8.5.

8.3. Personal practical contribution

8.3.1. Practical achievements

For the fourth objective of this document - **Preventive maintenance in electrical distribution networks - Monitoring step voltage in the vicinity of electrical networks**, a model was analyzed and built using an Arduino controller, a portable device for measuring step voltage, so that measurements can be made quickly and accurately, involving a single operator.

The portable device would help operational personnel performing maintenance work on electrical distribution installations to be warned in advance in the event of entering a dangerous area, with step voltage above the value imposed by the regulations, thus maintaining the safety of operational personnel throughout the work in the area of electrical installations.

The proposed device can be used even by the operator performing the intervention, in real time, with very low resistance plates attached to his protective equipment (insulating boots) to facilitate the circulation of electric current.

The measured step voltage can be converted into a lower voltage signal and with the help of a rectifier bridge and a transformer the signal can be converted into:

- acoustic signal using a loudspeaker mounted on the operator's protective helmet
- optical signal using LEDs with 3 colors distributed by voltage levels: safe, attention and do not pass. The LEDs will be mounted on the protective helmet or goggles.
- haptic signal using a bracelet on the operator's hand which, following the recorded voltage level, will produce a sensory signal on the hand: heating or vibration.

By using step voltage monitoring/measurement schemes with Arduino boards, step voltage measurements can be performed instantly, without the need for an additional injection source, without the need for bulky equipment or multiple operators to perform the measurements.

8.3.2. Participation in energy projects during doctoral

Practical applications in renewable energy were developed together with colleagues from several companies, especially with the company Electroprecizia AG S.R.L. where I work as Head of Design Office.

Among the most important projects developed during 2021-2026 were the following applications for connecting renewable energy sources to the national energy system.

8.3.2.1. PV plant 60 MW Teius, Jud. Alba

The project was carried out between 2023-2025 and provided for the connection to the National Power System of a photovoltaic power plant located in the Teius area, Alba County by building a 110/20 kV 63 MVA substation connected input-output to a 110 kV overhead line, including the provision of protections on the new power lines formed by the sectioning of the existing 110 kV line. In order to achieve differential protection on the 110 kV overhead line and transmit operating parameters to the dispatcher, it was planned to install a fiber optic cable between the end stations and the new power plant.

8.3.2.2. Windfarm 75 MW Avrămeni, jud. Botoşani

The project is underway, starting with the construction of the new 110/30 kV 2x100 MVA transformer station connected input-output to a 110 kV OHL. The station will be connected with a 110 kV LES over a length of approximately 0.9 km. Commissioning is scheduled for 2027.

8.4. Designating the results

Part of the results obtained in the thesis were published in prestigious journals and in the volumes of recognized scientific events from abroad or in the country: 3 articles published in renowned journals at a national level and 3 articles published in internationally recognized conferences.

- **R.A. Moise, A. Fratu**, *Parallel Operation of Transformers with Different Voltage Ratio*, Magazine RECENT nr. 67, 2022, p.81-86.
- **R.A. Moise, A. Fratu**, *Protecția maximală dinamică a liniilor electrice*, Magazine AGIR nr. 1, 2023, p.45-49.
- **R.A. Moise**, *Earth-fault detection using Fuzzy Logic in electrical distribution networks*, ERAZ Conference, 2023, p.550-565.
- **R.A. Moise, A. Fratu**, *Artificial Intelligence in Power Distribution Systems*, SMART Mobile Communication, 2024, p.151-159.
- **R.A. Moise, M. Fratu**, *Riscurile la care sunt supuse rețelele de distribuție a energiei electrice și soluții de reducere a acestora*, Magazine AGIR nr. 1, 2025, p.30-35.
- **R.A. Moise, A. Fratu**, *Voltage Stability Analysis in Power Distribution Networks for Connecting Renewable Energy Sources*, AI SMART Conference, 2025, p.353-362.

8.5. Future research directions

Smart grids are the concept towards which the energy system in our country is moving. Small steps are being taken, supported every day, with each modernization of a station or electrical network we are getting closer to the designed concept.

Of course, research has its place in this process, elements resulting from research are used in the national energy system. Inventions that were part of energy studies and research in the past are now used for protection and automation in electrical networks.

Research areas such as the method of transmitting energy wirelessly over small areas where electrical cables cannot be used are a direction to be taken into account in further research.

The theoretical and practical analyses carried out within the doctoral thesis, as well as the results obtained, open a series of perspectives and directions for further continuation and deepening of research in the field:

- Implementation of the SMARTGRID concept at the national level with the trend towards a significant percentage of autonomy of electrical networks through automation implemented at key points
- Increasing cyber security at the level of electrical distribution networks

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- [26] R.A. Moise, A. Fratu, *Parallel Operation of Transformers with Different Voltage Ratio*, Revista RECENT nr. 67, 2022, p.81-86.
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