INTELLIGENT CONTROL SYSTEM FOR A 315 kVA TRANSFORMER STATION TO OPTIMIZE PROSUMER INTEGRATION IN SMART GRIDS

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Abstract: *This paper proposes an automation solution applied to a 315 kVA transformer station—a benchmark unit in distribution networks—to address the challenges posed by the large-scale integration of renewable energy sources. The core issue addressed is the uncontrolled rise of the voltage profile at consumer terminals during periods of peak solar radiation. The technical solution involves implementing an automated tap-changer control system (Digital OLTC), which utilizes the existing regulation taps to maintain voltage within normative limits. This study demonstrates how the digitalization of classical 315 kVA infrastructure transforms a passive component into an active, intelligent node, essential for the stability of Smart Grids.*

Keywords: Smart Grid, 315 kVA Transformer, Digital OLTC, Prosumer Integration, Voltage Regulation, IoT Monitoring, Automated Control, Power Quality

1. INTRODUCTION: EVOLUTION TOWARDS BIDIRECTIONAL NETWORKS AND THE STRATEGIC ROLE OF THE TRANSFORMER

The modern energy system is undergoing a historic transition from the traditional model of unidirectional power flow to the Smart Grid concept. While energy previously flowed exclusively from large power plants to end-users, the explosive emergence of prosumers has necessitated a bidirectional power flow, placing unprecedented technological pressure on existing infrastructure. In this context, the 315 kVA transformer remains, even looking toward 2026, the critical component of low-voltage networks, serving as the primary interface between the medium-voltage grid and small-scale producers/consumers. Originally designed to serve purely passive loads, this cornerstone of distribution substations must now handle operating regimes for which it was not originally equipped in terms of manual control.

The primary technical challenge arises during peak solar production (midday), when local consumption is minimal and surplus energy is injected into the grid. This "reverse power flow" causes a voltage rise at consumer terminals beyond the permissible ± 10% limits. Without automated intervention, this situation leads to cascading disconnections of photovoltaic inverters, negating the economic benefits of green energy, accelerated aging of the transformer insulation due to dielectric stress, and malfunctions of downstream electrical equipment. Therefore, optimizing the control of the 315 kVA transformer is not merely a technical improvement but a mandatory condition for the stable and efficient operation of modern electrical networks [1].

2. TECHNICAL PARAMETERS AND VOLTAGE PROFILE ANALYSIS

To develop and validate the intelligent control system, this paper utilizes a reference model based on a 315 kVA distribution transformer, representing the current standard in low-voltage networks . The unit is designed for continuous duty (S1 operation), serving a mix of passive consumers and photovoltaic producers. The fundamental data is summarized in table 1.

Table 1. Rated data of the reference transformer

Parameter	Symbol/unit	Value
Rated Power	S_n [kVA]	315
Primary Rated Voltage	U_1 [V]	6000
Secondary Rated Voltage	U_2[V]	400
Secondary Rated Current	I_{2n} [A]	454.66
Short-circuit Voltage	u_k [%]	6
Vector Group	-	Y_y6

The proposed automation algorithm acts upon the tap-changer system, which features a regulation range of $\pm 5\%$ of the rated voltage in steps of $2 \times 2.5\%$. This regulation is performed on the medium-voltage winding to directly influence the secondary terminal voltage. Furthermore, the system's efficiency depends on the loss regime, which becomes dynamic under bidirectional power flows.

The analyzed transformer presents no-load losses (P_0) of 740 W, originating from core magnetization, and load losses (P_{Cu}) of 5650 W, which increase quadratically with the current injected by prosumers.

Table 2: Analysis of energy losses at rated load

Loss Type	Value	Impact in Smart Grid Operation
No-load Losses (P_0)	740 W	Magnetization losses, permanently present in the network.
Load Losses (P_{Cu})	5650 W	Increases quadratically with the current injected by prosumers.

In the traditional configuration of distribution networks, power flow is unidirectional, leading to a gradual voltage drop toward the end of the line. However, prosumer integration radically changes this dynamic through the "Power Reversal" (reverse flow) phenomenon.

To visualize the technical impact of this shift on the 315 kVA transformer, the comparative simulation of the voltage profile in figure 1 highlights how massive solar energy injection during peak periods raises the voltage at consumer terminals beyond safety limits, causing system instability [2].

These results demonstrate the inadequacy of the conventional operating regime (blue curve) when faced with prosumer dynamics (red curve), as photovoltaic power injection causes a flow reversal that, at distances exceeding 300 m from the transformer, raises the voltage above the normative limit of 253V [3].

This phenomenon forces inverter disconnections and accelerates insulation degradation, confirming that the benchmark transformer's fixed regulation taps are insufficient and demonstrating the technical necessity for an active control system to maintain network stability.

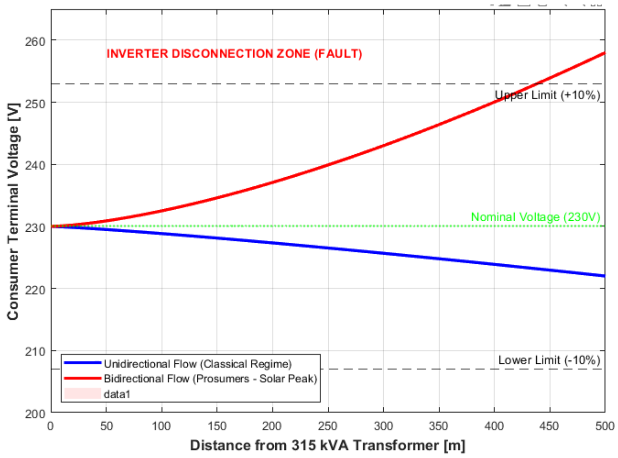

Figure 1. Comparison between voltage profiles in conventional regime vs. Smart Grid regime with prosumers

3. ENERGY REGIME AND THERMAL STRESS ANALYSIS

The efficiency and reliability of the 315 kVA transformer within the Smart Grid context are conditioned by the management of power losses and the resulting thermal stress. In the prosumer regime, load dynamics undergo changes that can lead to accelerated equipment degradation. The efficiency and thermal behavior are directly influenced by active losses in the magnetic circuit and windings; modeling parameters (P_0 = 740W, P_{Cu} = 5650W$) comply with design standards for 315 kVA units, providing a realistic basis for analysis under bidirectional power injection conditions. Transformer operation involves core losses (P_0 = 740 W), which remain constant through magnetization, and copper losses (P_{Cu} = 5650 W), which vary with the square of the current. In prosumer regimes, these losses reach peak values during solar maximum periods, often overlapping with high ambient temperatures.

The conventional design of distribution transformers assumed a predictable, unidirectional load curve. Reverse power flow introduces additional stresses: flow reversal can alter magnetic field lines, generating unsimulated stray losses, while thermal saturation occurs at midday when natural convection cooling is limited by high ambient temperatures. Consequently, managing these stresses requires a transition from preventive maintenance to an active control system capable of correlating electrical parameters with equipment thermal limits [4]. Continuous temperature monitoring is a strategic asset conservation approach [5]. According to Montsinger's Life Law, a sustained increase of only 6-8°C above the rated temperature can halve the lifespan of cellulosic insulation. Oil overheating risks the formation of dissolved gases and decreased dielectric strength, increasing the risk of inter-turn breakdown. To quantify these challenges, table 4 correlates operating regimes with thermal impacts, highlighting the necessity of advanced digital monitoring to mitigate risks.

Table 4. Correlation between operating regime and thermal impact

Parameter	Passive Regime (Conventional)	Prosumer Regime (Active)	Technical Consequence
Peak Load	Evening (Cold ambient)	Noon (Warm ambient)	Poor cooling efficiency
Flow Direction	Primary $\rightarrow$ Secondary	Bidirectional	Asymmetric thermal stress
Monitoring	Non-existent / Visual	Digital (PT100 Sensors)	Necessity for automation

4. REVERSE POWER FLOW ISSUES AND THE IMPACT ON VOLTAGE

The transition toward Smart Grids transforms 315 kVA transformer stations from consumption nodes into energy collection nodes. This paradigm shift introduces technical challenges related to voltage stability that were not foreseen in classical design standards. In the conventional regime, current flows from the transformer toward the load, generating a positive voltage drop. This is governed by the simplified equation:

$$\Delta U = I \cdot \left(R \cdot \cos\phi + X \cdot \sin\phi \right) \tag{1}$$

where R and X represent the resistance and reactance of the line. In this case, the consumer voltage (U_{cons}) is remains lower than the transformer terminal voltage (U_{trafo}). However, when prosumers inject energy, the current direction (I) reverses and becomes negative relative to the source, transforming the voltage drop into a rise:

$$U_{cons} = U_{trafo} + \Delta U_{invers} \tag{2}$$

Consequently, higher solar production causes the voltage at consumer terminals to deviate further from nominal values, rising toward the upper limit of the regulation band .

4.1. Peak solar impact and normative compliance

To understand the severity of this phenomenon, we analyze the network behavior at 1:00 PM on a clear summer day, when solar production reaches 80-90% capacity and local consumption is at a minimum. The resulting massive energy surplus is "pushed" through the low-voltage cables back toward the 315 kVA transformer. Line impedance forces the voltage at inverter terminals to rise beyond the nominal grid voltage to overcome it. According to the EN 50160 power quality standard, voltage must remain within 230V ± 10\% (207V – 253V) [3].

Voltages between 255V and 260V are unacceptable as they trigger several critical issues: photovoltaic inverters disconnect automatically above 253V, leading to economic losses and grid instability. Furthermore, domestic appliances suffer from power supply overheating and premature failure at constant voltages above 250V. For the 315 kVA transformer, this secondary voltage increase heightens dielectric stress on inter-turn insulation, risking internal electrical arcs. These dynamics, summarized in table 5, confirm the technical necessity for active control.

Table 5. Comparative analysis of parameters at 1:00 PM

Parameter	Nominal Value	Value at Solar Peak (No Control)	Status
Phase-to-Neutral Voltage	230 V	255 - 258 V	Critical (Exceedance)
Power Flow Direction	Unidirectional (Trafo → Load)	Bidirectional (Prosumer → Trafo)	Reversed
Line Losses	Low	High (due to injection)	Low Efficiency

The voltage values for the solar peak regime were extracted from the simulation model presented in figure 1, corresponding to the injection points located at the maximum distance from the transformer station.

5. CONTROL SYSTEM ARCHITECTURE AND SOFTWARE LOGIC

To correct the voltage profile identified in the previous chapter, it is necessary to implement an active control solution that transforms classical manual regulation into an automated Digital OLTC process [6]. The proposed architecture is organized into three functional levels, as represented in figure 2, ensuring minimum latency: an **Acquisition Level** consisting of bidirectional sensors and PT100 modules; a **Processing Level (PLC)** which serves as the decisional core; and an **Execution Level (Actuator)** where a precision servomotor operates the tap changer.

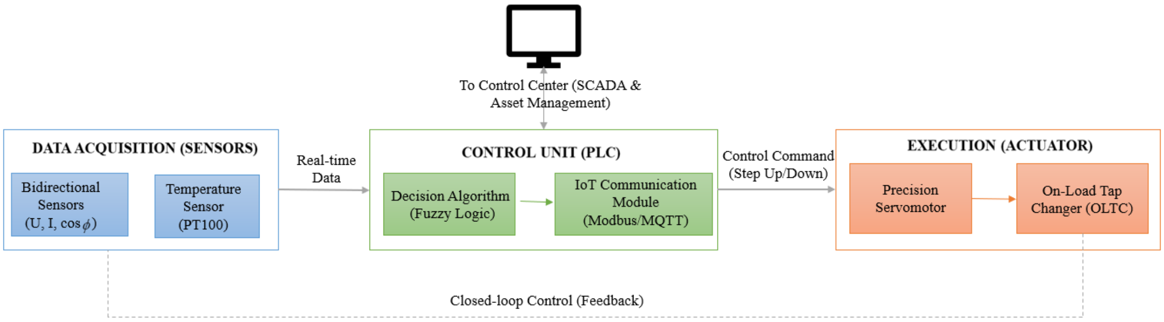

Figure 2. Functional Block Diagram of the Automated Voltage Control System for a 315 kVA Transformer

Unlike a conventional voltage stabilizer, the system anticipates the "solar peak" by analyzing the production increase slope, allowing reactions within milliseconds. The system's "intelligence" is based on a dead-band and a digital hysteresis delay function to prevent the "hunting" phenomenon—repeated switching caused by intermittent cloud cover. As soon as a massive power injection reaches the critical threshold of 253V, the control unit commands a reduction in the transformation ratio (e.g., from +2.5% to 0% or -2.5%), pushing the voltage profile back into the nominal 230V band. This operational efficiency is governed by a dedicated algorithm where, if $U > 1.05 \cdot U_n$ and reverse flow is confirmed, the controller initiates a "Minus" step tap change [7], [8], [9]. Furthermore, a protection module monitors if total prosumer injection power exceeds transformer capacity ($P_{prosumers} > S_{nominal\_trafo}$), generating a limitation signal to maintain the thermal integrity of the 315 kVA unit. This closed-loop logic ensures that every switching operation is mathematically justified and executionally safe.

5.1. IoT monitoring and predictive maintenance

All collected data—including voltage, current, temperature, and switching operations—are transmitted via Modbus TCP or MQTT protocols to a centralized SCADA dispatch center. This real-time information enables advanced operational strategies such as Predictive Maintenance, where analyzing tap-changer operations and operating temperatures allows for maintenance scheduling based on actual equipment condition rather than fixed intervals . Furthermore, it facilitates Network Optimization by providing dispatchers with a real-time "Health Index," enabling remote intervention if anomalies exceed the local automation's capacity . The technical specifications are summarized in table 6.

Table 6. Technical specifications of the monitoring system

Module	Technology	Role in Smart Grid
Communication	Gateway 4G/5G / NB-IoT	Data transmission to Cloud/SCADA
Protection	Anti-Oscillation Algorithm	Prevents repeated switching (wear)
Visualization	Real-time Dashboard	Remote monitoring of prosumers

The integration of these technologies transforms the transformer station into an active node of the smart grid, enabling continuous supervision without direct human intervention. This robust infrastructure supports the intelligent control algorithm, ensuring accurate execution of switching decisions based on prosumer dynamics [10], [11].

6. ANALYSIS OF EXPECTED RESULTS AND ECONOMIC IMPACT

The implementation of the automation system generates immediate benefits by optimizing existing assets within the energy transition. The primary effect of the Digital OLTC algorithm is maintaining the voltage within an optimal band, regardless of solar production variability [12, 13]. As shown in figure 3, without automation (red line), the voltage exceeds the 253V limit at approximately 410 meters from the transformer station. By activating the system (blue line), the exact moment of the tap change is observed, immediately stabilizing the voltage around 240V and ensuring continuous prosumer operation in compliance with the EN 50160 standard.

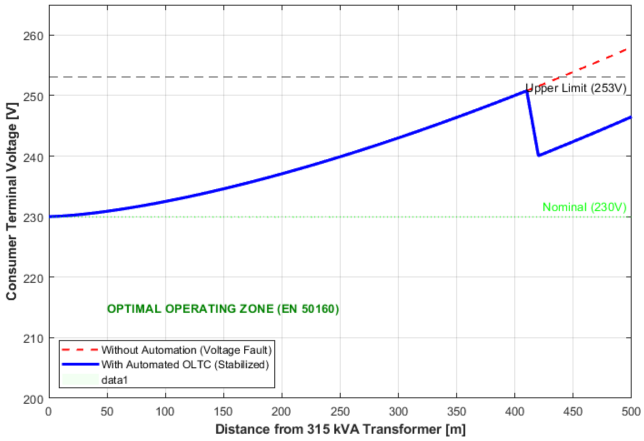

Figure 3. Comparative analysis of voltage stabilization performance through the automated OLTC system

Beyond stabilization, this active management allows the 315 kVA transformer to support a photovoltaic capacity up to 30% higher without replacing existing low-voltage conductors, maximizing the rated capacity calculated during design [14], [15], [16], [17] . Furthermore, the system extends equipment lifespan by reducing mechanical stress—eliminating current surges and electrodynamic forces during transient regimes—and preserving insulation . By correlating thermal control with copper losses (P_{Cu} = 5650 W$), the aging of cellulosic insulation is slowed, potentially extending service life by 25% [18], [19], [20]. As centralized in table 7, this transition represents a rapid-amortization investment that maximizes green energy ROI and ensures long-term grid stability.

Table 7. Comparative analysis of performance indicators

Performance Indicator	Conventional Regime	Smart Regime (Automated)	Benefit
PV Integration Level	Limited by voltage	+30% Capacity	Additional revenue
Failure Rate (Inverters)	High (U > 253V)	Minimal (Stable U)	Customer satisfaction
Transformer Lifespan	Reduced by thermal stress	Maximized (Active control)	CAPEX cost reduction

7. CONCLUSIONS

This paper has addressed the complexity of modernizing electrical infrastructure by automating a 315 kVA transformer, providing a viable solution to the challenges posed by the growing number of prosumers in low-voltage networks.

Based on the analysis and simulations performed, the following conclusions were formulated:

- Modernizing existing transformers in operation by integrating automated on-load tap changer (Digital OLTC) systems proves to be the fastest and most efficient strategy for supporting the energy transition. This technological approach allows the adaptation of current infrastructure to new energy market requirements, avoiding the massive costs and long timelines required for the total reconstruction of distribution networks.
- Grid stability is guaranteed through the use of the proposed algorithm, which has demonstrated the capacity to maintain the voltage at consumer terminals within the strict normative limits of 230V ±10%. By eliminating overvoltages that reach the 258V threshold, the system prevents unwanted disconnections of photovoltaic inverters, thereby ensuring constant green energy production and eliminating economic losses suffered by prosumers.
- Asset optimization is achieved through more intelligent load management of the 315 kVA unit, facilitated by continuous monitoring of operating parameters. Automation allows for active control of thermal and mechanical stress, preventing the accelerated degradation of cellulosic insulation and extending the equipment's lifespan. This transforms the classic transformer into a robust and reliable point within the Smart Grid architecture.
- The originality of this work lies in its hybrid approach: the rigorous combination of traditional electro-mechanical design (loss calculation, winding sizing, tank mechanical calculation) with cutting-edge digital technologies (IoT, bidirectional sensors, and closed-loop control algorithms). This synthesis transforms static equipment into an active and intelligent node of the Smart Grid.

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