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THE STABILITY OF LOW VOLTAGE NETWORKS IN THE CONTEXT OF INCREASING DISTRIBUTED ENERGY SOURCES

STABILITATEA REȚELELOR DE JOASĂ TENSIUNE ÎN CONTEXTUL CREȘTERII SURSELOR DE ENERGIE DISTRIBUITĂ

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Abstract: *The paper presents an original approach to the stability of low voltage networks in the context of increasing distributed energy sources and electric vehicles. A key personal contribution is the analysis of the implementation of LVRSys technology for active voltage regulation in a semi-rural network in Romania. The study highlights the system's efficiency in reducing voltage fluctuations and enhancing grid stability.*

***Keywords**:* prosumers, low voltage network, grid stability, LVRSys, OLTC, voltage fluctuations, electric vehicles, active voltage regulation

Rezumat: *Lucrarea prezintă o abordare originală asupra stabilității rețelelor de joasă tensiune în contextul creșterii surselor de energie distribuită și a vehiculelor electrice. O contribuție personală importantă este analiza implementării tehnologiei LVRSys pentru reglarea activă a tensiunii într-o rețea semi-rurală din România. Studiul evidențiază eficiența sistemului în reducerea fluctuațiilor de tensiune și în creșterea stabilității rețelei.*

Cuvinte cheie: prosumatori, rețea de joasă tensiune, stabilitate rețea, LVRSys, OLTC, fluctuații de tensiune, vehicule electrice, reglare activă a tensiunii

1. Introduction

In recent years, photovoltaic (PV) installations have experienced significant growth, both in large-scale projects and smaller residential applications. This rapid expansion has delivered notable benefits, including

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increased renewable energy production and reduced dependency on fossil fuels. However, it has also posed considerable challenges to the electrical distribution system, particularly within low voltage (LV) networks.

One of the primary challenges linked to the widespread adoption of PV systems is the phenomenon of reverse power flow. Traditional electrical networks were designed for unidirectional power flow, where electricity is delivered from centralized power plants to end consumers. With the rise in distributed generation from PV installations, this paradigm has shifted. During periods of high solar energy production — often in the middle of the day — local PV systems can generate more electricity than is consumed locally. This surplus energy is fed back into the grid, causing reverse power flow, were electricity flows from local areas toward substations, contrary to the conventional direction from substations to consumers.

Reverse power flow introduces significant voltage regulation challenges for distribution operators. Since the existing infrastructure was not originally designed to accommodate such reverse currents, issues such as overvoltage can arise on power lines. Conversely, during periods of high demand—when electricity consumption exceeds the supply from PV systems—voltage drops may occur, particularly in areas farther from substations or with weaker grid infrastructure. These fluctuations, which range from overvoltage during peak PV production to voltage drops during high demand, compromise grid stability and may result in power quality problems for consumers, including potential damage to sensitive electrical devices.

To address these challenges, the ORD Performance Standard 46/15.06.2021 was introduced, establishing acceptable voltage limits and performance requirements for distribution operators. This standard provides guidelines for maintaining voltage levels within permissible ranges to ensure reliable and high-quality electricity supply, even amidst increasing PV generation and associated reverse power flows.

Various strategies have been analyzed and implemented to mitigate voltage curve quality issues—fluctuations above and below nominal levels. These measures aim to stabilize voltage within allowable limits, thereby enhancing grid reliability and ensuring consistent power quality for consumers.

2. Possibilities of solving (methods of reducing the voltage curve)

The traditional voltage regulation methods used in electrical distribution networks were essential for maintaining voltage stability and ensuring the quality of electricity before the increase in the use of renewable sources. Thus, with the transition towards a more complex energy mix, these traditional solutions face certain limitations.

2.1. *On-Load Tap Changers (OLTC)*

OLTCs are one of the most common methods of voltage regulation in distribution networks. These transformers allow adjusting the voltage by changing the transformation ratio, without interrupting the supply of consumers. OLTCs work by changing the number of transformer plates, which allows either an increase or a decrease in the output voltage.

Advantages: OLTCs are reliable and efficient in handling moderate voltage variations and can respond to short term load changes. They have been widely used in traditional power networks to keep the voltage within acceptable limits.

Limitations: OLTC regulates the voltage identically on the 3 phases and only in relation to the voltage at the transformer terminals. OLTCs are not always able to react quickly enough to sudden and frequent voltage fluctuations, such as those caused by increasing PV and EV usage. In addition, frequent switching operations can lead to equipment wear, thus reducing the life of the transformers.

2.2. *Reactive Powe Capacitors*

Reactive power capacitors are used to compensate for voltage variations by supplying or absorbing reactive power. Depending on the needs of the network, these devices can be connected or disconnected to maintain the balance between the demand and supply of reactive power.

Advantages: Capacitors are effective in regulating voltage and improving power factor, helping to reduce network losses. They are also relatively simple from a technological point of view and can be installed at moderate cost.

Limitations: Like OLTCs, reactive power capacitors have limitations in response speed. They are less effective in handling fast and large voltage variations caused by intermittent PV sources or variable EV loads. In addition, their excessive use can lead to overcompensation problems, where the voltage increases too much, especially in networks with a significant increase in PV use.

2.3. *Replacing old conductors*

Rewiring consists of replacing old conductors in the network with conductors of higher capacity, which brings several advantages. First, it increases the capacity of the grid to carry energy, which is essential to meet the increased demands generated by renewable sources and electric vehicles. Reconduction also helps reduce power losses, leading to greater energy efficiency. In addition, it helps to maintain a more stable voltage in the network, even when the load is high, thus extending the life of infrastructure equipment.

However, retraining also involves a few disadvantages. The process requires significant financial investment, both for the necessary materials and for the associated labor and logistics. During the works, temporary power outages may occur, affecting consumers. Implementing retrofitting is complex, especially in hard-to-reach areas, and may require special equipment and rigorous planning. The process can also have an impact on the environment, both through the work required and the management of the replaced conductors.

2.4. *Voltage Regulators and Control Relays*

In addition to OLTCs and capacitors, distribution networks also use voltage regulators and control relays to monitor and adjust voltage. Voltage regulators work by continuously adjusting the output voltage, and control relays trigger corrective action when the voltage falls outside the preset operating range.

Advantages: These devices provide precise and continuous voltage regulation and can operate automatically based on detected network conditions.

Limitations: However, they can become obsolete in a context with rapid and unpredictable voltage fluctuations, as is the case in modern networks with a significant increase in the use of renewable sources and electric vehicles. In addition, traditional voltage regulators and relays are not always integrated with more advanced control systems, which limits their ability to effectively respond to complex scenarios.

2.5. *Active Voltage Regulation (AVR)*

The concept of Active Voltage Regulation (AVR) is a modern and efficient solution to face the challenges generated by the increase in the use of renewable sources.

Active voltage regulation is based on the use of advanced control algorithms that monitor real-time network conditions and continuously adjust the voltage to maintain stability. Unlike traditional methods, which tend to be slower and reactive, AVR allows a fast and accurate reaction to voltage variations caused by fluctuations in PV production.

AVR offers numerous advantages over traditional methods:

– Fast and accurate response: The AVR can react almost instantly to changes in the mains, thus preventing large voltage variations.

– Adaptability: The system can be configured to respond to various scenarios, including rapid and unpredictable fluctuations caused by renewables and EV loads

– Improving network stability: By maintaining a stable voltage, the AVR helps to extend the life of equipment and reduce network losses

Limitations of AVR technology include the complexity of implementation and the need for upfront investments in equipment and infrastructure. Also, the AVR may require continuous control software updates to remain efficient in the face of ever-changing network conditions.

AVR represents an essential step towards modernizing distribution networks, offering superior control and increased adaptability over traditional methods.

2.6. *Low Voltage Regulator (LVRSys)*

LVRSys (Low Voltage Regulator System) is a voltage regulation technology designed to correct voltage fluctuations in low voltage (LV) networks. The system is built around a voltage regulator that works by adding or subtracting an additional voltage in series with the supply voltage to keep the voltage within desired limits.

LVRSys uses 2 transformers per phase, a total of 6 transformers for the 3 phases that can introduces an additional voltage in series with the existing voltage on the supply line. The transformer is controlled by a set of thyristors that switch between different combinations of windings to achieve voltage correction steps. The system can correct the voltage in steps of ±1.5%, with a total compensation of up to 20%.

The regulator can be set to maintain a certain reference voltage and adjust tolerances for deviations, being able to react quickly to fluctuations. The system can operate on a phase-by-phase basis, allowing individual corrections on each phase and eliminating phase imbalances.

LVRSys is useful in low-voltage networks with distributed sources, such as photovoltaic (PV) installations, or in networks with high charging requirements, such as those that include electric vehicle (EV) charging stations. The system helps to maintain the voltage quality within the required limits, allowing the integration of higher generating or charging capacity without affecting the stability of the grid.

One of the strengths of the system is the high energy efficiency, thanks to the reduced energy losses through the optimized use of semiconductors and the transformer. LVRSys also does not introduce harmonics or flicker into the network, ensuring clean and stable operation. It allows voltage regulation for each phase, which is essential in low-voltage networks where loads and generation can vary significantly from one phase to another. The system has very low power losses, below 0.5%, due to the use of semiconductors only for switching the transformer windings, which minimizes additional power consumption. It can be applied to various types of low voltage networks, either at the level of local transformers, or on individual lines or even on individual phases. The system can correct voltage fluctuations in under 30ms, making it efficient in handling rapid variations in load or power generation. Compared to other solutions such as OLTC (On-Load Tap Changer), LVRSys is more economical and can be implemented in a shorter time, providing a practical solution in the short and long term.

As disadvantages, the system has a maximum regulation capacity of 20%, which may not be sufficient in extreme cases of voltage variations, such as a sudden drop or a large increase in voltage. The system requires proper configuration and maintenance, especially in complex networks or in networks with multiple charging points or distributed generation. Accurate voltage regulation at a remote node requires a good knowledge of the network impedance, which can complicate implementation in certain scenarios.

Each of these methods offers unique benefits and drawbacks depending on the specific conditions of the LV network. The LVRSys is emphasized for its simplicity, low operational losses, and its ability to correct individual phases, making it particularly suited for handling modern grid challenges posed by renewable energy and EV loads.

3. Results – Case Study of LVRSys in the Retele Electrice LV network

A case study was conducted on a very long feeder cable in a semi-rural area in Muntenia Area on which consumers were experiencing both over and under voltages. In this area multiple complaints and contraventions regarding the voltage level were registered at ANRE.

A strategic location that could potential accommodate a LVRSys was identified, and voltage monitoring exercise was conducted for a week.

The low voltage regulator system, A-Eberle, LVRSys 110kVA model was installed on the public domain, in Corbeanca, Ilfov, in the proximity of PTA 7720.

It can be observed that the voltage on the three phases was controlled successfully for most of the time close to the programmed setpoint. The voltage rises were completely compensated. The voltages downstream of the regulator are maintained within the imposed limits of -10% and +5% of U=230/400Vac. The highest voltage value is recorded on phase 2 (235.3V), and the lowest on phase 1 (222.6V).

For example, we can see phase 2 upstream and downstream of the regulator. For phase 2, it can be seen from the graph that upstream of the regulator the voltage is between 209 and 245V, while downstream of the regulator the voltage is maintained within the limits imposed by the ANRE electricity quality standard of +5 and -10% of U=230/400Vac. Thus, the downstream voltage is between 223.6 and 235.3V.

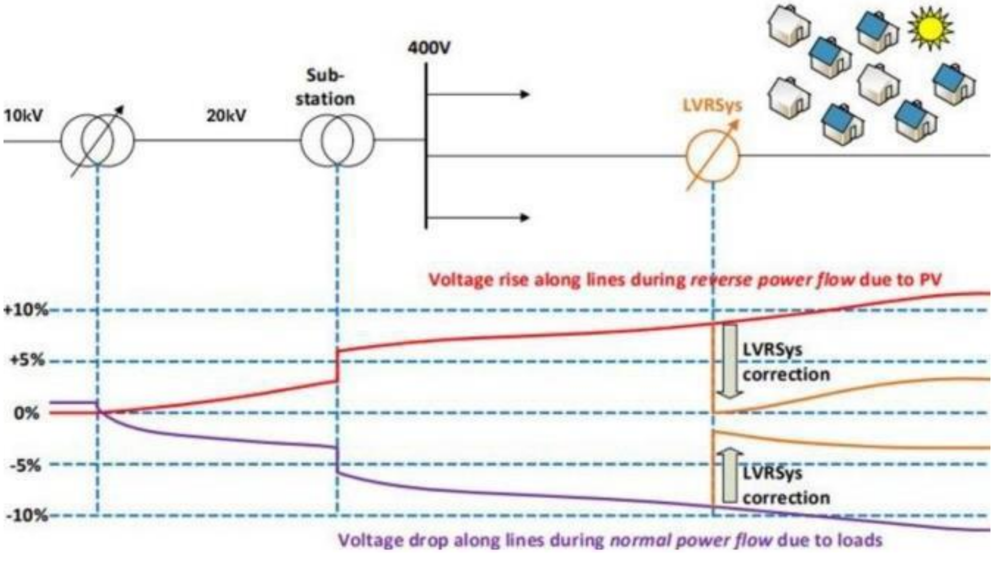


Figure 1. Presentation of LVRSys equipment

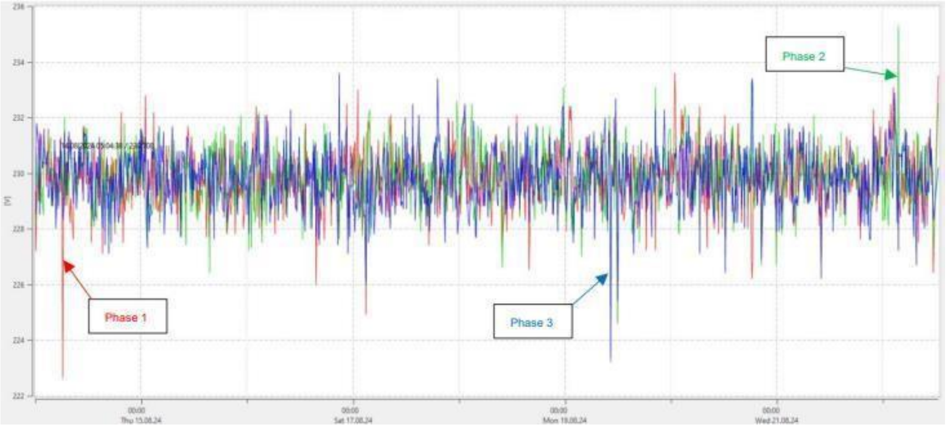


Figure 2. Voltage curves on phases downstream of the regulator

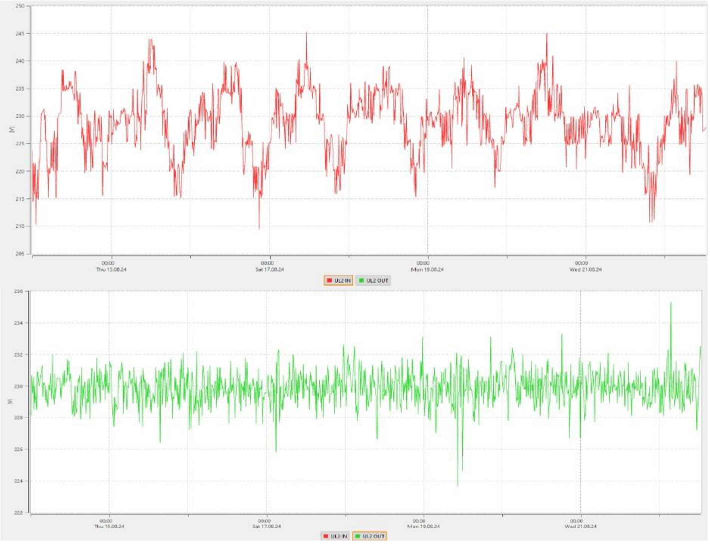


Figure 3. Voltage curves on phase 2 upstream (red) and downstream (green) of the regulator

On the current side, the graph in Figure 4 was obtained.

For example, we can see phase 2 upstream and downstream of the regulator. For phase 2, it can be seen from the graph that upstream of the regulator the voltage is between 209 and 245V, while downstream of the regulator the voltage is maintained within the limits imposed by the ANRE electricity quality standard of +5 and -10% of U=230/400Vac. Thus, the downstream voltage is between 223.6 and 235.3V.

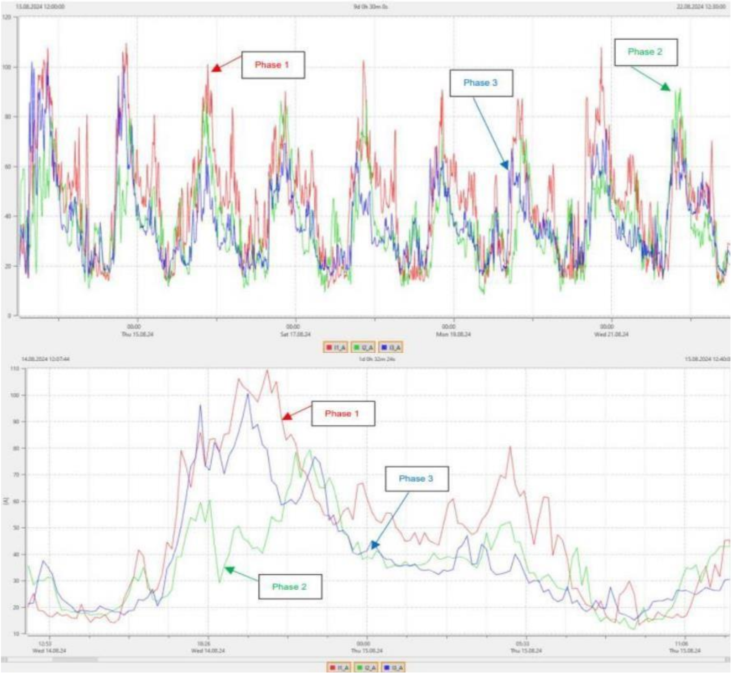


Figure 4. Current curves per phase downstream of the regulator

Looking at the current graph, on phase 1 we have the highest values (max 109.5A), and on phase 2 we have the lowest values (min 8.3A).

The power diagram and power loss diagram for the 110kVA 10% system (Muntenia):

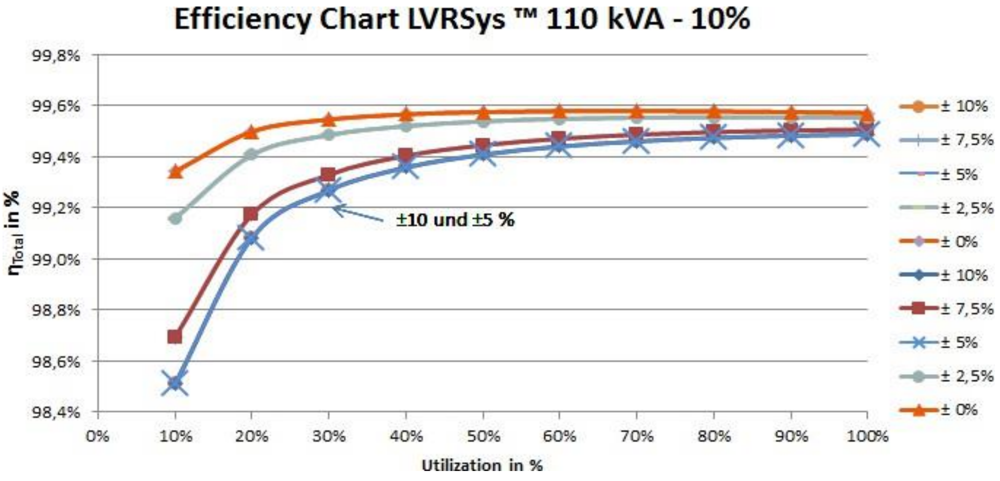


Figure 5. The power diagram for the 110kVA 10% system

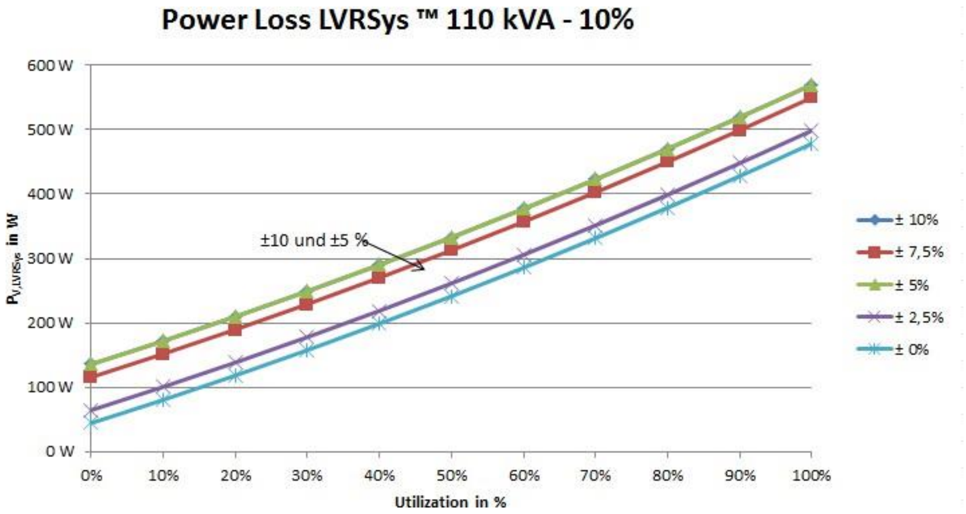


Figure 6. The power loss diagram for the 110kVA 10% system

Next, we used the data taken from the analyzer installed on the output terminals of the regulator as shown in the figures below. The extracted data were analyzed with the analyzer specific program, Power View, and the graphic results for the voltage and current curves were presented in the following.

Figure 7. The analyzer located upstream and downstream of the regulator

Table 1. **Data extracted from the power quality analyzer downstream of the regulator**

Percent of intervals	Voltage (230,00 V)			Voltage THD (0,00 %)			Frequency (50,00 Hz)
	207,00 V ... 253,00 V			0,00 % ... 8,00 %			49,50 Hz ... 50,50 Hz
	U1 [V]	U2 [V]	U3 [V]	THD U1 [%]	THD U2 [%]	THD U3 [%]	f(10s intervals) [Hz]
User defined % of intervals	227,29 V ... 232,67 V	227,83 V ... 232,17 V	227,24 V ... 232,38 V	2,41 % ... 5,48 %	3,04 % ... 5,26 %	2,77 % ... 6,09 %	49,93 Hz ... 50,07 Hz
100% of intervals	0,21 V ... 233,20 V	0,17 V ... 232,97 V	0,17 V ... 233,27 V	---	---	---	49,27 Hz ... 50,09 Hz

The reference values for the nominal voltage in this context are 230 V. The voltage measured on all three phases shows very little variation around this nominal value, which indicates a good stability of the electrical system. For example, the voltage on phase U1 varies between 227.29 V and 232.67 V, while on phase U3 it is recorded between 227.24 V and 232.38 V. These minimal variations confirm adequate stability of the electrical network.

All phases fall within the range of variation allowed according to the standard, namely +5% and - 10% of the face value. The lowest recorded voltage of 227.24 V (on phase U3) represents a deviation of about -1.2% from the nominal value of 230 V, but is still well above the lower limit of 207 V.

Also, the highest measured value, of 232.67 V (on phase U1), is +1.2% above the nominal voltage, but remains below the upper limit of +5% (241.5 V).

According to the performance standard, the measured voltages demonstrate high stability, being within the allowed range of 207 V - 241.5 V (+5% and -10%). No significant deviations were recorded to indicate the presence of under- or over voltages, and these reduced variations ensure optimal and safe operation of electrical equipment. In conclusion, the stability of the system is guaranteed, without major risks for the operation of sensitive equipment.

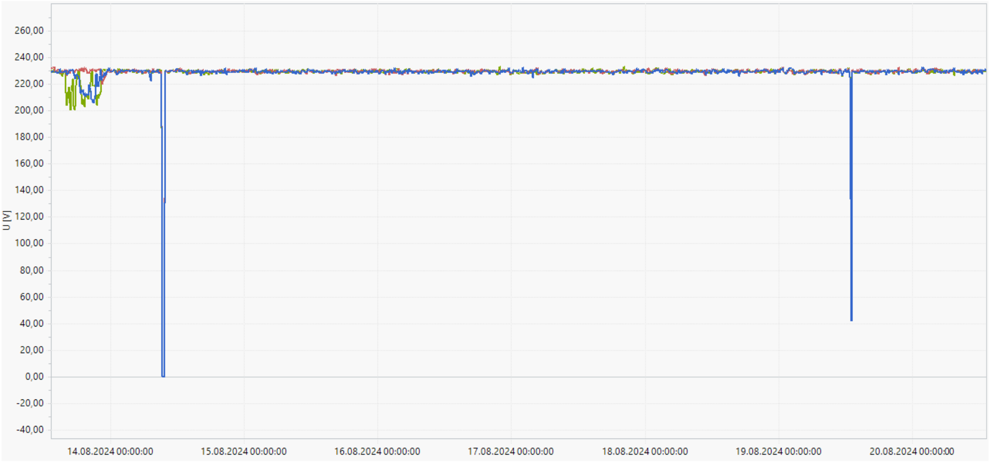


Figure 8. Voltage curve downstream of the regulator

On a working day, under normal conditions, when the consumption on the line on which the regulator was placed is a medium one, a measurement was made in PTA 7720 and at the end of the low voltage line.

In PTA 7720 there is a 20kV/420V transformer of 250kVA power with several 5 plots of operation. For the data from this case study, the transformer is placed on plot 2 of operation. On the respective line there are many consumers with high consumed powers and thus there is a large variation in consumption day-night, and the LVRSys equipment allowed a compensation of the voltage drop in addition to the additional injection between PTA 7720 and mounting point.

At the beginning of the line, the voltage is 235.7V, a value slightly above the standard nominal voltage of 230V, but which is within the normal variation limits for electrical networks. This small difference from the nominal voltage can be influenced by various factors such as the current load in the network, the configuration of the electrical equipment or the distance from the power source. At the end of the line, the measured voltage is 234.6V.

This is a very small drop of 1.1V from the original voltage, indicating negligible line losses, which are expected in a well-maintained system.

Figure 9. The voltage at the beginning and at the end of the line on which the regulator was placed

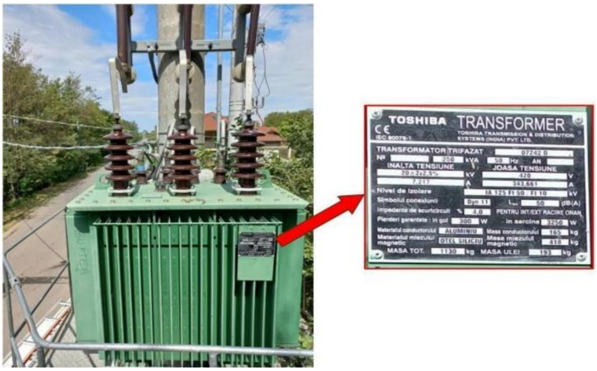


Figure 10. 20kV/420V power transformer 250kVA from PT 7720

This minimal voltage difference suggests that the power system and cables used are in good condition and there are no significant problems with voltage drops or power losses along the line. Such a system ensures a stable power supply for electrical equipment, preventing large fluctuations or losses that could lead to low performance or even equipment damage.

In conclusion, the voltage at the beginning of the line, 235.7V, and the voltage at the end of the line, 234.6V, show a well-balanced electrical system with minimal voltage losses. This confirms that the voltage regulator and wiring are effective in maintaining the stability of the network, ensuring a constant and safe voltage for all connected equipment.

4. Conclusions

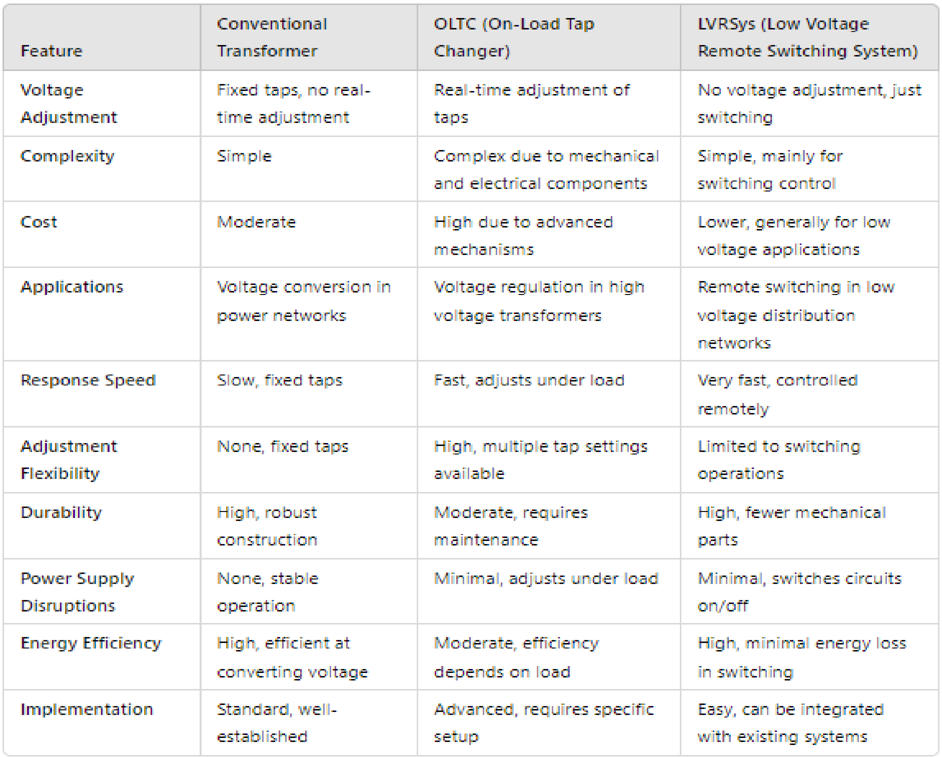
This paper explores common approaches for addressing voltage surges and dips caused by high photovoltaic (PV) generation and increasing network loads. A case study focuses on a low-voltage (LV) feeder in the semi-rural Muntenia region, initially designed to serve a small community and not equipped to handle the large-scale integration of PV systems and electric vehicles (EVs).

The study demonstrates that voltage across the load was effectively stabilized around the nominal value of 230V, confirming the Low Voltage Regulation System (LVRSys) as a viable solution for managing voltage variations beyond regulatory limits. Furthermore, the LVRSys enables the integration of multiple PV systems on a single feeder, enhancing the network's capacity for distributed energy generation.

A comparison of LVRSys with conventional transformers and tap-changer transformers highlights the varied methodologies and technologies employed to maintain voltage within desired parameters. Each system offers specific benefits and limitations, depending on operational context and requirements. Key distinctions in voltage regulation, complexity, cost, and applications are summarized in the table below.

The LVRSys stands out for its minimal operational losses and cost-effective, expedient alternative to traditional grid reinforcement. This makes it an appealing solution for network operators facing the rapid expansion of PV and EV installations in LV networks. Another notable advantage of the LVRSys is its capability for individual phase correction, an essential feature in scenarios where PV system proliferation and phase load distribution are in constant flux.

Tabel 2. **The comparison of the LVRSys system with conventional transformers and tap-changer transformers**



Feature	Conventional Transformer	OLTC (On-Load Tap Changer)	LVRSys (Low Voltage Remote Switching System)
Voltage Adjustment	Fixed taps, no real-time adjustment	Real-time adjustment of taps	No voltage adjustment, just switching
Complexity	Simple	Complex due to mechanical and electrical components	Simple, mainly for switching control
Cost	Moderate	High due to advanced mechanisms	Lower, generally for low voltage applications
Applications	Voltage conversion in power networks	Voltage regulation in high voltage transformers	Remote switching in low voltage distribution networks
Response Speed	Slow, fixed taps	Fast, adjusts under load	Very fast, controlled remotely
Adjustment Flexibility	None, fixed taps	High, multiple tap settings available	Limited to switching operations
Durability	High, robust construction	Moderate, requires maintenance	High, fewer mechanical parts
Power Supply Disruptions	None, stable operation	Minimal, adjusts under load	Minimal, switches circuits on/off
Energy Efficiency	High, efficient at converting voltage	Moderate, efficiency depends on load	High, minimal energy loss in switching
Implementation	Standard, well-established	Advanced, requires specific setup	Easy, can be integrated with existing systems

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Author biographie

Georgiana STANCIU graduated from the Faculty of Power Engineering at the University Politehnica of Bucharest, Romania, with a focus on Electrical Power Systems. She pursued postgraduate studies in the master's program Monitoring and Control of Power Systems (MS2) within the same faculty. Her academic background and interests lie in the fields of Power System Operation and Monitoring, Control Strategies for Electrical Networks, Renewable Energy Integration, and Energy Efficiency.

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