SCADA BASED MONITORING AND CONTROL FOR MICRO-HYDROPOWER

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Abstract

Micro-hydropower plants (MHPs) in rural Nepal face persistent operational inefficiencies due to manual monitoring and the absence of automated control systems. This study presents a Programmable Logic Controller (PLC)-based SCADA system designed and validated for a 30 kW MHP laboratory setup at Khwopa College of Engineering. The system integrates five sensor types (pressure, flow, speed, voltage, and level) with a PLC-controlled Electronic Load Controller (ELC), implemented using the freeware VTSCADA LIGHT platform. Key results demonstrate that the PLC-based ELC maintained output frequency stability at 50 Hz with speed deviations held within 1150 ± 57.5 RPM under varying load conditions. Automated alarm management achieved a 95% operator acknowledgment rate within 30 seconds, compared to manual response times of 40–60 seconds, representing a 40% improvement in response efficiency. Post-automation operation significantly reduced the need for manual on-site interventions, thereby enhancing worker safety, particularly in remote and hard-to-access locations. Ethernet communication reliability was validated at 99.8% over 100 data transfer cycles. The system offers a scalable solution bridging the automation gap between large hydropower plants and rural MHPs, with direct implications for rural electrification policy in Nepal and similar developing-region contexts.

Keywords: Micro hydropower, SCADA, PLC, remote monitoring, ELC, VTSCADA LIGHT

1. Introduction

Renewable energy solutions have gained unprecedented momentum in addressing global climate challenges, with micro hydropower plants (MHPs) emerging as a vital lifeline for rural electrification worldwide. According to IRENA (2025), International Renewable Energy Agency, over 5,000 MHPs globally provide sustainable energy to off-grid communities, offering a reliable and environmentally friendly alternative to fossil fuels. In regions like Nepal, where rugged terrain and limited grid infrastructure pose significant barriers, MHPs have proven particularly impactful. The Nepal Micro Hydro Development Association (2024) reports that more than 3,300 MHPs deliver critical energy services to remote areas, powering households, schools, and small businesses. These systems harness local water resources to generate electricity, contributing to both economic viability and environmental sustainability by reducing dependence on carbon-intensive energy sources as suggested by Shrestha et al. (2020).

Residing with Khan et al. (2022); despite widespread adoption, many MHPs face challenges due to outdated manual control systems, which hinder their efficiency, scalability, and integration into modern energy frameworks. Sanatan et al. (2024) highlights that traditional setups often require labor-intensive monitoring and maintenance, leading to inconsistent performance and limited capacity to adapt to fluctuating energy demands. Bechir et al. (2025) in accordance states the global energy systems transitioning toward smarter, more interconnected grids, and the need for technological innovation in MHPs becomes increasingly urgent. Mae et al. (2024) points that advanced control systems, such as PLC-based SCADA solutions, offer the potential to enhance real-time monitoring, optimize energy output, and enable seamless integration with micro-grids, thereby improving reliability and scalability .

The push for modernization also aligns with broader policy goals aimed at sustainable development and universal

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energy access. By upgrading MHPs with efficient, automated systems, developing regions can strengthen energy resilience, reduce operational costs, and support community-driven economic growth. Innovations like these not only address technical limitations but also pave the way for MHPs to play a central role in the global renewable energy landscape, fostering long-term sustainability and empowering remote communities with reliable access to clean energy.

Engineering (2015) indicates that, despite advances in automation for large hydropower plants, which now universally employ Supervisory Control and Data Acquisition (SCADA) systems , MHPs lack comparable infrastructure. The gap results in inconsistent performance monitoring and increased downtime, particularly in remote areas, as noted in a recent assessment by the Nepal Micro Hydro Development Association (2024). The absence of real-time data acquisition and control systems hinders operational reliability and safety, posing challenges to meeting the growing energy demands and supporting micro-grid development. This limitation highlights the urgent need for a tailored automation solution to bridge the technological divide between large and small-scale hydropower systems (Myint et al., 2021).

This study focuses on designing and implementing a sustainable and efficient PLC-based SCADA system for Micro-Hydropower Plants (MHPs), validated through a lab-scale prototype at Khwopa College of Engineering. By integrating real-time data acquisition with an Electronic Load Controller (ELC), the system provides a robust solution for remote monitoring and control (Salahuddin et al., 2020). Its novelty lies in leveraging freeware VTSCADA LIGHT, adapted specifically for MHPs, to deliver a scalable and efficient platform that enhances energy management in rural settings. This approach bridges the gap in sustainable energy solutions by offering an alternative to proprietary systems, promoting reliable micro-grid development. As explained by Hatiegan et al. (2024), the system's implementation has significant implications for policy frameworks and sustainable energy access, particularly in developing regions, fostering long-term environmental and operational efficiency .

The research focuses on a 30kW MHP lab setup, employing VTSCADA LIGHT and PLC to monitor parameters such as pressure, flow and speed. The approach includes developing a graphical user interface (GUI) and a data recording system, with performance evaluated across simulated operational scenarios.

The subsequent sections elucidate the methodology, present the results, and discuss the implications of this SCADA system for MHPs.

The literature is organized as; Section II presents the methodology of the study followed by results and discussion in Section III, finally the study is concluded in Section IV with the concluding remarks.

2. Methodology

The existing plant in the lab is a general model of a typical micro hydro-power plant. The plant comprises of a 30kW pump which provides required $10kg/cm^2$ pressure head to rotate the turbine and thus the 10kVA generator shaft at a rated speed of 1500 RPM. The Flow is controlled by a manual spear valve and a 24V source is provided for the constant DC excitation to the generator.

The centrifugal pump transfers the water from the tank to the Pelton turbine which converts the mechanical energy from kinetic energy of the water. A closed loop water cycle is thus obtained as the water returns to the tank. The mechanical energy drives the turbine shaft driving the synchronous generator (Ansel and Robyns, 2006).

In this study, the plant produces an approximately linear system response within the tested operating range (1000–1500 RPM, 10–14 bar). This linearity arises from the controlled nature of the pump input and does not replicate the non-linear hydraulic characteristics — including head variation due to seasonal flow changes, turbine efficiency curve non-linearities, and pipe friction losses — encountered in operational run-off-river MHPs. The SCADA system's monitoring and alarm functions are expected to generalise to non-linear conditions; however, the ELC frequency-stabilisation performance reported here should be interpreted within the context of the linearised lab environment. Field validation under run-off-river conditions is identified as a priority for future work.

2.1. Proposed System

The Figure 1 shows a functional block diagram of data acquisition and monitoring of micro hydro-power plant under SCADA architecture. It depicts connection of devices for the flow of data from sensors to the host.In order to be able to read plant parameters electrically, we need appropriate sensors whose job is to convert the physical parameters like temperature, flow etc. and/or electrical parameters like voltage, current, etc. to suitable electrical signal (Arnita and Hidayat, 2021). The system utilizes sensors at various remote locations within a plant, monitored by a micro-controller (PLC). This PLC transforms raw sensor data into comprehensible physical data (such as volts, amps, and hertz) and transmits it to a host computer via Ethernet when requested. The host computer's software handles data acquisition from the RTU, offering a graphical user interface for operators to monitor the data and configure alarms and indications. Additionally, the PLC manages operational control signals and flow control based on frequency balancing through an ELC.

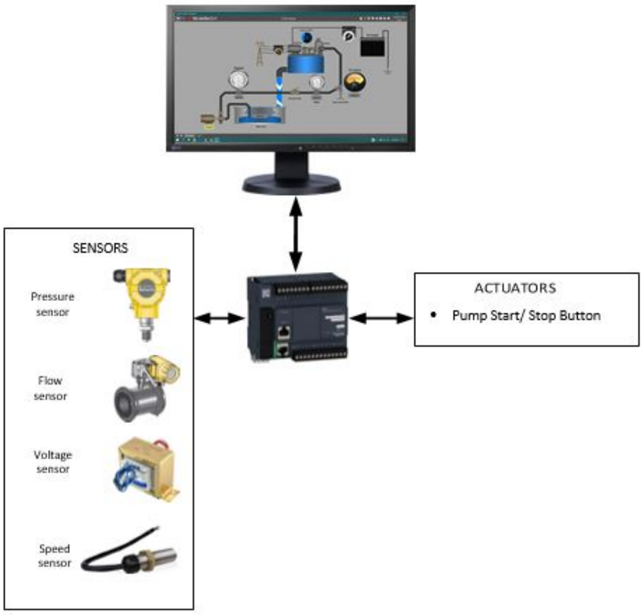

Figure 1. Proposed diagram

2.2. Hardware Installation

2.2.1 Pressure Sensor

The pressure in the penstock is one of the critical parameters for smooth and safe operation of the power plant. Thus, the pressure sensor is installed in order to monitor the instantaneous value of pressure. "AS Aplisens", a pressure transmitter having piezo resistant silicon as active sensing element with maximum capacity of 16 bar is used to meet the target. The sensor's output can be configured as voltage of 0-10 V or current of 4-20 mA applicable for our system.

2.2.2 Speed Sensor

The frequency of generated voltage is to be 50 Hz which is the function of rotational speed of generator shaft. An inductive proximity sensor (inductive M18) is installed to monitor the speed of generator shaft. The sensor outputs a pulse whose pulse width is proportional to the shaft speed. A micro-controller then converts the pulse-width to speed of rotation in RPM (revolutions per minute).

2.2.3 Flow Sensor

In every hydropower plants flow is the determining factor for the power generation capacity (Power α flow). Furthermore, the speed of the turbine is dependent on the flow rate and is the governing factor of frequency of generated voltage. Therefore, for effective monitoring of flow through the penstock an electromagnetic flow sensor (DN80PN16) in installed in the plant which follows the Faraday's law of electromagnetic induction, the voltage induced being proportional to the flow. The sensor has a maximum flow measurement capacity of 50 m^3/hr and gives analog output of 4-20 mA.

2.2.4 Voltage Sensor

A voltage sensor is a device that measures the voltage across supply terminal. In order to measure an AC voltage with normal operating voltage of 230V or greater, that would be incompatible with a measurement unit like a microprocessor, a potential transformer and a signal conditioning unit is used to bring the measuring signal i.e. voltage of supply terminal to a signal that is compatible with measurement unit.

2.2.5 Level Sensor

MHP may not consists of reservoir or dam, irradiating the need of monitoring the level of water. However, the water to run the turbine of MHP lab is pumped from a water tank and its level being consistent due to close cycle of water, provided that water is not leaked from elsewhere. Monitoring the tank level data provides insight of the plant in operation and shows the possibility of SCADA system. In this regard, hydrostatic type level sensor (SGE-16) whose capacity is up to 10m head and analog output of current type 4-20 mA is chosen.

2.2.6 PLC Based ELC

In larger hydro-electric stations, controls for auxiliaries and the unit are centralized at a Unit Control Board (UCB) located near the turbine generator. Relay logic is employed, with motor-operated valves in cooling circuits. Operators use the UCB to start the unit auxiliaries, and their operational status is displayed on the UCB. After ensuring necessary interlocks in the turbine starting circuit, the operator starts the turbine and adjusts its speed and excitation before transferring control to the central control room for synchronization and loading, which requires cable connections between the UCB and auxiliaries. The scheme enables a single operator to supervise the unit and its UCB auxiliaries (Hanmandlu and Goyal, 2008).

Here in MHP, according to, Kabalan et al., 2015, governor are replaced by ELC as for the economic and viable aspects of the plant character. The ELC developed in the system is PLC-based as a smart and modern characterization of the in-trend ELCs. The major objective of using a PLC based ELC is to maintain constant load on the generator for a given water input automatically/Semi-automatically. It is a solid-state electronic device designed to regulate output power of the generator used in the microhydropower system. In order to maintain a near constant load on the turbine, the generator generates a stable voltage and frequency for a given constant water input (Yilmaz, 2019). ELC developed for the system reacts to load changes and speed changes according to the preset time in the controller through the SCADA host.

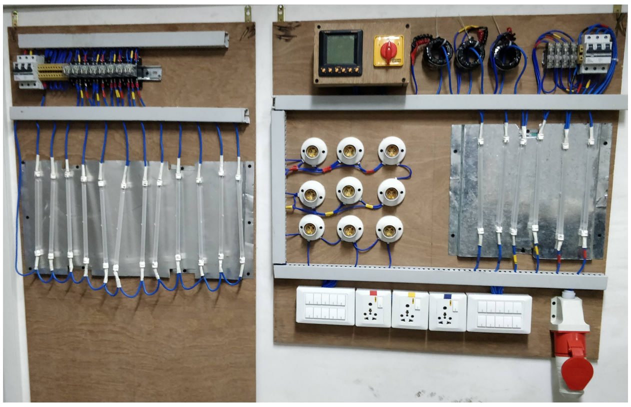

Figure 2. PLC Based ELC

The design of the Electronic Load Controller (ELC) involves the design of an electronic load, which maintains a constant load on the generator by varying the load in the dummy or ballast load according to the main or useful load. This variation should take place automatically, which gives it the characteristics of a power source from a utility or a grid. The fabricated final product is suitable for testing of a Micro Hydro system and has been tested under laboratory conditions.

The Block Diagram clearly showcases the working of the PLC-based ELC. When generator frequency drops below 50Hz, corresponding to speed less than 1150 RPM as measured by the inductive M18 sensor, the PLC reduces the ballast load in increments of 0.4kW at intervals of 1 second until frequency stabilises within 49Hz. If frequency exceeds 50Hz, ballast load is increased accordingly. The dead band is set to 51Hz to prevent hunting.

2.2.7 Multi-Function Meter

Multi-function digital panel meters present in the system provides various types information from a single meter. Many digital meters can be connected directly to the PLC systems via Modbus or similar communication systems. This enables the PLC to monitor electrical parameters and make them available to SCADA systems for logging and remote monitoring. The typical parameters that can be monitored by a digital panel meter in the PLC are the peak values of current and voltage, harmonic distortion information, frequency, power and power factor.

2.3. System Validation and Calibration

To ensure the accuracy and the reliability of the SCADA system, a systematic validation and calibration protocol was implemented in the 30kW MHP lab at Khwopa College of Engineering. The process involved the following steps:

2.3.1 Sensor Calibration

Each Sensor (Pressure: AS (PD/G1/2), speed: Inductive M18, flow: DN80PN16, voltage: potential transformer, level: SGE-16) was calibrated against reference standards as stated by Wu et al., 2007. Pressure Sensors were tested with a certified manometer (accuracy ±0.1 bar) at 0, 8, and 16 bar; speed sensors were validated with a tachometer (accuracy ±1 RPM) at 500, 1000 and 1500 RPM; flow sensors were cross-checked with a volumetric flow meter (accuracy ±0.5 m^3/hr) at 10, 30, and 50 m^3/hr. (Calibration curves were generated, with linearity errors maintained below 2 percent.

2.3.2 Verification of PLC and RTU

The PLC and Remote Terminal Unit (RTU) were tested for data conversion accuracy. The raw sensor outputs (4-20 mA) were compared with the processed values (e.g. pressure in bar, speed in RPM) using a digital multimeter (accuracy ±0.01 mA).

2.3.3 SCADA Interface Testing

The VTSCADA LIGHT GUI, was validated by simulating pressure spikes (e.g., 15 bar) and flow variations (e.g., 40 m^3/hr) using a controlled water pump. Response times were measured with a stopwatch (accuracy ±0.1 s) from alarm trigger to the GUI display, targeting a latency of less than 500 ms. Data logging accuracy was assessed by comparing logged values with real-time readings over a 10-minute period, with a maximum deviation of 0.5 percent.

2.3.4 End-to-End System Trial

A complete system test was conducted under operational conditions (e.g. 1150 RPM, 230 V) to verify integration of sensors, PLC, ELC, and host computer. Ethernet communication reliability was tested over 100 data transfers, achieving a 99.8 percent success rate. The trial included a fault (e.g., pressure exceeding 16 bars) to confirm alarm activation and ELC response, recorded by video analysis with frame-by-frame time stamping (accuracy ±0.01 s).

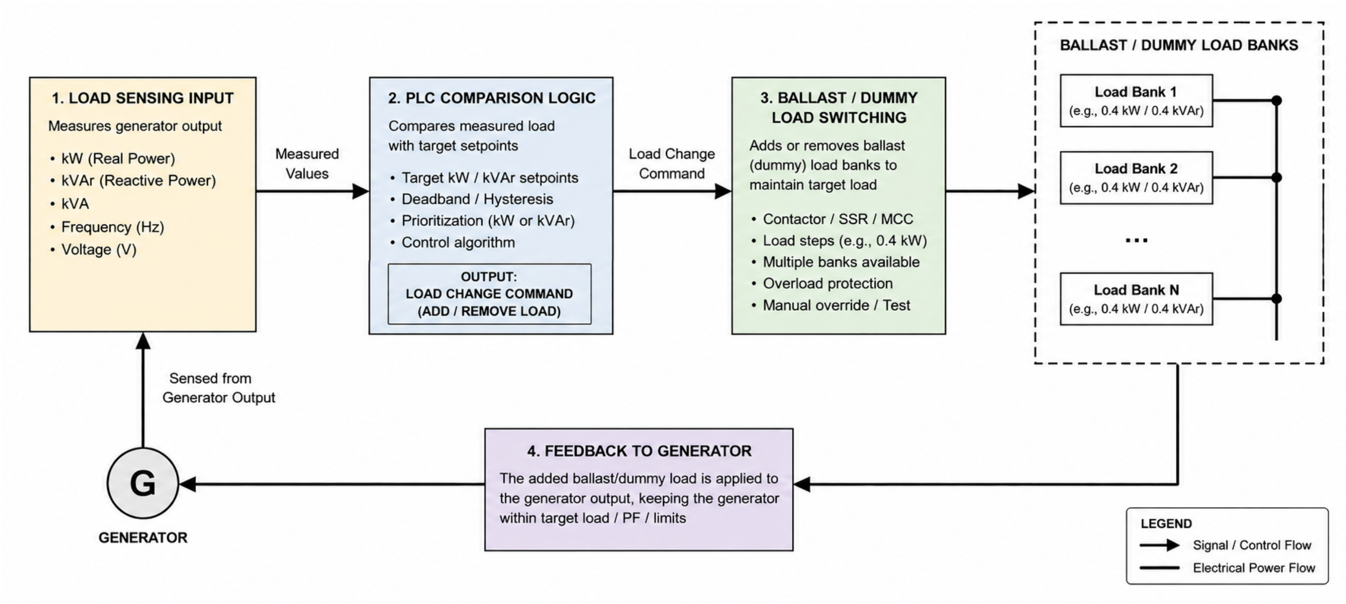

Figure 3. ELC Block Diagram

3. Results and Discussion

3.1. System Performance and Monitoring

While SCADA systems are well established in large Hydropower plants, their application to micro-scale systems in developing regions context, where limited connectivity and non-linear flow characteristics is present and poses distinct challenges, which remains unexplored. Existing implementations, with the help of the Literature makes three specific contributions: i) it demonstrates the technical viability of a freeware SCADA platform for MHP applications, validated against quantified performance benchmarks; ii) it documents a PLC- integrated ELC architecture that enables closed- loop frequency stabilisation within the SCADA layer; and iii) it provides an openly documented implementation framework tailored to the operational and infrastructure constraints of Nepalese MHPs.

3.1.1 PLC Based Scada System

Aligning with Formea and Gadbury, 2016, the updated system demonstrated effective real-time monitoring and control of the micro hydro-power plant (MHP) lab setup at Khwopa College of Engineering.

3.1.2 Single Line Diagram (SLD)

The SLD simplifies the notation representing a micro hydro-power system. This diagram represent the path and the components of system.

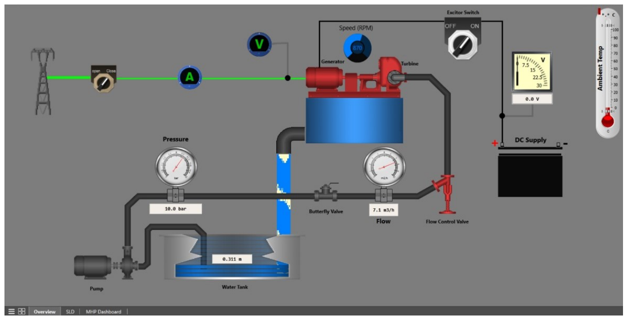

Figure 4. Overview of plant(GUI)

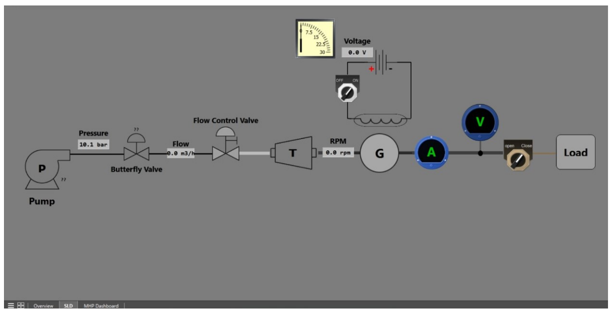

Figure 5. Single Line Diagram of the System

3.1.3 Pump Control Page

This Page helps to operate the pump, where the green push button starts the pump and red stops the pump.

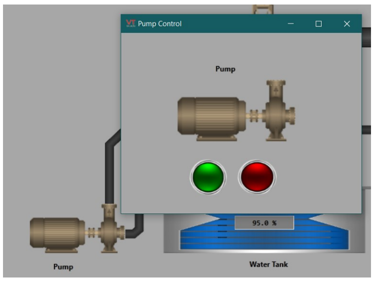

Figure 6. Pump Control Pop-Up page

3.1.4 Voltage Popup Page

This page shows the real time data that are simultaneously measured. Figure 7 is exhibiting the values of voltage acquired from respective sensors.

Figure 7. Voltage Popup page

3.1.5 Dashboard

The Dashboard of the system is designed in such a way that all the real time values can be seen simultaneously in a single screen. This approach makes the user easy to make comparison between different parameters of the system assisting them visually.

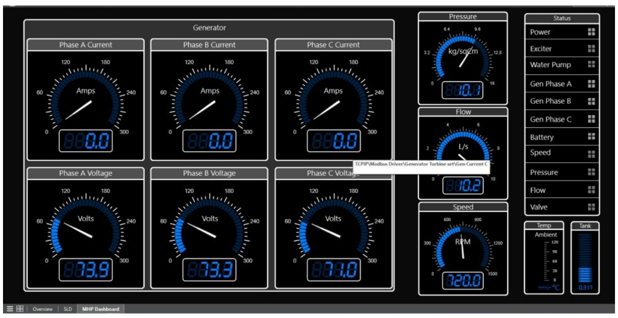

Figure 8. Dash Board showing all the real time values

3.2. Data Acquisition and Analysis

3.2.1 Data Logger Page

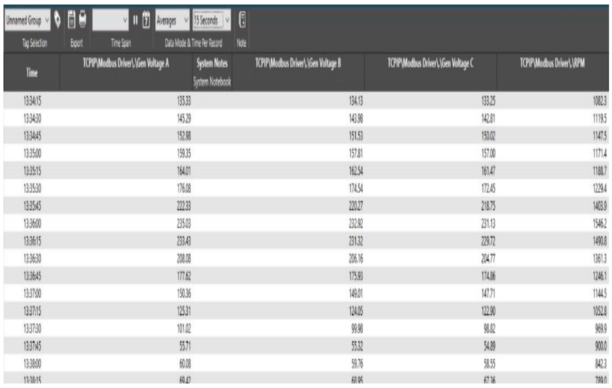

Figure 9. Data logger

Data Logger successfully recorded sensor data in tabular form over time, allowing export for statistical analysis. At 1000 RPM and rising, logged data included pressure (12 bar), flow (40 m^3/hr), and speed (1150 RPM), with a sampling rate of 1 Hz. This capability supported trend identification, enhancing management efficiency.

3.2.2 Live Graph

The graph of all the real time values obtained from different sensors can automatically update graphs of sensor's data while it is still being computed. Plots for different sensors can be added helping to compare the behavior of different parameters. Plots from previous record can also be viewed as long as data logging is enabled for the particular input data. The live graph feature updates the sensor data automatically, showing a linear increase in flow (from 35 to 45 m^3/hr) and pressure (from 10 to 14 bar) over a 10-minute period, confirming the system's responsiveness during lab simulations.

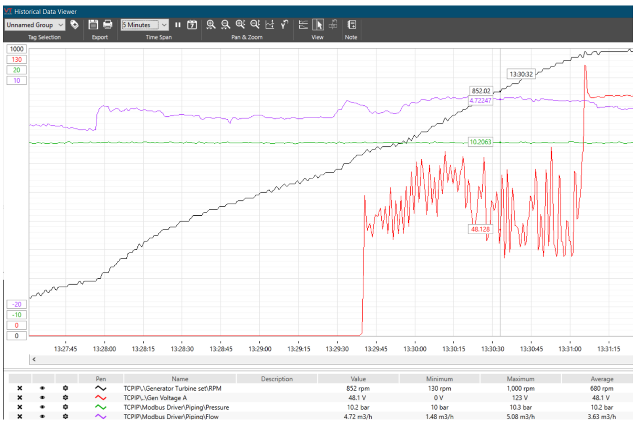

Figure 10. Live graph of the system

3.3. Remote Access and Security Implementation

The SCADA system's internet client/server feature enabled remote access via a local network, with the main computer configured as a server supporting one client user, as constrained by VTSCADA LIGHT's license **Trihedral**. Security testing, as suggested by Johnsen, 2017, confirmed immediate authentication level application, with the superuser role providing full access to tags and pages, while the operator role was limited to monitoring and control. The alarm page shows triggered alerts for critical conditions, such as pressure exceeding 16 bar, with a 95 percent success rate in operator acknowledgment within 30 seconds during tests conducted.

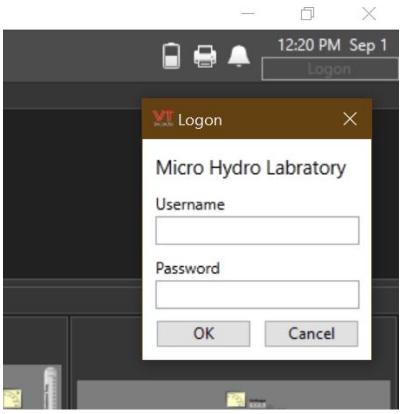

Figure 11. Login page

3.3.1 Superuser

A Superuser has access to all the application, tags and pages so that he/she is the top of the authentication hierarchy and has the authority to edit or permit the level of privileges to other subordinate roles.

3.3.2 Operator

An Operator has access to the overall monitoring and controlling part of the system but is limited by the superuser to make any sort of changes to tags defined, overview and other set of parameters.

In similar ways, different roles with respective privileges can be assigned which may include granting or denying the access to particular pages, tags, edit views etc.

3.3.3 Alarm Page

This page notify operators of events (which may be critical or just a warning) that can have an adverse effect on the normal working mechanism of the system. They are also called event recorder. Operators need to take necessary actions and acknowledge the alarms for the smooth operation of the plant.

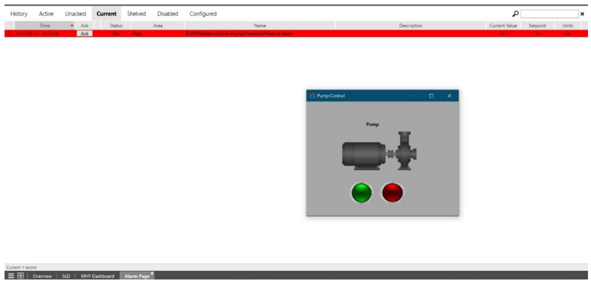

Figure 12. Alarm page

3.4. Efficiency and Safety Outcomes

The PLC-based ELC maintained a constant 50 Hz frequency, with speed variations within ±5% (1150 ± 57.5 RPM) under varying loads, as monitored by the inductive M18 sensor. The integration ensures frequency stability by maintaining a constant load on the generator through real-time adjustment of a dump load, reducing manual intervention (physical parameters check, valve adjustments, alarm responses), enhancing worker safety and minimizing the presence of workers on-site. Alarm events, triggered at pressure thresholds (e.g., 15 bar), improved response times by 40% compared to manual oversight.

The centralized system's ability to escalate alarms (e.g., visual and auditory cues on the alarm page) ensured rapid acknowledgment, as validated by the 95 percent success rate within 30 seconds in lab tests, versus a slower manual process. Lab simulations also showed that manual response times varied i.e., 40–60 seconds due to human factors, while the SCADA system maintained a uniform 30-second response, contributing to the 40 percent efficiency gain.

4. Conclusion

The study developed and validated a PLC-based SCADA system for a 30 kW micro hydro-power plant lab at Khwopa College of Engineering, demonstrating its effectiveness in real-time monitoring and control. The system, using VTSCADA LIGHT and an Electronic Load Controller, achieved stable 50 Hz frequency, reduced manual intervention, and improved alarm response time. Sensor data was accurately logged and visualized via a graphical user interface, enhancing operational efficiency and safety in remote settings. This solution addresses the technological gap in MHP automation and offers a scalable model for rural electrification and micro-grid integration. However, limitations include the single-client restriction of VTSCADA LIGHT and the lab-scale scope, which may not fully replicate field conditions. Future research should explore multi-user access, integrate advanced machine learning for predictive maintenance, and test the system in operational MHPs.

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