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Original Research Paper

Smart Grid Design and Simulation for Goma TMK Substation Regulation

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Abstract: Power distribution networks in places like Goma, Democratic Republic of Congo, face the challenges of voltage control, energy loss, and power quality because they depend mainly on manual control provided at substations such as TMK. This study proposes a smart grid solution for automated voltage regulation through On-Load Tap Changer (OLTC) control for inefficiencies stemming from the above challenges using a Programmable Logic Controller (PLC). The system utilizes real-time electrical parameters monitoring, thereby employing dynamic adjustment processes to ensure voltage levels are kept at their optimum, as well as limiting overcurrent and improving thermal stability. The hybrid simulation approach uses Siemens TIA Portal for PLC logic and MATLAB Simulink to check the system's dynamic analysis under varied loads and faults. The results proved to enhance voltage stability and operational efficiency, and robustness while minimizing human intervention. The architecture is amenable to SCADA integration and distributed energy resources for future incorporation, thus providing a scalable solution to aging grids in resource-poor settings.

Keywords: Adaptive Voltage Control, OLTC, PLC, Real-Time Monitoring, Smart Grid.

1. Introduction

Electricity distribution has been, and still is, a very critical factor for economic growth, industrial productivity, and social development, but developing regions such as Goma in the Democratic Republic of Congo (DRC) have repeatedly felt the interventions of aging infrastructures, increasing demand, and poor voltage regulation [1] [2]. The TMK substation, which belongs to the Société Nationale d'Électricité (SNEL), still practices manual voltage control, leading to imbalances and huge energy losses (supply: 12.3 MW; demand: 55 MW) and to the deterioration of the equipment [3] [4]. These deficiencies affect the quality of power [5] - [7], increase operational costs [8], and retard socio-economic development [9] [10]. This study proposes a solution aimed at automatic voltage regulation utilizing a Programmable Logic Controller (PLC) for real-time control of the On Load Tap Changer (OLTC), ultimately dampening voltage fluctuation and minimizing losses, while also strengthening grid resilience against external disturbances. The solution encapsulates the spirit of a smart grid and presents a possibility for future scalability of SCADA and distributed energy integration.

Got to admit that it captures the point, indeed: Goma TMK substation, which is run by SNEL, has voltage regulation that is so slow and manual, such that it has a large susceptibility to errors under fluctuating load settings and has a high propensity towards instability. The means to strengthen the grid through this research is an automated control system for voltage stabilization in real-time through PLCs as the basis of control, which is capable of giving a faster and more seamless response to faults, as well as easy connection and merging with advanced grid infrastructures. Proposed design-and-simulation: on a smart grid controlled and monitored via PLCs, toward improved reliability and dynamic performance. It is hoped that by improving the controllability of voltages, this system will optimize power delivery, ensuring fewer outages, thus enhancing sustainable development in Goma and the wider North Kivu Province.

2. Literature Review

Undoubtedly, stabilizing voltage aids in qualifying for power quality, minimizing energy losses, and safeguarding equipment [11] [12] [13]. Goma, in DRC, is undergoing tremendous power constraints on account of the weak grid of the region, dangerous overhead line transmission caused by volcanic terrain, and long-distance transmission from the 200 km from the Ruzizi hydropower plant [3] [4] [14] [15]. SNEL's network, comprised of one 2×10 MW transmission substation, five feeders, and 55 distribution substations, is generally characterized by lingering voltage sags, blackouts, and a 12.3 MW supply deficit in comparison with demand for 55 MW [16]. While some generation is supplemented by independent power producers (Virunga Energy, NURU), such inefficient operations are aggravated by a lack of grid interconnections and manual voltage regulation at the TMK substation [17] [18].

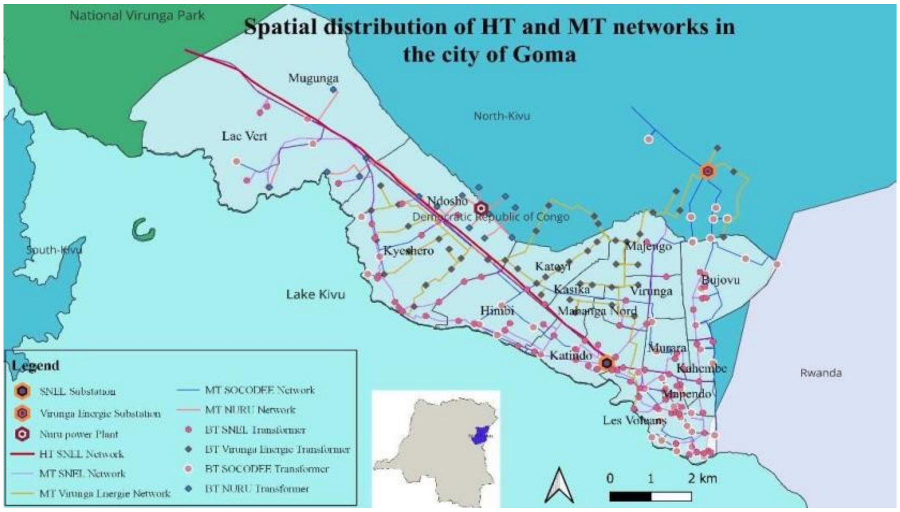


Figure 1. Spatial Distribution of HT and MT Networks in Goma

Past studies have shown the use of automation in fixing the voltage. Al-Muhaini & Heydt [19] verified the effective use of control by digital means of the voltage; Yadav et al. [20] confirmed that PLCs have a better time response than electromechanical relays. Hybrid grid studies [21] [22] and studies on smart grid integration [23] [24] provide some insight, but Goma's particular hydropower dependency and infrastructure limitations call for targeted solutions. The study attempts to fill the identified gap by proposing a PLC-controlled voltage regulation system specifically optimized for local applicability to Goma's aging grid in concert with smart grid developments [25] [26].

Recent literature reviews indicate that the PLC solutions designed for power distribution stability still leave critical gaps in real-time automation and predictive control [27].

This study develops a real-time dynamic response to Moura et., al. PLC-based voltage regulation, thus overcoming the lack of monitoring afforded by a grid-wide perspective [28]. With fault isolation being their focus, Powell et al. failed to consider smart grid-integrated voltage control [29]. Maretto, Faccio and Battini merged PLC with SCADA but suffered latency and manual dependence [30]. Accordingly, the proposed system for the TMK substation fills these gaps through fully autonomous PLC deployment, advanced algorithms for self-regulated, real-time adjustments to enhance stability in constrained grids such as Goma [31] [32].

4. Methodology

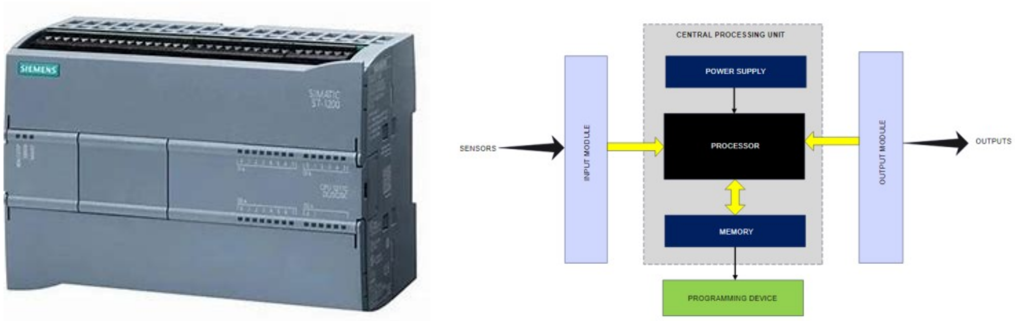
4.1. Design and Architecture

(1) System Components and Architecture

The research incorporates the design of a PLC-based voltage regulation and stabilization system for a 10 MVA, 70 kV/15 kV transformer fitted with an On-Load Tap Changer (OLTC), supplying a total of five 15 kV feeders in Goma city. The proposed system aims at keeping the secondary voltage within the ±5% band of 15 kV, following the IEC 60214-1 and IEEE C57.91- 2011 standards.

- PLC Controller

The PLC controller is the brain of the voltage stabilization system. It continuously monitors the voltage levels and maintains real-time voltage regulation on its programmed control logic.



(a) (b)

Figure 2. Programmable Logic Controller
(a) Body
(b) Block Diagram

- Voltage & Current Sensors

After sensing voltage and current, the measurement will allow power parameters to be monitored inside the network, thus enabling real-time system monitoring. With continuous feedback to the PLC, variations in voltage can be factored in by the control algorithm to provide a corrective action. Figure 3 shows the voltage sensors and current sensors.

- Actuators

Voltage stabilization mechanisms are actuators (Tap Changers & Relays), including On-Load Tap Changers (OLTC) and relays, which dynamically control voltage levels. The OLTC in a transformer sets the voltage by changing the winding connections of the transformer itself, thus keeping the output steady even through input supply fluctuations. Figure 4 shows the actuator types.

Figure 3. Voltage and Current Sensors

(a) (b)

Figure 4. Actuators
(a) Tap Changers
(b) Relays

Figure 5. Temperature Sensor PT100

- Temperature sensor (PT 100)

The PT100 temperature sensor is a Platinum Resistance Temperature Detector (RTD) that measures temperature by a change in platinum resistance as per $R_T=R_0\ (1+\alpha t)$ where $R_0=100\Omega$ and $\alpha=0.00385$. A signal conditioner transforms the resistance into a voltage for PLC integration purposes (0–10V). Figure 5 shows the temperature sensor PT100.

- Communication Interface

The interface of communication is for the remote monitoring and control of the voltage stabilization process. This will be accomplished through Human-Machine Interface (HMI) systems for real-time visualization of the voltage levels and adjustments whenever necessary.

(a) (b)

Figure 6. Communication Interface
(a) Communication Interface
(b) HMI Device for System Monitoring

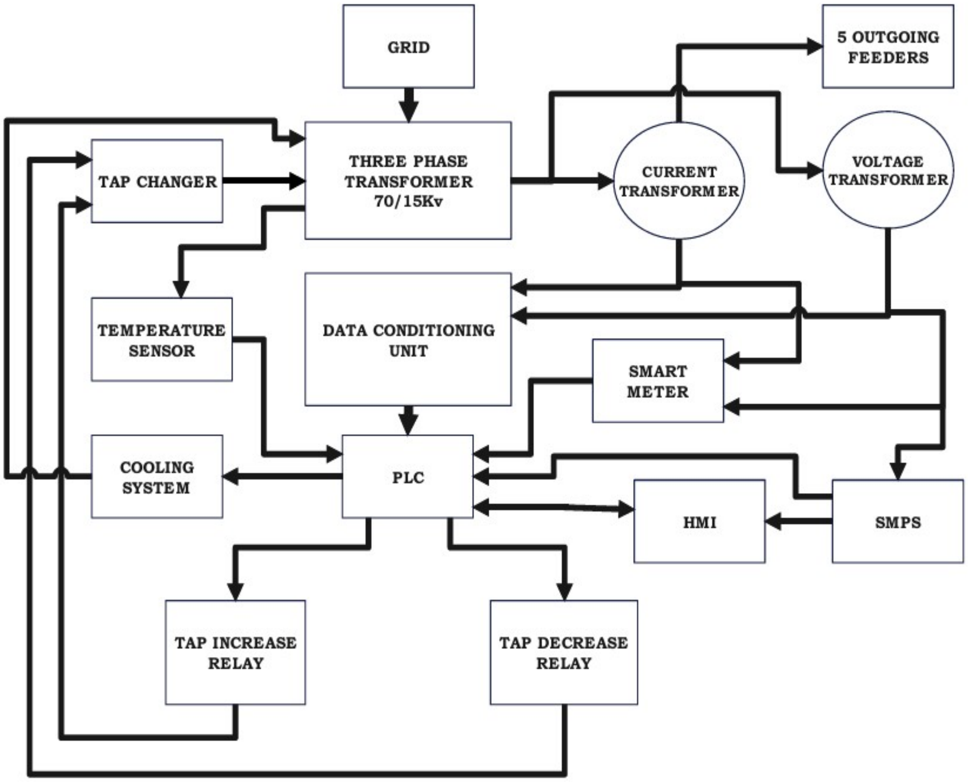


Figure 7. Block Diagram of the Proposed System

(2) Block Diagram Representation

The overall system architecture contains integrated subsystems that ensure the reliable operation of the AVR system. The transformer steps down the voltage from 70 kV to 15 kV, with the OLTC taking care of secondary voltage levels. The VTs and CTs reduce high-voltage and high-current signals suitable for processing by PLC. The data conditioning unit removes noise and formats signals for the PLC's A/D converter.

The PLC is the main control unit performing threshold-based and PID algorithms to regulate voltage. A relay-driven tap changer alters the transformer turns ratio to bring the voltage back to normal. The cooling system ensures temperature stabilization with the help of PT100 temperature sensors. HMI enables real-time monitoring and control, and the smart meter records power quality parameters for continuous optimization of the system.

4.2. Signal Acquisition and Conditioning

Voltage and current measurements are made using Voltage Transformers (VTs) and Current Transformers (CTs). The VTs scale down high voltage to a compatible range of 0- 10V for accurate monitoring in the analog input of the PLC. The CTs output current signals converted to a 4- 20mA loop using precision transducers for signal integrity and reduced transmission losses.

Table 1. System's Thresholds and Programming Setpoints

Parameter	Actual Threshold	PLC Input Range	Reference Setpoints
Voltage Regulation	0–15 kV	0–10V	10V = 15 kV
Overvoltage Alarm	15.9 kV	10.6V	Alarm Trigger
Undervoltage Alarm	14.1 kV	9.4V	Alarm Trigger
Overcurrent Trip	800 A	20mA	Trip at 20mA
Normal Current	666.7 A	16mA	Nominal Condition
Overtemperature Alarm	105°C	14.2mA	Alarm Trigger
Overtemperature Trip	110°C	14.8mA	Trip at 14.8mA

Figure 8. Signal Acquisition and Conditioning Module

4.3. PLC Programming

The system uses error signals (Error_voltage, Error_current, Error_temperature) to detect issues like disconnected sensors, out-of-range values, or analog input failures. The PLC checks if inputs (0- 10V, mapped as 0-27648 internally) are within default ranges, flagging errors if they exceed limits. Valid inputs trigger PLC_output_range for further processing.

Validated values are normalized to a 0-1 scale, with voltage (0-15 kV), current (0-800 A), and temperature (0-150°C) scaled to their actual ranges. This ensures only accurate data is used for control operations. The PLC converts raw inputs (0-27648) to normalized (0-1) and real-world values using NORM_X and SCALE_X functions, enabling easy adaptation for other sensors. Comparators check scaled values against thresholds for real-time fault detection. Final measurements are stored in PLC variables, allowing comparison with preset limits for automated control.

Based on Figure 9, this PLC system automates voltage regulation by adjusting transformer taps based on real-time monitoring. A pulse counter (%DB2) tracks voltage changes (%I0.1) and stores values (%MD1). If voltage exceeds 9V, %Q0.1 reduces it while %Q0.2 triggers an overvoltage alarm; below 5V, %Q0.0 increases voltage with an undervoltage alarm (%Q0.3). A 4V-9V range activates %Q0.4 for stable operation. Manual mode (%I0.3) allows override via %I0.6/%I0.7 for tap control, with smooth transition via %M6.4. This hybrid approach ensures stability, fault tolerance, and operational flexibility.

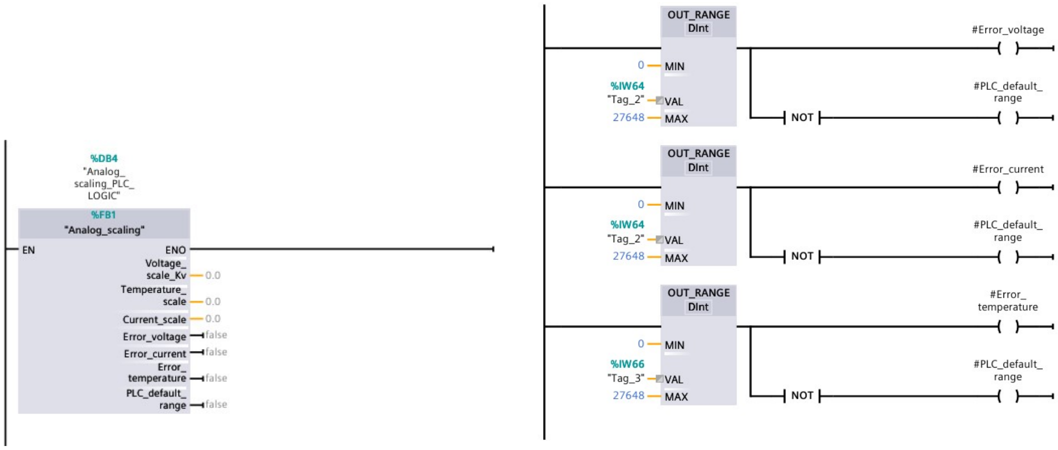


Figure 9. Network of the Data Block for Analog Scaling and Outrange Instruction Logic

Based on Figure 10, this PLC system regulates temperature by monitoring pulses (%I0.2) counted in %DB3, storing the value in %MD2 ("TEMP_VAL"). If the temperature exceeds 110°C, %M0.2 and %M0.3 trigger %Q0.5 ("ALARM_HT") and activate cooling: first %Q0.6 ("FAN1"), then %Q0.7 ("FAN2"), %Q1.0 ("FAN3"), and finally %Q2.0 ("WATER_PUMP") for rapid cooling. Below 110°C, %Q1.1 ("IN_RANGE_TEMP") keeps cooling off to save energy. Once stabilized, the system resets all cooling outputs automatically, ensuring efficient thermal management without unnecessary energy consumption.

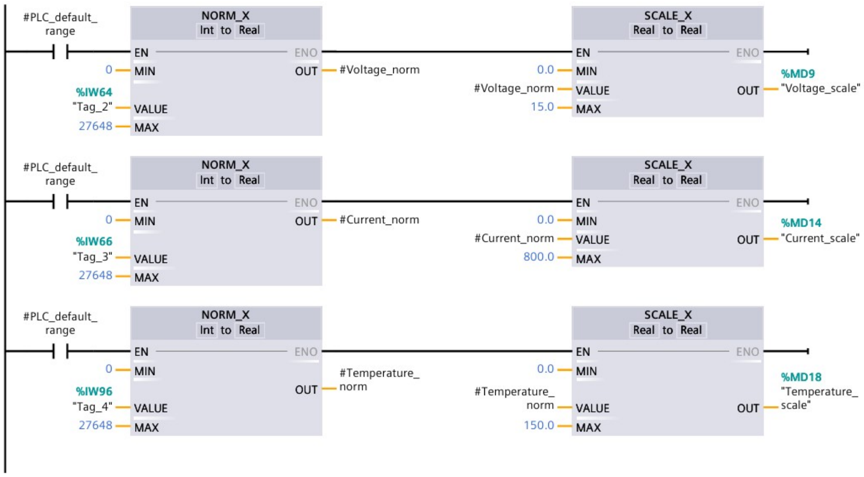


Figure 10. Analog Scaling Logic

Based on Figure 11 and Figure 12, the logic provides overcurrent protection by monitoring current pulses and comparing them against thresholds. If current exceeds 800A, it triggers %M0.6 (My_flag3) and alarms (%Q0.5) while maintaining stability between 500-800A. During faults, it isolates the affected section via circuit breakers (%Q1.2-%Q1.6) and transfers load to healthy feeders, preventing blackouts. The automated detection and switching ensure reliable, uninterrupted power distribution.

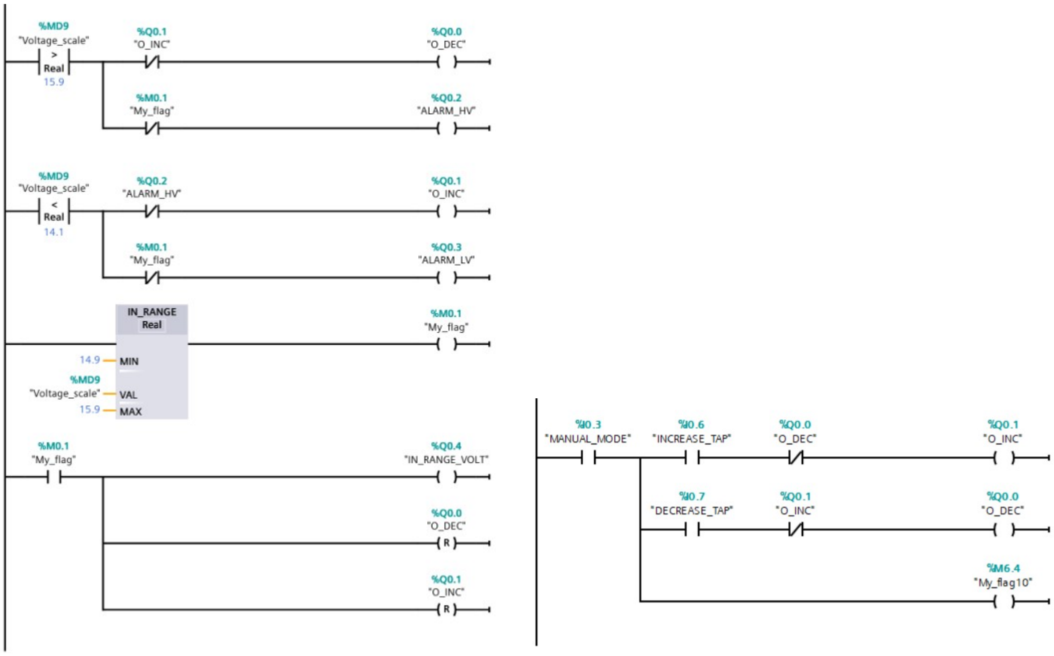


Figure 11. Network Program for Temperature Control Logic

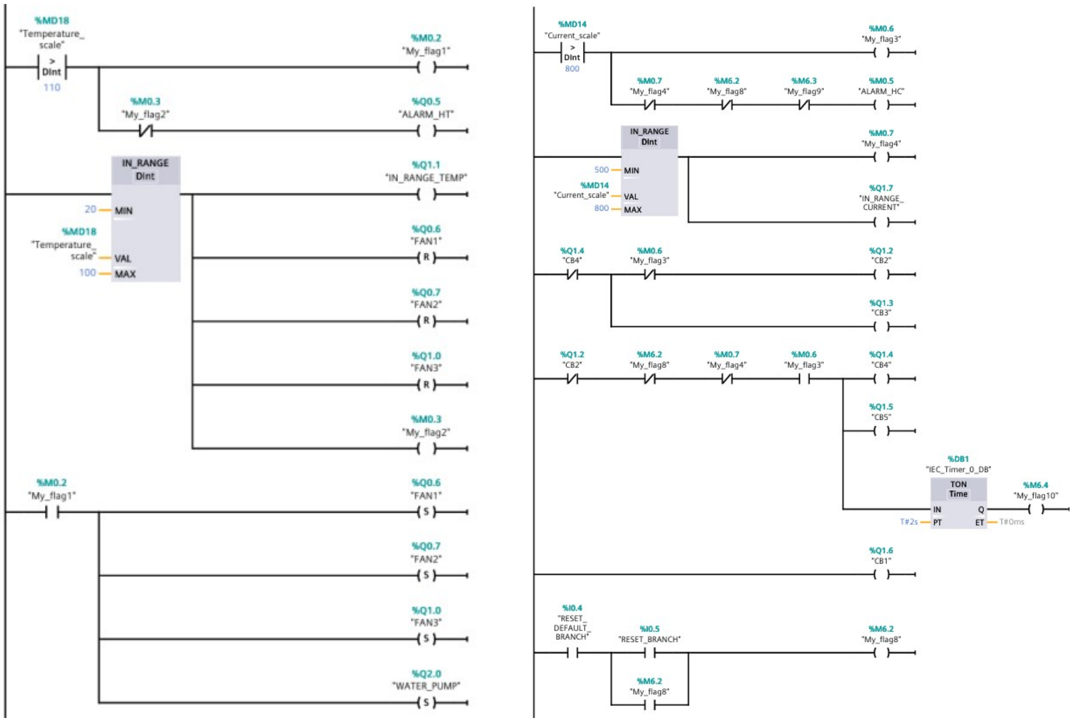


Figure 12.
(a) Network Program for Voltage Regulation Logic
(b) Network Program for High Current Fault and Automatic Load Transfer Regulation Logic

The Siemens SIMATIC HMI Root Screen, as shown in the Figure 13, serves as a central hub for the designed system, featuring intuitive touch controls for harsh environments. It displays a 70kV/15kV power distribution model with transformers (TFO_1, TFO_2), circuit breakers (CB1-CB5), and dual-bus (LB/RB) topology for reliability. Real-time monitoring includes alarms for voltage (NV/LV/HV), current (NC/HC), and temperature (NT/HT) conditions. IEC 61850-compliant, it enables rapid load shedding and capacitor switching while supporting future integration of smart devices, digital relays, and SCADA for predictive grid management and scalability.

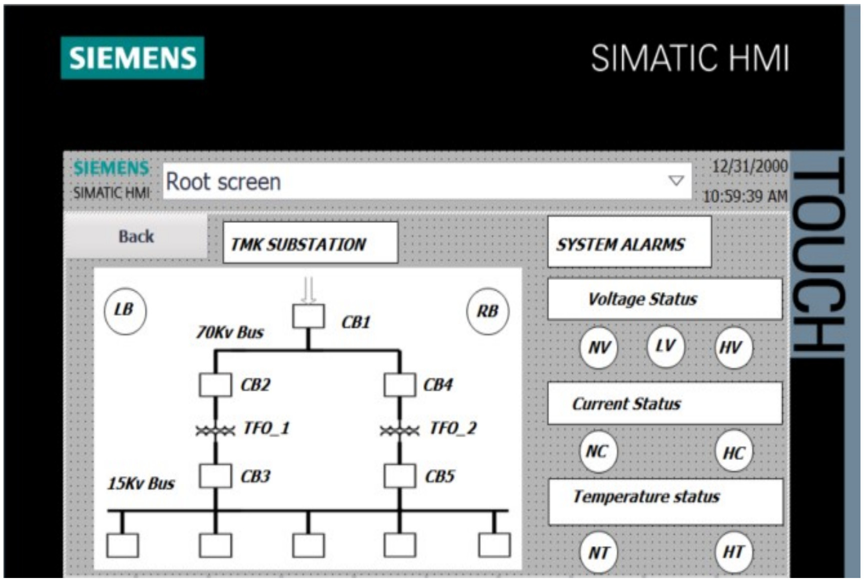


Figure 13. System Screen of the Designed HMI

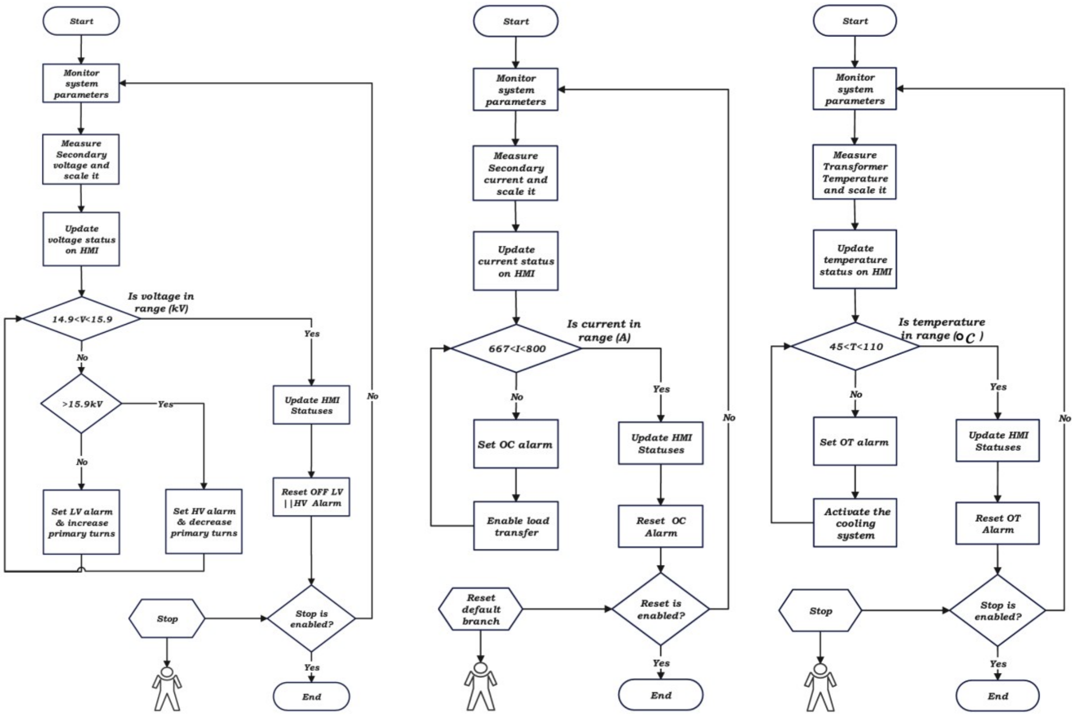


Figure 14. Flowchart of the Designed System

The system initializes all components, CBs, sensors, and PLC to default states, continuously monitoring data against predefined thresholds. Normal operation displays "System Normal" on the HMI, while faults (overcurrent, voltage fluctuations, overheating) trigger alarms. The PLC isolates faults by tripping affected CBs and transferring loads to backup branches, updating the HMI in real time. Post-fault, manual/auto-reset options keep faulty sections offline until maintenance. Real-time logging aids troubleshooting and optimizes reliability, minimizing outages and enhancing operator insights

4.4. Matlab Model of the Transformer with OLTC

The voltage regulation network uses a 70kV/50Hz three-phase source connected to a 10MVA OLTC transformer, which automatically adjusts taps to maintain a stable 15kV output under varying loads. A sequence analyzer converts three-phase voltage into a magnitude for comparison with reference values, enabling continuous voltage correction without disrupting power flow. The regulated 15kV output then supplies radial distribution lines (3-30km) to various loads, ensuring adaptive and stable substation control. Table 2 shows the PLC and OLTC operational simulation.

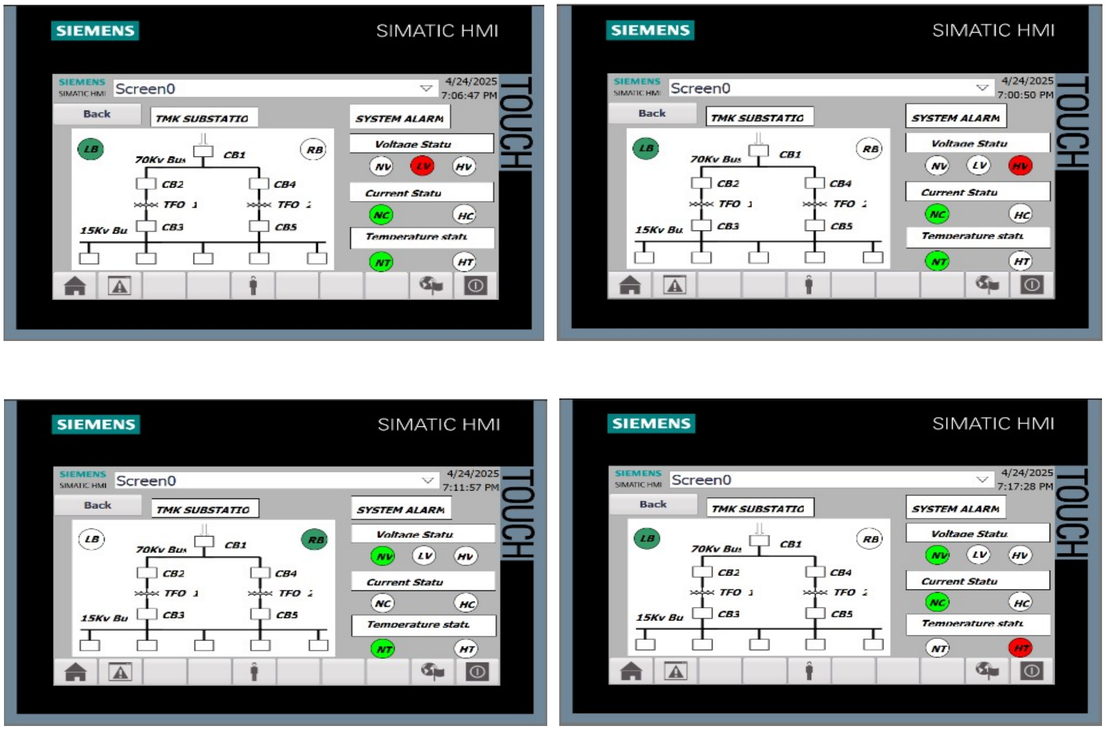


Figure 15. Various Parameter Statuses Observed from the HMI During Operation

The system detects abnormal conditions through comparator checks - when voltage (%MD1) drops below threshold, %Q0.1 activates tap-increase with undervoltage alarm (%Q0.3); when exceeding limits, %Q0.0 triggers tap-decrease with overvoltage alarm (%Q0.2). Similarly, overcurrent (%MD8) activates %M0.6/%M6.2, initiating load transfer from Transformer 1 (disabling CB2/CB3) to Transformer 2 (enabling CB4/CB5), while CB1 remains closed. Post-transfer, alarms clear after 2 seconds, requiring manual reset to restore normal operation. Manual mode remains disabled during all automatic corrective actions.

The simulation demonstrates the transformer tap changer's effective voltage regulation, with two tap adjustments at 2.5s and 8s causing slight voltage increases from 0.4pu while maintaining stable ~2.5MW active power (as show in Table 2). A 20-20.2s fault on the secondary side caused complete voltage collapse, while primary voltage remained stable. The results validate the system's dynamic response to both tap changes (showing voltage-reactive power coupling) and faults, confirming the simulation's accuracy in modeling power system behavior under controlled disturbances.

Table 2. PLC and OLTC Operational Simulation

Condition	System Impact	PLC / OLTC Logic Response	Indicators / Registers
Normal (Voltage)	Voltage remains stable within nominal ranges.	Maintains stable operational status ("Healthy").	%MD1 (9-10V), %M0.1 Active.
Normal (Current)	Load current stays within the design capacity limits.	No overcurrent alarms are triggered; operation continues.	%MD8 (5-10V), %M0.7 Active.
Low Voltage	Voltage drops below the threshold (e.g., < 9V analog).	Sends a command to the OLTC to **raise the tap**.	Secondary Tap Adjustment.
High Voltage	Voltage exceeds the safety limit (e.g., > 10.5V analog).	Sends a command to the OLTC to **lower the tap**.	Alarm %Q0.3 Active.
High Current	Overload or fault occurs on one of the feeders.	Triggers Overcurrent alarm. If persistent, triggers a **trip** on the Circuit Breaker.	Alarm %M0.5 Active, CB Digital Output.
Overtemp	Oil or winding temperature exceeds critical limits.	Activates cooling systems (fans/pumps) or performs **interlocking** (load shedding).	Cooling System & Transformer Protection.

Figure 16 shows the comparison of the voltage deviation for the old and new system.

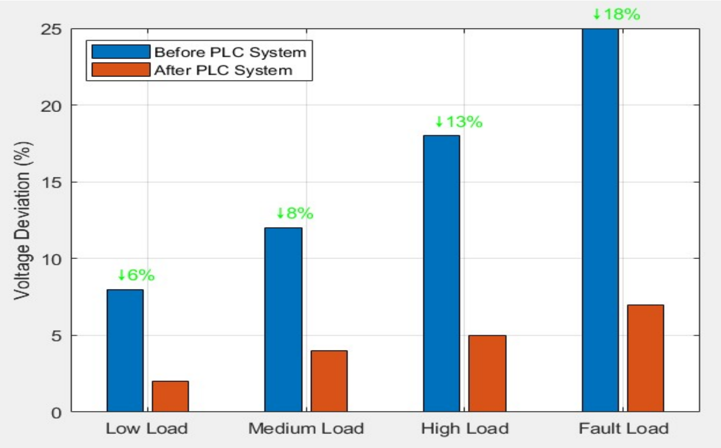


Figure 16. Comparison of the Old System to the New System

5. Conclusion

To control voltage instability and mitigate manual regulation inefficiencies at the TMK substation in Goma, DRC, a PLC-based smart grid solution was developed. By creating a combined system with PLCs, OLTCs, and MATLAB/Simulink simulations, the proposed scheme allows for real-time monitoring of voltage, adaptive tap changing, and the automation of fault detection, thus enhancing power stability and reducing energy losses. Automation minimizes human intervention, increases reliability, and will ultimately provide a socio-economically developed nation to regions deficient in power supply. On the downside, the approach is somewhat far removed from the simulator may not be able to capture fully real-world complexities, while practical application may be challenged by poor infrastructure, costs, and skill. The field testing, renewable energy integration, AI-based predictive control, and expansion to additional substations are some of the forthcoming steps. The current research provides an elegant, scalable, and well-established solution in modernizing the power distribution of the developing world, transitioning from manual to intelligent grid management for a more resilient energy future.

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