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SOLUTIONS FOR IMPROVING EFFICIENCY IN DISTRIBUTION NETWORKS

SOLUȚII PENTRU ÎMBUNĂTĂȚIREA EFICIENȚEI ÎN REȚELELE DE DISTRIBUȚIE

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***Abstract**: The transport and distribution of electrical energy are accompanied by active losses that reduce the performance of the power supply system for users. Losses of 8 ... 15% of the total generated power are mainly localized in the electrical distribution system and are primarily due to active losses in power transfer through conductors defined by their electrical resistance and transformers. During the energy billing processes, commercial losses may occur, which decrease with the increasing informatization of the network. The paper analyzes solutions for limiting technical losses within a real network and emphasizes the technical and economic aspects of the implemented solution.*

Keywords: distribution network, energy losses, network informatization, commercial losses.

***Rezumat**: Transportul și distribuția energiei electrice sunt însoțite de pierderi active care reduc performanța sistemului de alimentare cu energie pentru utilizatori. Pierderile de 8 ... 15% din puterea totală generată sunt localizate în principal în sistemul de distribuție electrică și se datorează în special pierderilor active în transferul de energie prin conductori definiti de rezistența lor electrică și transformatoare. În timpul proceselor de facturare a energiei, pot apărea pierderi comerciale, care scad odată cu creșterea informatizării rețelei. Lucrarea analizează soluții pentru limitarea pierderilor tehnice în cadrul unei rețele reale și subliniază aspectele tehnice și economice ale soluției implementate.*

Cuvinte cheie: rețea de distribuție, pierderi de energie, informatizarea rețelei, pierderi comerciale.

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1. Introduction

Like any physical process, electricity distribution and transmission inevitably involve energy consumption associated with irreversible thermodynamic conversions. This consumption, called „grid losses", is distinct and external to useful energy and is recognised as such in the literature and in international statistics.

In the process of delivering energy to consumers, losses occur at various stages, including generation, transmission and distribution of electricity. On average, it is estimated that around 8% of the energy produced is lost in the generation process, while in the transmission and distribution of electricity, losses are around 10%.

In setting tariffs for electricity transmission and distribution, the cost of network losses plays a crucial role and is an important factor in competitiveness between companies, especially in a market economy.

Losses in electricity grids, according to the statistics, are the result of the discrepancy between the energy fed into the grid or imported and the energy actually sold to consumers, including that exported. These losses are made up of three distinct components [1, 2]:

1. Own technological consumption (TOC): This is the energy consumed directly by the equipment and systems used in the transmission and distribution of electricity according to the design of the installation. It is necessary for the optimal operation of the system according to the original specifications.

2. Technical losses: These occur when there are deviations from the designed operating regime, either due to incomplete development of installations or due to improper operation. These losses are related to technical aspects of the network and can be reduced by improvements in design, operation and maintenance.

3. Commercial losses: These include errors introduced by the quality of the metering groups and the organisation of electricity accounting. They also involve some unmeasured consumption, such as of metering transformers and meters, and include electricity theft. Commercial losses can be either positive or negative, depending on the nature of errors and inefficiencies in the energy distribution and metering system.

These components contribute to the total losses in electricity networks and are essential for the assessment and management of the operational efficiency of the power system. Reducing these losses is crucial for improving the efficiency and sustainability of electricity networks.

2. Active losses in the distribution network

Electricity losses increase with the volume of electricity transported and the distance between generation facilities and consumption sites. On the one hand, the greater the volume of electricity transported or the greater the distance energy travels between generation sources and consumers, the greater the likelihood of grid losses. On the other hand, electricity losses can be reduced with increasing grid voltage, especially in low atmospheric humidity conditions, as the higher voltage can compensate for some of the energy losses [3, 4].

In general, the management and optimisation of electricity networks is essential to minimise energy losses and ensure efficient and reliable transmission of electricity to consumers. This involves the use of appropriate technologies, proper network design, and regular monitoring and maintenance to reduce losses and improve system performance.

Electricity losses in the electricity grid, also known as technological own consumption (TOC), are the result of several physical phenomena, including:

– Joule phenomenon, which occurs when electric current flows through the electrical conductors of lines and the copper windings of transformers and coils. This phenomenon generates heat losses due to the electrical resistance of the materials, thus contributing to energy losses in the grid.

– Losses in iron components, which are caused by eddy current and hysteresis phenomena. These losses occur in components such as the iron cores and cores of transformers and other electromagnetic devices, and are due to the conversion of magnetic energy into heat.

All these phenomena contribute to electricity losses in the power grid and are important to consider in the efficient design, operation and maintenance of power grids. Reducing these losses is essential to improve the efficiency and reliability of the power system.

In order to reduce the Technological Own Consumption (TOC) recorded in electricity distribution networks, technical solutions are needed to address both technical and commercial TOC.

3. Solutions for reducing losses

3.1 .Technical TOC

The main solutions for reducing technical losses are:

– Replacing medium and low voltage (MV/LV) transformers that are over 80% loaded and more than 30 years old with more efficient, low-loss and more accurately regulated ones. For example, the voltage of MV/LV transformers can be adjusted from Un ± 5% to Un ± 2 x 2.5%.

– Change low load transformers to lower power ones.

– Creation of new injection points in the medium voltage (MV) network (transformer substations), thus reducing the length of the low voltage (LV) network.

– Phase load balancing to ensure even load distribution.

– Increasing the cross-section of power lines to reduce energy losses.

– Reducing the load on network elements by redistributing consumption to new or less loaded elements.

– Optimisation of operating schemes at all voltage levels to minimise energy losses.

– Construction of new transformer substations and branches to reduce the length of low voltage networks by more than 0.5 km.

– Upgrade networks to a higher voltage level, such as from 6, 10 kV to 20 kV or from 0.4 kV to 0.6 kV.

– Reducing the length of distribution networks and rebuilding them to cope with increased consumption density.

3.2. Commercial TOC

The main solutions for limiting commercial losses are:

– Installation of power blockers (BMPs).

– Securing niches and wire distribution boxes.

– Moving meters to more accessible and secure locations, such as on the ground floor of buildings or outside apartments.

– Equip the task force with more accurate measuring equipment.

– Upgrade IT systems to reduce errors in the reading and billing process.

The checks carried out are focused on reducing commercial Own Technological Consumption (TOC) by identifying unauthorised interventions and network faults. These checks are established and implemented within the Distribution System Operator (DSO). The main actions carried out include:

– Checks generated by structured analyses investigating the electricity consumption of different types of consumers.

– Checks generated from the analysis of parameters recorded by meters transmitting remote data in order to identify non-conformities of the measuring groups.

– Checks carried out with the legal authorities to identify consumers fraudulently connected to the distribution network in areas with a bad reputation.

The actions undertaken by distribution operators to improve energy performance are predominantly directed towards internal services for substations, substations and equipment installed in the network, as well as administrative offices and fleet. These actions include:

– Installation of photovoltaic systems in transformer stations to cover part or all of the energy consumption.

– The use of LED lighting solutions and efficient air conditioning units in refurbishment, retrofit and modernisation projects.

– Installation of photovoltaic systems on administrative buildings to reduce energy consumption from the grid.

– Automation of air-conditioning systems in administrative offices.

– Transition to a hybrid fleet (conventional fuel and/or plug-in electric) to reduce fuel consumption and carbon emissions.

– Optimisation of operating regimes for air conditioning equipment in transformer stations.

3.3. Maintaining voltages along the power line

In order to keep the electrical voltage constant and within the desired limits on a distribution or transmission line, the following solutions can be considered [6]:

a) Automatic Voltage Regulators (AVR): Use AVR devices to regulate the voltage at the ends of the line according to load requirements and fluctuations in the network, thus maintaining the voltage at the nominal value.

b) Reactive compensation: Installation of reactive compensation equipment, such as capacitors and inductors, to control and compensate for reactive power losses and maintain voltage within acceptable limits.

c) Network automation: Implement automation and control systems that monitor voltage in real time and make automatic adjustments to maintain voltage within specified limits.

d) Dynamic voltage control capabilities: Implement dynamic voltage control capabilities, such as automatic voltage regulators and fast response switches, to maintain voltage within specified limits under load conditions and load variations

e) Energy storage systems: The use of energy storage systems, such as batteries or accumulators, to provide additional energy or to absorb excess energy and thus maintain voltage within desired limits.

f) Network topology optimization: Analyze and optimize the network topology to minimize voltage losses and ensure balanced load distribution between the different branches of the network.

g) Improved insulation and conductors: Use thicker conductors and better insulation materials to reduce power losses and keep voltage within desired limits.

h) Regular monitoring and maintenance: Conduct regular inspections and regular maintenance of equipment and conductors to detect and remedy any faults or problems that could affect voltage along the line.

These solutions can be implemented individually or in combination, depending on the specific network needs and operating conditions.

3.4. Changing some network elements

Replacing existing transformers with ones with reduced losses.

- **Replacement of 250 kVA transformer**

Transfor-mator tipe	Sn (kVA)	Smax (kVA)	T (h)	Tsm (h)	ku	τ*	τ (h)	Pcu (W)	Pfe (W)	Losses (kWh/ year)	Bene-fits (MWh/ year)
Normal transformere	250,00	200,00	8.760	2.628	0,30	0,13	1.156,32	3.250	630	7.923,95	**2,89**
Transformer with reduced losses								**3.250**	**300**	**5.033,15**	

- **Replacement of 400 kVA transformer**

Transfor-mator tip	Sn (kVA)	Smax (kVA)	T (h)	Tsm (h)	ku	τ*	τ (h)	Pcu (W)	Pfe (W)	Losses (kWh/ year)	Benefits (MWh/ year)
Normal transformer	400,00	320,00	8.760	2.628	0,30	0,13	1.156,32	4.600	930	11.551,01	**4,38**
Transformer with reduced losses								4.600	430	7.171,01	

- **Replacement of 250 kVA transformer**

Transfor-mator tip	Sn (kVA)	Smax (kVA)	T (h)	Tsm (h)	ku	τ*	τ (h)	Pcu (W)	Pfe (W)	Losses (kWh/ year)	Benefits (MWh/ year)
Normal transformer	630,00	504,00	8.760	2.628	0,30	0,13	1.156,32	6.500	1.300	16.198,29	**6,13**
Transformer with reduced losses								6.500	600	10.066,29	

- **Upgrade of the transformer station from 250 kVA to 400 kVA**

Transfor-mator tip	Sn (kVA)	Smax (kVA)	T (h)	Tsm (h)	ku	τ^*	τ (h)	Pcu (W)	Pfe (W)	Losses (kWh/ year)	Benefits (MWh/ year)
Normal transformer	250,00	200,00	8.760	2.628	0,30	0,13	1.156,32	3.250	630	7.923,95	**0,75**
Transformer with reduced losses	400,00	320,00						4.600	430	7.171,01	

- **Upgrade of the transformer station from 400 kVA to 630 kVA**

Transfor-mator tip	Sn (kVA)	Smax (kVA)	T (h)	Tsm (h)	ku	τ^*	τ (h)	Pcu (W)	Pfe (W)	Losses (kWh/ year)	Benefits (MWh/ year)
Normal transformer	400,00	320,00	8.760	2.628	0,30	0,13	1.156,32	4.600	930	11.551,01	**1,48**
Transformer with reduced losses	630,00	504,00						6.500	600	10.066,29	

Economic Analysis of Replacing Normal Loss Transformers with Reduced Loss Transformers

1. **250 kVA Transformer:** Replacing a 250 kVA transformer with standard losses with a low-loss transformer enables the purchase cost to be recovered in approximately **9.2 years**, solely through energy savings achieved by reducing own technological consumption (TOC).
2. **400 kVA Transformer:** Replacing a 400 kVA transformer with standard losses with a low-loss transformer enables the purchase cost to be recovered in approximately **9.14 years**, through the reduction of energy losses associated with own technological consumption.
3. **630 kVA Transformer:** Replacing a 630 kVA transformer with standard losses with a low-loss transformer enables the purchase cost to be recovered in approximately **7.6 years**, through the reduction of energy losses associated with own technological consumption.

The analysis above highlights the economic benefits and the investment payback periods for different types of transformers, emphasizing energy efficiency.

Losses on medium voltage underground line

MV network	Length (km)	T (h)	Tsm (h)	ku	τ*	τ (h)	P (kW)	PF	Un (kV)	Imax (A)	I (A)	Ro (Ω/km)	Losses (kWh/an)
Linie aeriana 3x35mmp	1,00	8.760	2.628	0,30	0,13	1.156,32	2.000	0,90	20	150	64,15	0,835	**11.920,09**

MV network	Length (km)	T (h)	Tsm (h)	ku	τ*	τ (h)	P (kW)	PF	Un (kV)	Imax (A)	I (A)	Ro (Ω/km)	Losses (kWh/an)
Linie aeriana 3x50mmp	1,00	8.760	2.628	0,30	0,13	1.156,32	2.000	0,90	20	180	64,15	0,594	**8.479,68**

MV network	Length (km)	T (h)	Tsm (h)	ku	τ*	τ (h)	P (kW)	PF	Un (kV)	Imax (A)	I (A)	Ro (Ω/km)	Losses (kWh/an)
Linie aeriana 3x70mmp	1,00	8.760	2.628	0,30	0,13	1.156,32	2.000	0,90	20	230	64,15	0,436	**6.224,14**

Losses on medium voltage underground cables

MV network	Length (km)	T (h)	Tsm (h)	ku	τ*	τ (h)	P (kW)	PF	Un (kV)	Imax (A)	I (A)	Ro (Ω/km)	Pd (kW)	Losses (kWh/an)
3x1x 185 mmp	1,00	8.760	2.628	0,30	0,13	1.156,32	1.000	0,90	20	360	32,08	0,164	0,030	**848,10**

MV network	Length (km)	T (h)	Tsm (h)	ku	τ*	τ (h)	P (kW)	PF	Un (kV)	Imax (A)	I (A)	Ro (Ω/km)	Pd (kW)	Losses (kWh/an)
3x 150 mmp	1,00	8.760	2.628	0,30	0,13	1.156,32	1.000	0,90	20	250	32,08	0,194	0,300	**3.320,36**

Conversion of an MV line from overhead line (LEA) to underground medium voltage cable (LES)

MV network	Length (km)	T (h)	Tsm (h)	ku	τ*	τ (h)	P (kW)	PF	Un (kV)	Imax (A)	I (A)	Ro (Ω/km)	Pd (kW)	Losses (kWh/an)	Benefits (MWh/an)
Linie aeriana 3x70mmp	27	8.760	2.628	0,30	0,13	1.156,32	2.300	0,90	20	180	73,77	0,436	0,000	222.248,56	**136,14**
LES 3x1x 185 mmp	33	8.760	2.628	0,30	0,13	1.156,32	2.300	0,90	20	360	73,77	0,155	0,030	86.105,98	

3.5. Replacement of LEA with LES of enlarged section

Replacing an overhead power line with an underground cable power line by increasing the conductor cross-section is a solution to improve urban aesthetics, reduce the risk of interference with other structures or transport environments, and increase the reliability and safety of the power grid. Here are some advantages and considerations related to this change:

3.5.1. Advantage

a) Improved urban aesthetics: The underground power line is invisible, removing poles and overhead wires can improve the urban appearance of the area and increase its attractiveness to residents and investors.

b) Reduced environmental impact: The removal of power poles reduces the impact on the environment, including the natural landscape and wildlife.

c) Increased reliability: Underground power lines are better protected against extreme weather conditions such as storms, heavy rain or high winds, reducing the risk of power failures and outages [7].

d) Increased safety: The risk of electrocution or other accidents associated with contact with overhead power lines is eliminated.

e) Reducing interference: If overhead lines interfere with other structures, such as buildings or transmission lines, replacing them with underground lines can eliminate this interference.

3.5.2 Economic aspects

a) Higher initial costs: Installing an underground power line with larger cross-section cable involves significantly higher initial costs than installing an overhead line. These costs include both the materials required (cables, equipment) and the labour costs associated with trenching and cable installation.

b) Lower maintenance and repair costs: Although initial costs may be higher, underground power lines typically have lower maintenance and repair costs than overhead lines because it is less exposed to weather and vandalism, which can reduce maintenance costs in the long run, However, when faults do occur, access to cables for repair can be more difficult and costly than overhead lines.

c) Operating costs: Underground power lines usually have lower operating costs compared to overhead lines because they do not require maintenance and replacement of poles and other equipment exposed to weather conditions.

d) Indirect costs: Changing the infrastructure may lead to indirect costs, such as disruption to traffic and other activities in the installation area, which may require financial or administrative compensation.

e) Increased infrastructure lifetime: Underground power line infrastructure typically has a longer lifetime than overhead lines, which can reduce replacement and upgrade costs in the long term.

f) Improved energy efficiency: Reducing energy losses and improving system efficiency can lead to significant long-term energy savings, reducing operational costs and environmental impact.

g) Increased property value: Removing poles and overhead wires can increase property values in the area and spur urban development and real estate investment.

3.5.3. Technical aspects

a) Increased transport capacity: Underground lines with larger cross-section cables can provide greater transmission capacity and better management of electricity loads, which can be important in areas with high energy demands, allowing more efficient power distribution and ensuring a more stable power supply.

b) Increased reliability: The underground power line is more protected against extreme weather conditions such as storms, ice or snowfall, which can reduce the risk of power outages [8]

c) Reduced power losses: Underground power lines tend to have lower power losses than overhead lines because the larger conductor cross-section can reduce power losses due to electrical resistance, thus improving system efficiency and reducing operating costs.

d) Weather protection: Underground lines are less susceptible to damage caused by extreme weather conditions such as storms, lightning or ice, which can contribute to greater network reliability.

e) Environmental impact: Replacing overhead lines with underground lines may have less impact on the environment because it eliminates the need for poles and other visible structures.

f) Improved safety: The underground power line eliminates the risk of accidents caused by falling poles or accidental contact with overhead lines, helping to increase safety for workers and the public [8, 9].

The paper analyzes a solution that is increasingly being adopted, particularly in major urban areas, to replace overhead lines with underground cables. This results in technical and economic benefits, including increased line reliability, reduced operating costs, and improved visual appearance of the area.

The analyzed line has a nominal voltage of 20 kV and a radial structure indicated in Figure 1. In the calculation of losses for the underground line compared to losses in the overhead line, the following assumptions were made:

– Transverse dielectric losses of the lines were neglected;

– It was assumed that the short-circuit power at the supply point of the line is determined by the IT/MT supply transformer;

– Losses in the MT/JT transformers were not calculated, assuming they have the same values in both equipment configurations of the line;

– The line loading was considered symmetrical, and the electric currents were assumed to be sinusoidal;

– The calculation program for determining losses on the 20 kV radial line was based on the loss time method calculated from relation [1]:

$$\tau = T_f \cdot [p \cdot k_u + (1-p) \cdot k_u^2], \tag{1}$$

where

T_f - Operating time [h];

p = 0,2 (calculation factor);

k_u –filling factor (for the load graphs in the analyzed scheme, it has been estimated k_u= 0,3456.

From relation (1), it follows that ku = 1442,93 hours.

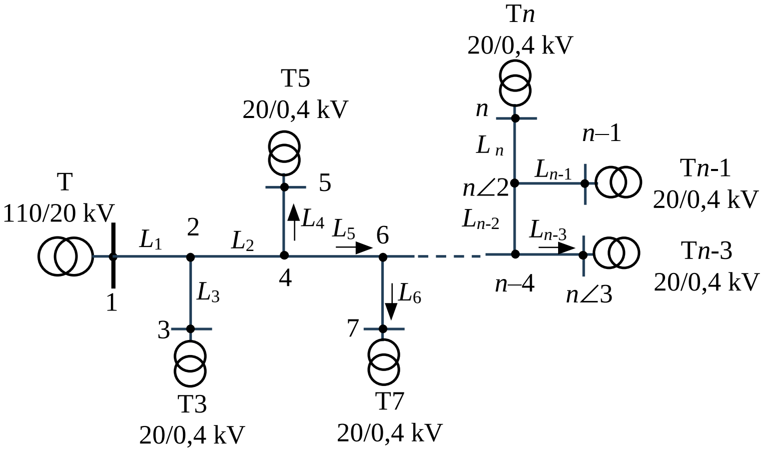


Fig. 1. Structure of the analyzed radial network.

The estimation of active losses ΔW_a and reactive losses ΔW_r was performed based on the maximum hourly values of active energy Wa.max and reactive energy Wr,max for each section k of the network line.

$$\Delta W_a = \frac{\tau}{U_N^2} \cdot \sum_{k=1}^{n_L} R_k \cdot (W_{ka,max}^2 + W_{kr,max}^2), \tag{2}$$

where n_L is the number of line sections considered.

The voltages at the network nodes analyzed can be determined based on the electric current values calculated from the hourly energy measurements from the energy meters at the network nodes and the corresponding section impedances.

Upgrading an overhead power line to an underground power line by increasing the conductor cross-section can bring many technical and economic benefits, helping to improve system reliability, reduce operating costs and improve the urban appearance of the area. The result is also a more uniform voltage profile along the line.

4. Calculation of losses on a medium voltage line

The calculation program used to determine energy losses in medium voltage electrical networks require the following input information:

- Apparent transformer power - Sn [kVA];
- Length of MV network section - l[km];
- Area of MV network section - s[mmp];
- Nominal voltage of MV line - U[kV];
- Maximum hourly active power kWh/h;
- Power factor - PF[-];
- Specific resistance ro (Ω/km);
- Specific reactance xo (Ω/km).

The following quantities are calculated:

- Apparent maximum power Smax [kVA];
- Transformer load factor - Smax/Sinst [-];
- Transmitted load on MV section - P[kW] .

As a result of the calculations performed:

- Own technological consumption - TOC [kWh];

- Voltage drops on the line ΔU[%];;
- Reactive power losses on the line ΔQ [kVAr];
- Active power losses on the line ΔP [kVW];
- Reactive energy losses Wr [MVArh] during the loss period;
- Active energy losses Wa [MWh] during the loss period.

Input data indicated in table 1 was considered.

Table 1. **Input data**

Tf [h]	8760,00
Trsm [h]	3028,00
Tau [h]	1442,93
Imax [A]	78,00
Smax [kVA]	2698,8
Wa(MWh)	2395,00
Wr(MVArh)	2876,82
U(kV)	20
PF	0,92

The analyzed medium voltage line and its main data are indicated in figure 2. Replacing overhead lines with underground cables, besides the advantages related to increased reliability in the electricity supply to users, reduced maintenance costs, and elimination of the visual impact of overhead lines, also results in a reduction in energy losses. Figure 3 shows the calculation data for the new configuration of the analyzed line.

Figures 4 show the voltage profiles along the line for the case of maximum line loading.

The voltage on the overhead line (blue line) is lower than that on the transition line, ranging between approximately 19,400 and 19,500 kV across most nodes. This suggests that the overhead line may experience higher voltage losses or lower stability compared to underground cables.

Based on these observations, we can conclude that underground cable networks perform better in maintaining a voltage closer to 20 kV than overhead lines, demonstrating superior stability across the network nodes.

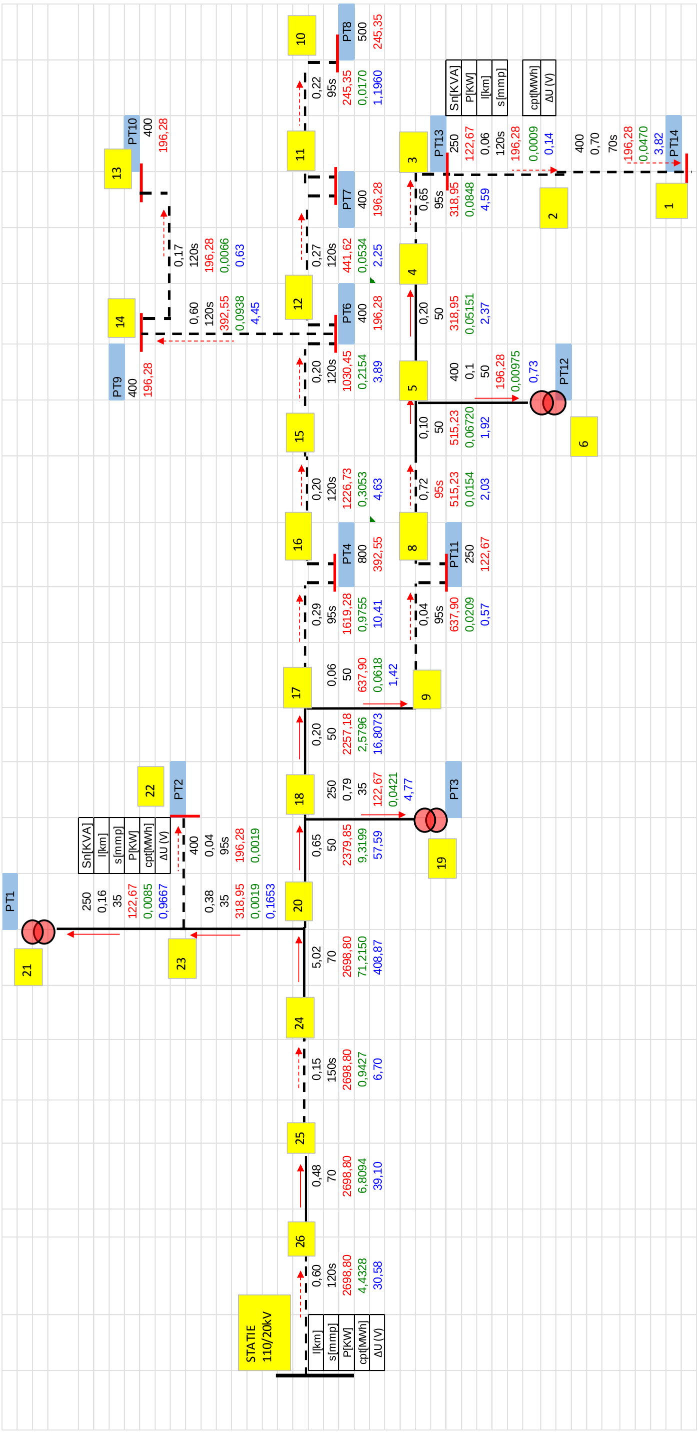


Fig. 2 Medium voltage line studied.

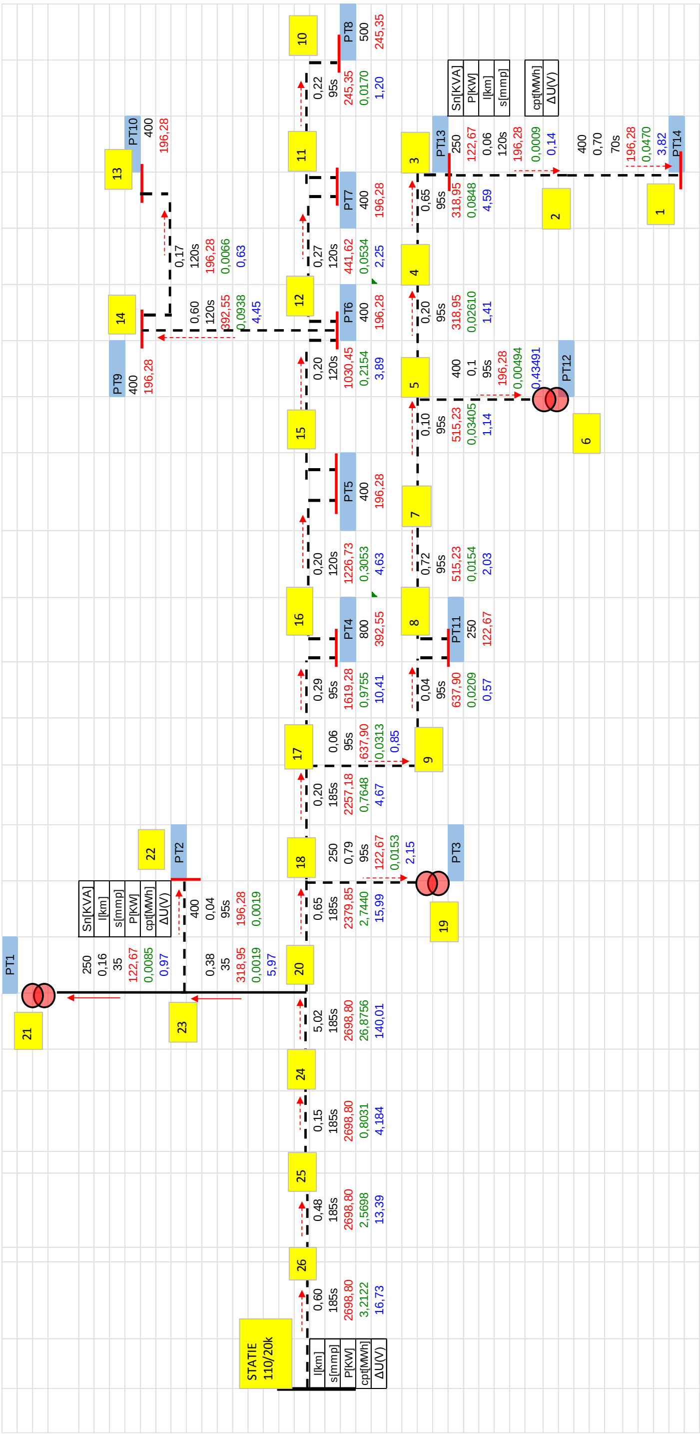
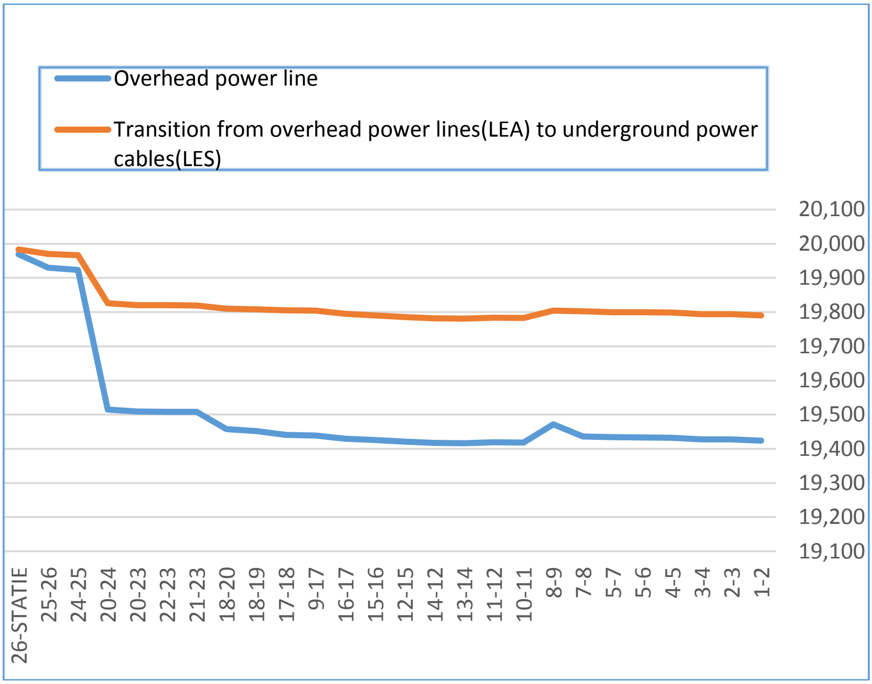


Fig. 3. Calculated data for the studied line.



Fig, 4. Voltage profiles on the overhead power line
for the case of maximum line loading.

5. Conclusions

Reducing energy losses and improving voltage drop are significant advantages in the electricity distribution process. Switching overhead power lines to underground power lines can reduce energy losses by limiting exposure to external factors that can influence the efficient transmission of electricity. This can include phenomena such as wind, rain, corrosion and other factors that can affect overhead lines. Switching from overhead to underground cables, network maintenance and durability can be improved, as underground cables are less exposed to weather and other external influences. However, it is also important to consider the costs associated with installing and maintaining underground cables.

Your calculations show a significant reduction in energy losses and an improvement in voltage drop, suggesting that switching to underground cables could be an energy efficient option. A comprehensive cost-benefit assessment is essential to make an informed decision about energy infrastructure.

It is evident from the calculations that there is a significant improvement in energy efficiency when switching from overhead to underground cables. There is a considerable reduction in energy losses, with TOC dropping from 97.51 MWh to 39.06 MWh per year and an improvement in voltage drop per line. If it is considered that on average each MWh is accompanied by an emission of about 300 kg CO2, the proposed solution results in a reduction of CO2 emissions by about 17,535 kg annually.

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Author's biography

Valentin DOBRE I graduated in 2001 from the Politehnica University of Bucharest, Faculty of Electrical Engineering, specializing in Metrology and Measurement Systems. In 2004, I completed a master’s program at the same faculty, specializing in Intelligent Sensors, Distributed Measurement Systems, and Information Security. Currently, he is a third-year Ph.D. student at the Politehnica University of Bucharest, within the Doctoral School of Energy Engineering, in the Fundamental Field of Engineering Sciences, specializing in Energy Engineering. He works at Rețele Electrice România, in the Department of Design and Execution of IT, Medium Voltage, and Low Voltage Works for the Muntenia region, where I hold the position of Site Manager.

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