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Title:

Designing a Safety PLC Based Gas Turbine Protection System with Integrated IIoT Solution

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Registration Number:……../2023

Dedication

I dedicate this modest work to

My beloved mother and father

My dear brothers and sister

My friends and mates

And to a very special person,

I prefer to keep it to my self.

Abstract

The project aims to design a gas turbine protection system to ensure safe and reliable operation. It addresses risks such as vibrations, high temperatures, and over speed, meeting SIL2 safety requirements. The core of the system is the Bently Nevada 3500, which collects real-time data on vibrations, temperature, and speed. A safety PLC, the S7-1500, analyzes this data to initiate timely actions for turbine protection. A user-friendly Human-Machine Interface (HMI) and Supervisory Control and Data Acquisition (SCADA) system, powered by the WinCC runtime, are implemented. This allows operators to visualize real-time data and make informed decisions about turbine performance. Additionally, an Industrial Internet of Things (IIoT) solution powered by Node-RED is integrated. Two instances of Node-RED are employed: one as a central hub for efficient data collection, processing, and storage, and another hosted on a cloud-based server for remote access and advanced data management.The system incorporates automatic notifications via email and Telegram in the event of a turbine trip, ensuring swift response and effective mitigation measures. By integrating advanced technologies, this gas turbine protection system offers comprehensive monitoring, control, and safety features. It optimizes data processing, visualization, and remote access, ultimately enhancing turbine performance, ensuring operational integrity, and improving overall safety.

Acknowledgements

I would like to express my gratitude and appreciation to Dr. OUADI Abderrahmane for his guidance and support throughout my project. I am also thankful to Mefdaoui Badreddine and Addila Houssem, the Instrumentation & Control Engineers, for providing the gas turbine documentations. Additionally, I extend my appreciation to my friend A. Mohamed Alamin for his guidance in database management. Their contributions have been invaluable to the success of my project.

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List of Abbreviations

PLC Programmable Logic Controller

CPU Central Processing Unit

PS Power Supply

UPS Uninterruptible Power Supply

I/O input / output

DO Digital Output

DI Digital Input

TIA Totally Integrated Automation

FBD Function Block Diagram

FB Function Block

SCADA Supervisory Control and Data Acquisition

HMI Human Machine Interface

MQTT Message Queuing Telemetry Transport

HMI Human Machine Interface

OPC UA Open Platform Communications Unified Architecture

SQL Structured Query Language

ESD Emergency Shutdown

IIoT Industrial Internet of Things

IoT Internet of Things

General Introduction

This project presents an advanced gas turbine protection system designed to ensure the safe and reliable operation of gas turbines. The system aims to prevent potential damage caused by vibrations, high temperatures, and unsafe speeds. Compliance with the Safety Integrity Level 2 (SIL2) requirements specified in the IEC 61508 standard is a key focus of this system.

The gas turbine protection system incorporates the Bently Nevada 3500 system [6] for real-time data collection on vibrations, temperature, and speed. This data is transmitted via the Modbus TCP/IP protocol to an S7-1500 safety PLC [14] , where it undergoes processing and analysis. The safety PLC is programmed to trigger appropriate actions when the data exceeds predetermined threshold levels, such as initiating a trip or shutdown mechanism to protect the turbine and its components from potential damage.

To enhance monitoring and control capabilities, a user-friendly Human-Machine Interface (HMI) and Supervisory Control and Data Acquisition (SCADA) system are implemented. The HMI and SCADA system, powered by the WinCC runtime platform, provide operators with real-time data visualization from the Bently Nevada system. Alarms are generated for high and high-high data, enabling operators to respond promptly to critical conditions. The SCADA system also allows authorized personnel to modify setpoints and offers trend visualization for each transmitter, aiding in performance optimization and informed decision-making.

Incorporating Industrial Internet of Things (IIoT) technologies [8], the gas turbine protection system leverages Node-RED [21] for enhanced data processing and accessibility. Two instances of Node-RED are employed to optimize system functionality. The first instance acts as a central hub, collecting real-time data from the safety PLC via the OPC UA protocol [22]. This data is efficiently processed and stored in both a local MySQL database [23] and a real-time database utilizing Firebase [25]. Within Node-RED, a comprehensive real-time dashboard is designed, providing operators with valuable insights into turbine performance and operational trends. The dashboard also allows for the download of real-time data in CSV format, facilitating further analysis and reporting.

The second Node-RED instance is hosted on a cloud-based server, offering remote access and advanced data management capabilities. Leveraging the MQTT communication protocol [11] through the HIVEMQ Cloud-based broker [12], this instance receives data from the local Node-RED installation. A comprehensive dashboard within the cloud-based Node-RED platform empowers stakeholders with real-time data visualization and analysis, facilitating monitoring and decision-making from anywhere in the world.

also enables the download of real-time data for comprehensive analysis and reporting purposes.

The integrated IIoT solution not only provides a user-friendly web interface but also includes a dedicated mobile application (available for Android and iOS). This ensures effortless access to gas turbine data, offering convenience and flexibility for users. In addition to its advanced monitoring and control features, the system incorporates automatic notifications via email and Telegram in the event of a turbine trip. These notifications ensure that authorized personnel receive immediate awareness of critical turbine conditions, enabling swift response and effective mitigation actions.

Figure 1 serves as a reference to better understand the overall architecture and design of the gas turbine protection system with integrated IIoT solution.

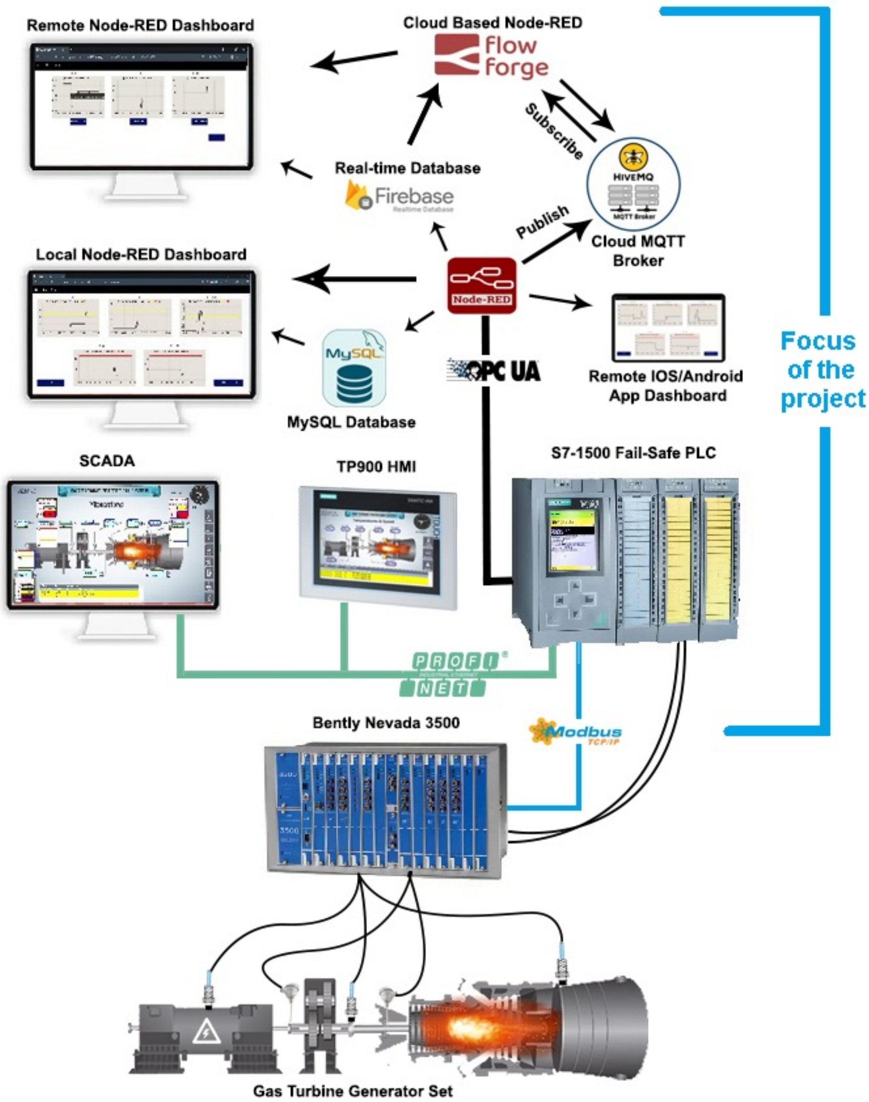


FIGURE 1: Project Overview

The following three chapters provide a comprehensive exploration of the theoretical background, methods and materials used, and the results and discussions of the implemented system. The theoretical background chapter introduces the gas turbine protection system, highlights its integration with IIoT, and discusses the benefits of MQTT protocol. The methods and materials chapter focuses on the specific hardware and software materials employed in the system's design. Finally, the results and discussion chapter presents the outcomes of the implemented system, evaluating the performance and effectiveness of TIA Portal as the programming environment for the S7-1500 safety PLC, as well as the design of the HMI and SCADA interfaces and the Industrial Internet of Things (IIoT) solution powered by Node-RED in the gas turbine protection context. These chapters contribute valuable insights to the advancement of gas turbine protection systems and data management practices in the industry.

Chapter 1

Theoretical Background

1.1 Introduction

This chapter presents the gas turbine protection system and its integration with the Industrial Internet of Things (IIoT). It covers the gas turbine generator set, including the GE MS5001 gas turbine, reduction gearbox, and DG 4-Pole Brush Electric Generator. The Bently Nevada 3500 system is introduced as the gas turbine protection system, highlighting its components, functionality, and features.

The chapter explores the benefits of integrating IIoT with gas turbine protection systems and introduces the MQTT protocol for efficient communication in IIoT applications. It also discusses the role of HiveMQ, a cloud-based MQTT broker, in IIoT deployments.

This chapter sets the stage for the subsequent chapters, which focus on the implementation, results, and evaluation of the gas turbine protection system with IIoT integration.

1.2 Gas Turbine Protection System

The gas turbine protection system is a critical element in ensuring the safe and reliable operation of gas turbine generator sets. It acts as a safeguard, continuously monitoring and controlling various parameters to prevent any potential damage or failure to the gas turbine, gear box, and generator. In this section, we will explore the gas turbine protection system in detail, understanding its role and significance in maintaining the integrity and efficiency of the gas turbine generator set.Additionally, we will introduce the Bently Nevada 3500 System, the prominent protection system used in the industry, and examine its hardware components, functionality, and key features. By gaining insights into the gas turbine protection system, we will appreciate its crucial contribution to the safe and reliable operation of gas turbine generator sets in power generation applications.

1.2.1 Gas Turbine Generator Set

The gas turbine generator set is a vital component in power generation systems, particularly in industrial and utility-scale applications. It combines three main elements: the gas turbine, gear box, and generator. Each component plays a critical role in the efficient and reliable production of electrical power. In this section, we will focus on exploring these three key components and their contributions to the overall operation of a gas turbine generator set.

1.2.1.1 GE MS5001 gas turbine

The MS5001 gas turbine is a compact and heavy-duty turbine designed by General Electric (GE) for power generation in industrial plants, particularly in power plants that require low maintenance, high reliability, and fuel economy. With its exceptional performance and efficiency, the MS5001 is an ideal choice for power generation in various applications, including cogeneration in industrial plants for the simultaneous production of power and process steam, as well as district heating systems.[1]

Key Features and Benefits for Power Plants

The MS5001 gas turbine offers several key features and benefits that make it a preferred choice for power generation in industrial plants, such as:

- Low Maintenance and High Reliability: The MS5001 is designed to withstand the demands of continuous power generation in industrial plants, ensuring long life and easy maintenance with minimal downtime.
- Fuel Economy and High Efficiency: This gas turbine is renowned for its fuel economy, allowing power plants to achieve significant fuel savings. With an efficiency of 26.3% and a heat rate of 12650 kJ/kWh, the MS5001 maximizes energy output while minimizing fuel consumption.[2]
- Cogeneration Capability: The MS5001 is ideally suited for cogeneration applications, where it can efficiently generate both power and process steam required by industrial plants. This capability enables power plants to optimize energy utilization and achieve a high fuel utilization index.
- Reliable Peak Load Generation: As a single-shaft turbine, the MS5001 excels in peak load generation scenarios. It can rapidly respond to fluctuations in power demand, making it a reliable solution for maintaining grid stability in power plants.
- Wide Application Range: The MS5001 gas turbine is widely utilized in both power generation and industrial applications. Its versatility allows it to meet the diverse needs of different industrial plants, providing a reliable source of power and thermal energy.
- Environmental Benefits: The MS5001 incorporates advanced combustion technology, resulting in reduced NOx and CO emissions compared to older gas turbine models. Power plants utilizing the MS5001 can contribute to environmental sustainability by minimizing their environmental footprint.[3]

Specifications for Power Generation

The MS5001 gas turbine specifications for power generation in industrial plants include:

- Power Output: 26.3 MW
- Fuel Type: Natural gas
- Frequency: 50/60 Hz
- Efficiency: 26.3%
- Heat Rate: 12650 kJ/kWh
- Speed: 5100 RPM
- Exhaust Mass Flow: 124.1 kg/s
- Exhaust Temperature: 487°C
- Weight: 87430 kg

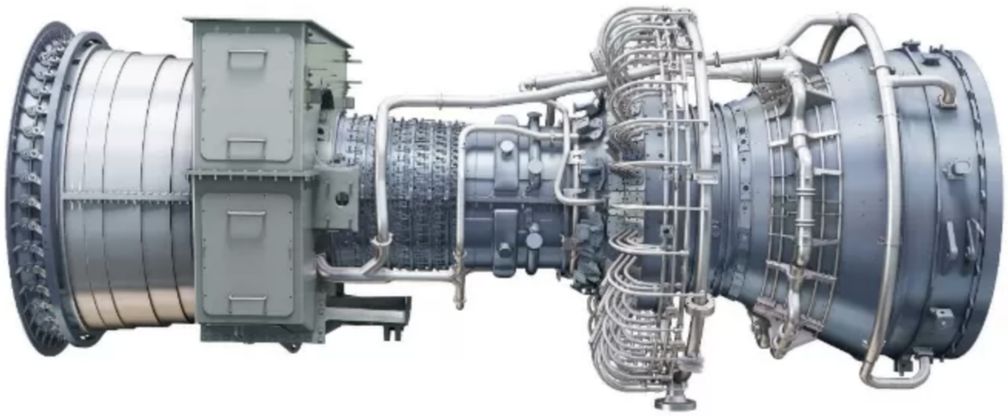


FIGURE 1.1: General Electric MS5001 Gas Turbine

1.2.1.2 Reduction Gearbox

A reduction gearbox is used in gas turbine engines to link the output of the engine to the input of the propeller or rotor. The gearbox reduces the high rotational speed of the gas turbine to a relatively low speed for propeller or rotor outputs, and it typically has multiple speed reduction stages, each stage adding to the overall size of the gearbox. Reduction gearboxes are used in high-speed gas turbine engines with two or more stages to reduce the very high rotational speed of the gas turbine to a relatively low speed for propeller or rotor outputs, and the speed reduction is dependent on the gearbox transmission ratio. Reduction gearboxes can be used for both steam and gas turbines, and they can be used to decrease the velocity of the input from the motor while also improving the torque the output can provide. Reduction gearboxes are also used in wind turbines to transform a comparatively slow turbine blade velocity to a great speed capable of producing electricity. In marine applications, a reduction gearbox is used to decrease the high-speed rotation of the steam turbine into the low rpm level needed by the propeller.[4]

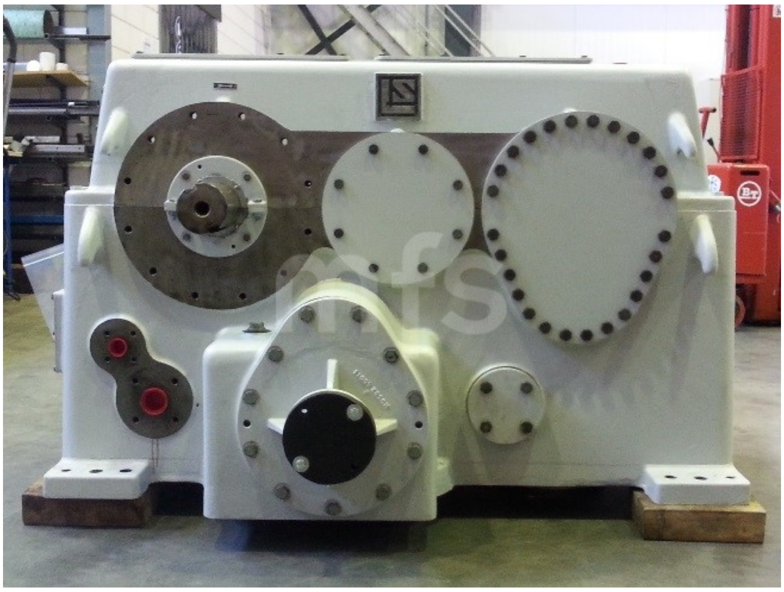


FIGURE 1.2: Reduction Gearbox

1.2.1.3 DG 4-Pole Brush Electric Generator

Brush Electrical Machines is the company that manufactures generators. The company has a long history of manufacturing electrical products, including turbo generators, salient pole machines, induction motors, traction motors and generators, traction locomotives, switchgear, transformers, and fuses. The company has various subsidiaries, including Brush Switchgear, Brush Transformers, Brush Traction, and Brush Control Gear.

The Brush Electric Generator model DG185ZL is a high-power generator manufactured by Brush Electrical Machines. It is designed for industrial applications and boasts a rated power output of 26 MVA. With a power factor of 0.85, it efficiently converts mechanical energy into electrical energy while minimizing power losses. The generator operates at a rated voltage of 6600 V (Line-to-Line) and can deliver a rated current of 2295 A.

Operating at a frequency of 50 Hz, the DG185ZL generator is designed with four poles and a rated speed of 1500 rpm. This configuration ensures a balanced electrical output, reduces vibrations, and enhances overall stability and performance. Its robust construction and advanced technology make it reliable and suitable for demanding environments.[5]

For more detailed specifications, please see Appendix A.

FIGURE 1.3: DG185ZL Brush Electric Generator

1.2.2 Gas Turbine Protection System

Gas turbine protection systems play a crucial role in ensuring the safe and reliable operation of gas turbines. These systems are designed to monitor various parameters and provide early warning or automatic shutdown in the event of abnormal operating conditions. In the following subsection, we will delve deeper into one of the leading gas turbine protection systems, the Bently Nevada 3500 system, and explore its introduction, capabilities, and significance in safeguarding gas turbine operations. Specifically, we will focus on how the Bently Nevada 3500 system integrates advanced technologies to monitor vibrations, temperature, and speed, providing comprehensive protection and enabling proactive maintenance to mitigate potential risks. Let us now turn our attention to the introduction of this powerful protection system and its pivotal role in ensuring the optimal performance and longevity of gas turbines.

1.2.2.1 Introduction to the Bently Nevada 3500 System

The Bently Nevada 3500 system is a machinery protection system that can be used to monitor and protect rotating and reciprocating machinery in a variety of industries. The system is designed to provide continuous, online monitoring of machine parameters such as vibration, temperature and speed. The system can also be used to provide machinery protection through the use of alarms and trip functions.[6]

FIGURE 1.4: Bently Nevada 3500 Series Machinery Monitoring System

The Bently Nevada 3500 system is a modular system that can be configured to meet the specific needs of each application. The system consists of a central rack that houses the system controller, power supplies, and input/output modules. The system can also be expanded to include a variety of optional modules, such as temperature modules, vibration modules, and keyphasor modules.

The Bently Nevada 3500 system is a highly reliable and versatile machinery protection system that can be used to protect a wide range of rotating and reciprocating machinery. The system is easy to install and maintain, and it provides a high level of protection for critical machinery.

The Bently Nevada 3500 system is a valuable asset for any organization that operates rotating and reciprocating machinery. The system can help to protect critical machinery from damage, improve operational efficiency, and reduce the risk of unplanned downtime.[6]

1.2.2.2 Hardware Components

The 3500/05 Instrument Rack

The 3500 System's modules were housed in the 3500/05 rack, which served the dual purpose of supplying power to the modules and facilitating their easy installation and internal communication.

The 3500/05 Rack is available in two sizes: a full-size rack measuring 19 inches and containing 14 module slots, and a mini-rack measuring 12 inches and containing 7 module slots.

The power supplies and rack interface module are located in the leftmost section of the rack, which is not considered as a slot. This means that in the full-size rack, 14 slots are available for the installation of other modules, and in the mini-rack, 7 slots are available for module installation.

Figure 1.5: 3500/05 Instrument Rack

The 3500/15 Power Supply Module

The 3500/15 Power Supply offers the flexibility to be ordered with either AC or DC input power, ensuring seamless compatibility with voltage sources worldwide. To maintain a high standard of performance, line noise filters are included as a standard feature.
In terms of power redundancy, the 3500 Rack provides the option to operate with a single power supply or utilize dual supplies for situations where uninterrupted power is crucial. These redundant supplies are strategically positioned in the upper and lower slots of the leftmost section of the rack, offering enhanced reliability.

FIGURE 1.6: 3500/15 AC Power Supply

The 3500/22M Transient Data Interface Module

The 3500/22M Transient Data Interface (TDI) serves as the connection point between the 3500-monitoring system and the 3500 System Configuration software. The TDI module is always placed in the rack beside the power supply module.
This module continuously collects data from all modules and sends them to other systems connected to this module through Ethernet. The Transient Data Interface (TDI) has the following LEDs:

- The OK LED indicates a healthy status.
- The TX/RX LED indicates communication with other modules in a rack.
- The TM LED indicates that the rack is in trip multiply mode.
- The CONFIG OK LED indicates the rack has a valid configuration.

By incorporating these LEDs, the TDI provides essential visual indications for monitoring and troubleshooting purposes.

FIGURE 1.7: 3500/22M Transient Data Interface Module

The 3500/40M Proximitor Monitor Module

The 3500/40M Proximitor Monitor is a four-channel monitor designed to receive input from Bently Nevada proximity transducers. It processes the signal to offer different measurements of vibration and position, and compares the processed signals with alarms that can be programmed by the user. Using the 3500 Rack Configuration Software, the user can program each channel of the 3500/40M to perform several functions, including :

- Radial vibration.
- Axial (Thrust) position.
- Eccentricity.
- Differential expansion.

The main objective of the 3500/40M Proximitor Monitor is twofold. Firstly, it provides machinery protection by continuously comparing the monitored parameters against preconfigured alarm thresholds to activate alarms when necessary. Secondly, it supplies essential machine information to both operations and maintenance personnel.

FIGURE 1.8: 3500/40M Proximitor Monitor Module

The 3500/25 Keyphasor Module

The 3500/25 module is a compact half-height module that provides power and termination for up to two Keyphasor transducers. It receives data from the field, particularly the proximity transducer system, enabling it to calculate the speed of the rotating part. When one or two Keyphasor transducers are required, a single 3500/25 module is installed. For applications with up to four Keyphasor transducers, two 3500/25 Keyphasor modules can be placed in the same rack slot, one above the other. The Keyphasor signals from the 3500/25 module(s) can be routed via the 3500's rack backplane to appropriate monitor modules.

FIGURE 1.9: 3500/25 Keyphasor Module

The 3500/65 Temperature Module

Figure 1.10: 3500/65 Temperature Module

The 3500/65 monitor is designed to provide temperature monitoring for up to 16 channels. It supports two types of temperature inputs: resistance temperature detectors (RTDs) and isolated tip thermocouples (TCs). These inputs are conditioned by the monitor and compared against alarm setpoints that can be customized by the user.
To program the monitor, the 3500 Rack Configuration Software is used. This software allows you to configure the 16-Channel Temperature Monitor to accept different types of inputs, such as isolated tip thermocouples, 3-wire RTDs, 4-wire RTDs, or a combination of TC and RTD inputs.
In Triple Modular Redundant (TMR) configurations, it is necessary to install temperature monitors in groups of three adjacent monitors. This configuration is implemented to enhance reliability and avoid single-point failures. The monitor utilizes two types of voting methods to ensure accurate operation and mitigate potential failures.
By employing the 3500/65 monitor, users can effectively monitor temperature conditions and employ appropriate measures to maintain system integrity and prevent any undesirable consequences.

The 3500/32M Relay Module

The 3500/32M Relay Module is a module that occupies the full height of the rack and offers four relay outputs. The user can configure these relays as either normally open (NO) or normally closed (NC) contacts from the rear of the module.

Each relay included in the 4-Channel Relay Module is equipped with Alarm Drive Logic, which allows for efficient control and activation.

By utilizing simple AND and OR logic in the programming of this module, the relays can be energized to generate trips in other connected systems via hardwire connections.

The module provides 2 setpoints for each specific tag: Alert and Danger. The Alert setpoint serves as a high alarm for user awareness, while the Danger setpoint functions as a High High alarm, resulting in the machine being tripped based on the specified logic.

In terms of indicators, the module features three LEDs: OK (indicating the module's health status and the status of connected transducers), TX/RX (indicating communication with the Transient Data Interface (TDI) and other modules), and individual ALARMS LEDs for each channel (indicating whether any relay is in an alarm state or not).

FIGURE 1.11: 3500/32M Relay Module

The 3500/92 Communication Gateway Module

The 3500/92 Communication Gateway module provides extensive communication capabilities for integration with process control and automation systems, including Programmable Logic Controllers (PLCs) and Distributed Control Systems (DCS). It supports Ethernet TCP/IP and serial (RS232/RS422/RS485) communications, allowing seamless connectivity. The module facilitates communication with PLCs and DCS systems, enabling the exchange of rack monitored values and statuses. Supported protocols include Modicon Modbus (via serial communications), Modbus/TCP (for TCP/IP Ethernet communications), and Bently Nevada's proprietary protocol (for communication with 3500 Rack Configuration and Data Acquisition Software packages). This capability ensures compatibility and efficient data transfer between the monitoring system and PLCs or DCS systems, enabling comprehensive process control, automation, and system monitoring.

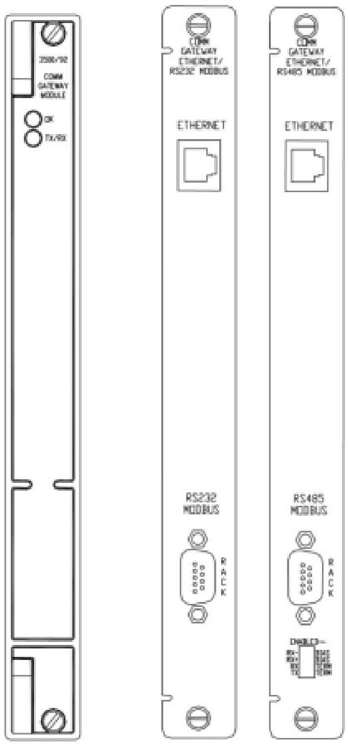


FIGURE 1.12: Front and Rear Views of the 3500/92 Communication Gateway

1.2.2.3 Functionality and Features

Vibration Monitoring

The Bently Nevada 3500 System for Gas Turbine Protection provides continuous vibration monitoring to detect any changes in the vibration patterns of the gas turbine. This is done using proximity probes and accelerometers, which provide data on the axial, radial, and casing vibration of the turbine. The system includes advanced algorithms that can detect early warning signs of potential problems, such as unbalance, misalignment, or bearing damage, allowing maintenance teams to take proactive measures to prevent damage and downtime. By monitoring vibration patterns and analyzing data, the system provides valuable insights into the health and performance of the gas turbine, enabling operators to optimize operation and reduce maintenance costs.[7]

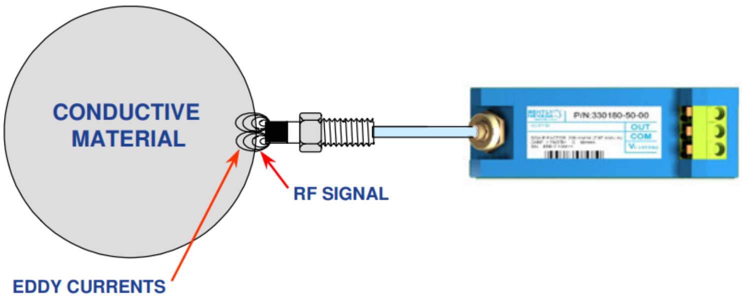


FIGURE 1.13: Bently Nevada Proximity Probe

Temperature Monitoring

The Bently Nevada 3500 system employs temperature sensors to monitor gas turbine components and gauge the operating temperatures, particularly in the bearings. These temperatures serve as an indication of the bearing's heat levels, which can be influenced by factors such as overloading, misalignment, and suboptimal lubricant pressure or flow.

By generating electrical signals proportional to the temperature levels, the temperature sensors transmit this data to the Bently Nevada 3500 system for effective processing. The system conducts real-time analysis on the temperature data, enabling the detection of abnormal patterns or trends. In instances where the temperature surpasses preconfigured thresholds, the system promptly triggers an alarm or initiates a gas turbine trip as a preventive measure against further damage.

This proactive approach aids in averting unplanned downtime and contributes to an extended lifespan for the gas turbine.

Figure 1.14: Pt100 RTD installed inside thrust bearing pads

Speed Monitoring

The Bently Nevada 3500 system can also monitor the speed of the gas turbine using a specialized sensor called a Keyphasor. A Keyphasor is a digital sensor that detects the precise position of a rotating shaft, usually by sensing a Notched wheel attached to the shaft.

The Keyphasor generates an electrical signal that is used to determine the rotational speed and position of the shaft. The Bently Nevada 3500 system uses this data to calculate the actual speed of the gas turbine and compare it to the setpoints for normal operation.

If the actual speed deviates from the setpoints, the system can trigger an alarm or shutdown the gas turbine to prevent any potential damage. The Keyphasor is a critical component in monitoring the speed of the gas turbine and ensuring safe and reliable operation.[7]

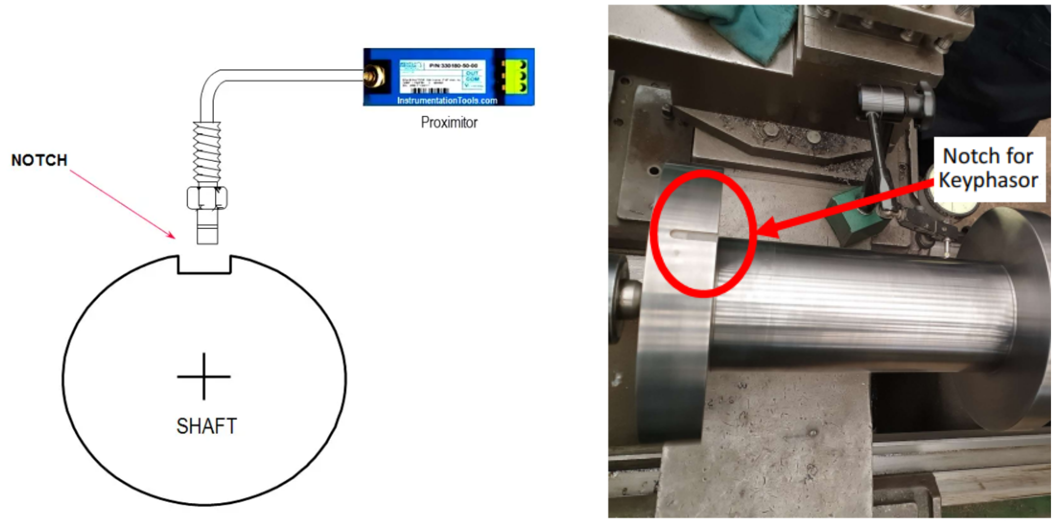


FIGURE 1.15: Keyphasor placement in the rotary machine

1.3 IIoT Integration with Gas Turbine Protection Systems

1.3.1 Introduction to Industrial Internet of Things (IIoT)

IIoT is a subcategory of the Internet of Things. The term refers to Internet of Things (IoT) technology that is used in industrial settings, specifically manufacturing facilities. IIoT is a critical component of Industry 4.0, the fourth industrial revolution. Industry 4.0 places a premium on smart technology, data, automation, interconnectivity, and other technologies and capabilities. These technologies are fundamentally altering how factories and industrial organizations operate. IIoT has a number of the same applications and benefits as IoT. Smart sensors can be integrated into manufacturing equipment, energy systems, and infrastructure such as piping and wiring. Through the data they collect and the advanced functionality they enable, these sensors can assist industrial businesses in increasing their efficiency, productivity, and employee safety, among other metrics. The IIoT enables improved machine-to-machine communication and provides plant managers with data that provides a more complete picture of their facility's operation. Industrial companies can keep a closer eye on their energy, water, and other resource consumption, as well as when and how much they produce, by collecting granular data on a continuous basis. Operators can then make manual adjustments to optimize their operation, or the equipment can do so automatically. Businesses can save significant amounts of energy, water, and resources while maintaining or increasing productivity levels through this continuous optimization. When used in this manner, IIoT can assist businesses in achieving their lean manufacturing goals. Additionally, you can use IIoT to inform predictive maintenance programs, accelerate product development, and accomplish other business objectives.[8]

1.3.2 Benefits and Advantages of Integrating IIoT with Gas Turbine Protection Systems

Integrating Industrial Internet of Things (IIoT) technology with gas turbine protection systems offers numerous benefits and advantages for the power generation industry. By leveraging the capabilities of IIoT in gas turbine protection systems, manufacturers can enhance operational efficiency, optimize maintenance processes, improve safety, and gain valuable insights for better decision-making. The following subsection explores the key benefits and advantages of integrating IIoT with gas turbine protection systems:

- **Enhanced Monitoring and Diagnostics:** IIoT enables continuous monitoring of gas turbine parameters, such as temperature, speed , vibration, and other critical operating conditions. Real-time data collection and analysis provide valuable insights into turbine performance, allowing operators to detect anomalies, identify potential issues, and perform timely maintenance or troubleshooting. This proactive approach minimizes the risk of unplanned downtime and maximizes turbine availability.

- **Predictive Maintenance:** IIoT integration enables predictive maintenance strategies for gas turbines. By analyzing data from various sensors and applying advanced analytics techniques, maintenance teams can identify patterns and trends that indicate potential equipment failures. Predictive maintenance allows for timely intervention, scheduling maintenance activities when needed, and preventing costly unscheduled shutdowns. This approach also optimizes maintenance schedules, minimizing downtime and reducing maintenance costs.[9]

- **Remote Monitoring and Control:** IIoT facilitates remote monitoring and control of gas turbine protection systems. Through secure connectivity, operators and maintenance personnel can access real-time turbine data, receive alerts and notifications, and remotely adjust system parameters or initiate actions when required. This capability improves operational efficiency, reduces the need for physical presence on-site, and allows for quick response and decision-making, even from remote locations.

- **Data-Driven Decision-Making:** IIoT integration provides access to vast amounts of data collected from gas turbine protection systems. This data can be analyzed and transformed into actionable insights using advanced analytics and machine learning techniques. By leveraging this information, operators and engineers can make data-driven decisions to optimize turbine performance, improve energy efficiency, and enhance overall operational effectiveness.

- **Improved Safety:** IIoT integration enhances safety in gas turbine operations. Real-time monitoring of critical parameters and the ability to detect potential faults or abnormal conditions allow operators to take immediate action to prevent accidents or equipment damage. IIoT-enabled safety systems can trigger alarms, shut down the turbine in case of emergencies, and enable quick response and intervention to mitigate risks and ensure a safe working environment for personnel.[9]

- **Cost Reduction:** Integrating IIoT with gas turbine protection systems offers cost-saving opportunities. By optimizing maintenance schedules, minimizing unplanned downtime, and improving turbine efficiency, manufacturers can reduce operational costs. The ability to remotely monitor and control turbines also reduces the need for on-site visits and associated travel expenses. Additionally, data-driven insights obtained through IIoT integration can identify energy-saving opportunities and operational inefficiencies, leading to further cost reductions.[9]

- **Performance Optimization:** IIoT integration enables the optimization of gas turbine performance. By continuously monitoring and analyzing operational data, manufacturers can identify opportunities to optimize turbine settings, improve energy efficiency, and enhance overall performance. Adjustments can be made based on real-time insights, resulting in better turbine operation, reduced fuel consumption, and increased power output.

In conclusion, integrating IIoT with gas turbine protection systems brings significant benefits to the power generation industry. From enhanced monitoring and diagnostics to predictive maintenance, remote monitoring and control, data-driven decision-making, improved safety, cost reduction, and performance optimization, the integration of IIoT technology empowers manufacturers to maximize operational efficiency, minimize downtime, and achieve better overall turbine performance.

1.3.3 MQTT Protocol for Efficient Communication in IIoT

1.3.3.1 Introduction to MQTT

MQTT stands for Message Queuing Telemetry Transport. MQTT is a machine to machine internet of things connectivity protocol. It is an extremely lightweight and publish-subscribe messaging transport protocol. This protocol is useful for the connection with the remote location where the bandwidth is a premium. These characteristics make it useful in various situations, including constant environment such as for communication machine to machine and internet of things contexts. It is a publish and subscribe system where we can publish and receive the messages as a client. It makes it easy for communication between multiple devices. It is a simple messaging protocol designed for the constrained devices and with low bandwidth, so it's a perfect solution for the internet of things applications.[10]

1.3.3.2 MQTT Architecture

MQTT's publish/subscribe (pub/sub) communication strategy, which aims to maximize bandwidth utilization, is a substitute for traditional consumer architecture directly interacting with an endpoint. However, in the pub/sub paradigm, the client who transmits the news (the publisher) is separated from the customers receiving the information (or the subscribers). Since neither the writers nor the customers communicate with each other immediately, their interactions in them are handled by third parties called brokers.[11]

Publishers and subscribers are two types of MQTT clients, depending on whether the client is publishing or getting messages. One can combine the two features in a single MQTT client. A publish is when a device (or client) wishes to send information to the server (or broker). In the middle, there is a central server or broker that acts as a mediator. Each incoming message is filtered by the broker, who then sends them to the appropriate customers.

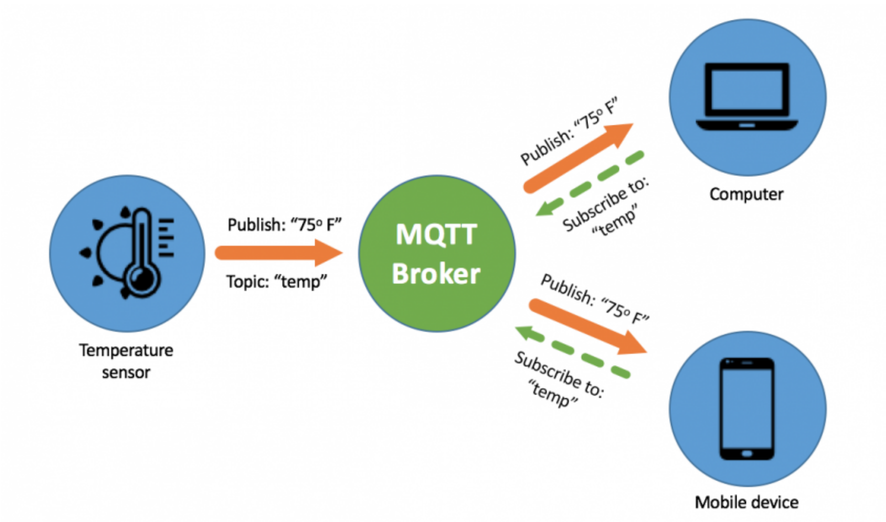


FIGURE 1.16: MQTT Architecture

1.3.3.3 Introduction to HiveMQ

HiveMQ Cloud is a fully-managed, cloud-native IoT messaging platform that connects IoT devices to any cloud platform in a reliable and scalable manner. It is a cloud-based MQTT broker that enables users to connect up to 100 devices for free. HiveMQ Cloud offers different packages to fit users' needs perfectly, including a free package, a pay-as-you-go package, and a dedicated package. [12]

HiveMQ Cloud is 100% compliant with the MQTT specification and offers enterprise-grade security from the ground up, including device authentication/authorization, TLS communication, and replication across 3 different data centers. HiveMQ Cloud provides out-of-the-box, fully managed integrations that let users instantly connect their MQTT broker to popular services.

The HiveMQ Cloud console is the center of operations for all cloud-related activities, including creating, managing, and tracking HiveMQ Cloud clusters, editing credentials, and integrating HiveMQ Cloud instances with popular data streaming services. HiveMQ Cloud is built for production and offers reliable, scalable, and secure MQTT cloud-broker clusters.

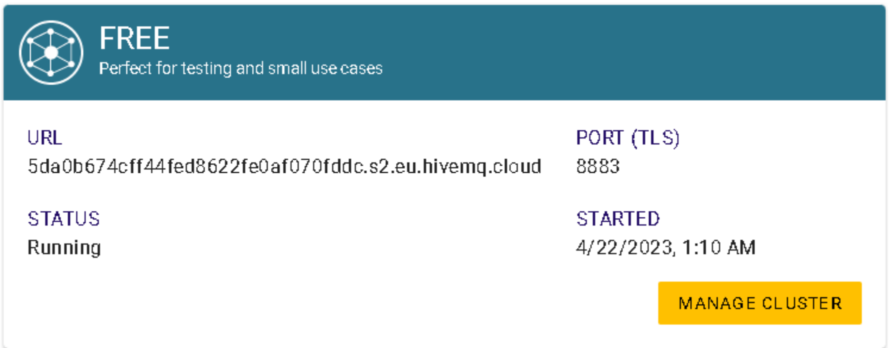


Figure 1.17: HiveMQ Cloud cluster

1.3.3.4 Benefits of HiveMQ Cloud in IIoT

Scalability: HiveMQ is designed to handle large-scale deployments in IIoT, supporting hundreds of thousands of devices with high message throughput on a single node and millions of devices in cluster mode. It offers exceptional performance and stability, with features like MQTT Broker Clustering ensuring mission-critical MQTT deployments run smoothly. HiveMQ allows both vertical and horizontal scalability, making it adaptable to growing needs.[13]

Security: HiveMQ prioritizes security for mission-critical deployments. It provides advanced authentication and authorization mechanisms to ensure secure MQTT communication. Additionally, HiveMQ's Java-based plugin system allows easy integration of advanced security mechanisms like OAuth 2.0. The broker supports state-of-the-art security standards, including TLS 1.0, TLS 1.1, and TLS 1.2, ensuring the safe transfer of data to and from HiveMQ.

Simplicity: HiveMQ emphasizes simplicity in its design and implementation. It offers a straightforward installation process, allowing users to download and start the broker without complications. For production deployments, startup scripts for Linux systems and a Windows Service are available. HiveMQ also provides an extendable monitoring approach using industry standards like JMX, allowing users to integrate their own business metrics seamlessly.

Reliability: Reliability is a key characteristic of HiveMQ, particularly for production use cases. As MQTT brokers serve as the communication hub between backends and devices, maintaining high availability is crucial. HiveMQ ensures superior reliability with sophisticated mechanisms in both single node and cluster modes. In the event of a broker instance restart, HiveMQ recovers all prior states due to disk persistence, minimizing disruptions and ensuring continuity of operations.

1.4 Literature Review

In the field of gas turbine protection systems, conventional approaches have exhibited certain limitations that hinder their effectiveness in ensuring optimal turbine performance and reliability. This literature review focuses on the identification of these limitations and the subsequent development of a robust gas turbine protection system integrated with an IIoT (Industrial Internet of Things) solution to overcome these challenges. The following sections delve into the specific limitations faced by conventional systems and highlight the innovative solutions implemented in the proposed system.

Integration of S7-1500 Safety PLC with SIL3 for Reliable System Operation

Ensuring the reliability of gas turbine protection systems is paramount to prevent catastrophic failures and ensure operator safety. To address this critical aspect, the proposed system incorporates the integration of an S7-1500 Safety Programmable Logic Controller (PLC) with SIL3 (Safety Integrity Level 3) certification. In the event of a trip or abnormal condition, the safety PLC activates predefined safety protocols, swiftly shutting down the turbine to mitigate potential risks. This integration enhances the overall reliability of the system, providing an additional layer of protection and ensuring compliance with stringent safety standards.

User-Friendly HMI and SCADA for Enhanced Monitoring

As depicted in the figure below, the conventional bargraphs used for transmitter monitoring present significant limitations, including a lack of user-friendliness and challenges in pinpointing the transmitter's location. To overcome these obstacles, a user-friendly Human-Machine Interface (HMI) and Supervisory Control and Data Acquisition (SCADA) system were meticulously developed. This innovative solution offers operators effortless monitoring and clear visualization through intuitive graphical representations, revolutionizing the user experience and facilitating the seamless analysis of transmitter data.

FIGURE 1.18: Bently Nevada 3500/94M Display HMI

Comprehensive Data Access, Collection, and Analysis

Conventional systems may face limitations in terms of data access, collection, and analysis, restricting the depth of insights into turbine performance and health. In response, a solution was developed to overcome these limitations. The proposed system incorporates advanced data acquisition and analytics capabilities, allowing for comprehensive data collection from various sensors and transmitters. This enables in-depth analysis and provides actionable insights into turbine condition, performance trends, and potential faults.

Extending Monitoring Beyond Local Boundaries

Conventional systems often offer limited local monitoring capabilities, restricting visibility and control to the immediate vicinity. To overcome this limitation, an IIoT-based solution was developed. This integrated IIoT solution enables remote monitoring and control by establishing a secure network infrastructure. With real-time turbine data and analytics accessible remotely, operators can make informed decisions and take proactive maintenance actions from any location, extending the monitoring reach beyond local boundaries.

Chapter 2

Methods & Materials

2.1 Introduction

In order to accomplish the project's objectives, the utilization of specific materials is crucial. Therefore, the subsequent sections will focus on discussing the hardware and software materials in detail to emphasize how they will be incorporated in the project's design and implementation.

2.2 Hardware

2.2.1 S7-1500 Fail-Safe PLC

2.2.1.1 Introduction to the S7-1500 Fail-Safe PLC

A Programmable Logic Controller (PLC) is an essential component in industrial automation systems, controlling and monitoring electromechanical processes. In gas turbine protection systems, the S7-1500 Safety PLC is a crucial part responsible for ensuring the safety of the processes involved.

The S7-1500 Safety PLC is a highly advanced PLC designed specifically for applications that demand high levels of safety and reliability. While it offers the power and flexibility of a standard PLC, it incorporates advanced safety features, making it an optimal choice for critical systems like gas turbine protection.[14]

As the core control unit, the S7-1500 Safety PLC receives and processes data from various sensors connected to the Bently Nevada 3500 System. These sensors measure parameters such as vibration, temperature, and speed. By continuously monitoring these parameters, the PLC can detect any deviations from normal operating conditions and take appropriate actions to ensure system safety.

Figure 2.1: The S7-1500 fail-safe PLC

Apart from monitoring, the S7-1500 Safety PLC also controls safety-critical processes within the gas turbine protection system. It utilizes safety logic and decision-making algorithms based on the received data. When certain thresholds or setpoints are exceeded, the PLC triggers alarms and initiates safety measures to mitigate potential risks. These measures may include activating protective devices, shutting down specific components, or alerting the operator to take necessary actions.

The integration of the S7-1500 Safety PLC with the Bently Nevada 3500 System enhances its functionality within the gas turbine protection system. Its advanced safety features and capabilities enable it to effectively monitor and control critical processes, ensuring the safe and reliable operation of the gas turbine. This, in turn, contributes to the overall efficiency, longevity, and operational safety of the system.

In the upcoming sections, we will explore the hardware aspects, integration with the Bently Nevada system, communication setup, and safety logic implemented within the S7-1500 Safety PLC. This comprehensive understanding will shed more light on the PLC's role in the gas turbine protection system and its significant contribution to maintaining operational safety.

2.2.1.2 Hardware Components

The CPU 1513F-1 PN

The CPU 1513F-1 PN is a powerful and versatile controller from the SIMATIC S7-1500 series by Siemens. It is a central processing unit (CPU) that plays a crucial role in industrial automation and control systems.[15]
Key features and functionalities of the CPU 1513F-1 PN include:

- Processing Power: The CPU 1513F-1 PN is equipped with a high-performance processor that enables fast and efficient execution of control tasks. It has ample memory capacity to handle complex automation processes.

- Communication Capabilities: The CPU 1513F-1 PN supports Profinet protocol for seamless integration into industrial networks. It offers Ethernet-based communication, facilitating connectivity with other devices and systems within the network.

FIGURE 2.2: The CPU 1513F-1 PN

- Safety Functionality: The CPU 1513F-1 PN supports safety-related functions according to the requirements of SIL3 (Safety Integrity Level 3), providing a high level of safety and reliability.
- Scalability and Flexibility: The CPU 1513F-1 PN allows for modular expansion with additional modules and peripherals, making it a scalable and flexible solution that can be tailored to specific application requirements.

In summary, the CPU 1513F-1 PN is a powerful and feature-rich controller that offers high-performance processing, extensive communication capabilities, built-in safety functions, and compatibility with the Profinet protocol. It provides a reliable and flexible solution for automation and control applications in various industrial sectors.

The 25W Power Supply

The PLC power supply is a critical component in the operation of a Programmable Logic Controller (PLC) system. In the case of Siemens' PLC power supply, such as the one designed for the SIMATIC S7-1500 controller, it serves several important functions. Key points to include in the brief overview:

- Voltage Regulation: The PLC power supply ensures that the backplane bus of the SIMATIC S7-1500 controller receives the correct voltage for safe and reliable operation. It provides the necessary voltage levels to power the various modules within the PLC system.
- Protection Features: The power supply incorporates essential protection features, including short-circuit and reverse polarity functions. These safeguards shield both the equipment and the operator from the harmful effects of excess current and prevent damage in the event of reversed polarity.

FIGURE 2.3: 25W Power Supply

- Mains Buffering: With its mains buffering capabilities, the power supply can bridge power failures lasting up to 20ms. This feature minimizes the risk of process downtime and equipment failure, ensuring continuity and reliability in industrial applications.

Fail-safe Digital Input/Output modules

Fail-safe I/O modules are an integral part of the Siemens Safety Integrated concept, offering reliable and certified functional safety capabilities for industrial automation systems. These modules provide fail-safe digital inputs (DI) and outputs (DQ) that are dimensionally compatible with standard modules, ensuring seamless integration into existing control systems.

Key features and benefits of Fail-safe I/O modules include:

- Functional Safety Certification: The Fail-safe I/O modules are certified according to the IEC 61508 standard for functional safety. This certification ensures that the modules meet rigorous safety requirements and can be used in safety-critical applications with confidence.
- Safety Ratings: The modules are designed to meet the safety integrity level SIL 3 according to IEC 62061 and performance level PL e according to ISO 13849. These ratings demonstrate their capability to handle safety-related tasks and provide a high level of safety performance.

FIGURE 2.4: Fail-safe Digital Input Module

2.2.2 The SITOP UPS1600

The SITOP UPS1600 is a parallel uninterruptible power supply (UPS) system designed by Siemens. It provides reliable and continuous power backup to critical electrical equipment in industrial applications, ensuring uninterrupted operation and protection against power disruptions.[16]

Key features and benefits of the SITOP UPS1600 parallel UPS include:

- Parallel Redundancy: The UPS1600 is designed to operate in a parallel configuration, allowing multiple UPS units to work together and share the load. This parallel redundancy feature provides increased reliability and availability, as each UPS can provide backup power to the connected equipment in case of a failure or maintenance of another UPS unit.

- Advanced Battery Management: The UPS1600 incorporates intelligent battery management features to optimize the performance and lifespan of the backup batteries. It continuously monitors battery health, charging status, and temperature, ensuring reliable operation and extending the battery life.

FIGURE 2.5: The SITOP UPS1600

2.2.3 SIMATIC HMI TP900 Comfort

The SIMATIC HMI TP900 Comfort is an advanced human-machine interface (HMI) panel designed by Siemens. It plays a vital role in monitoring the vibration, temperature, and speed of gas turbines. With its high-resolution 9-inch color touch screen display and user-friendly interface, operators can easily access real-time data related to these parameters. The TP900 Comfort enables comprehensive monitoring of vibration levels, temperature variations, and turbine speeds, ensuring safe and optimal turbine operation. Its flexibility allows seamless integration with other components, while its robust design ensures durability in demanding turbine environments. By offering advanced functionality and integration with the TIA Portal software, the TP900 Comfort significantly contributes to efficient gas turbine operation by facilitating real-time monitoring, issue identification, and informed decision-making.

Figure 2.6: The SIMATIC HMI TP900 Comfort

2.3 Software

2.3.1 Modbus Poll

Modbus Poll is a software tool used in the project to simulate communication between the Bently Nevada 3500 communication module and the S7-1500 safety PLC via Modbus TCP/IP protocol. It allows for testing and verification of the communication system before the actual installation of hardware.

During the development phase, we used Modbus Poll to send simulated data packets to ensure that the communication system was functioning correctly.
This was especially important since any errors in the communication system could lead to erroneous readings and potentially dangerous conditions for the gas turbine.

After the system installation, Modbus Poll will be still used as a diagnostic tool to troubleshoot any issues that arose in the communication system. It allowed for easy identification of communication failures and pinpointing the source of the issue.

Overall, the use of Modbus Poll played a crucial role in ensuring the reliability and safety of the gas turbine protection system by facilitating effective communication between the various components.

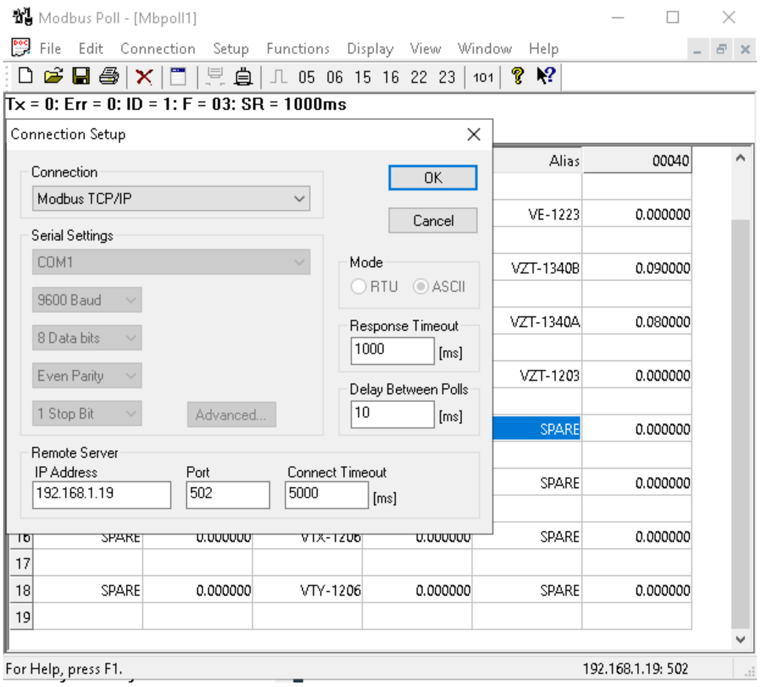


FIGURE 2.7: Modbus Poll

2.3.2 S7-PLCSIM Advanced

PLCSim Advanced is a versatile software tool that allows users to simulate different applications for programmable logic controllers (PLCs). It enables the creation of virtual controllers, specifically for S7-1500 controller. With PLCSim Advanced, a single PC can emulate multiple working PLCs, supporting up to 16 instances. The software includes a powerful API for seamless communication with other devices and is compatible with TIA Portal, a popular PLC programming and configuration platform. Simulation capabilities allow users to test applications and interfaces without physical hardware.[17]

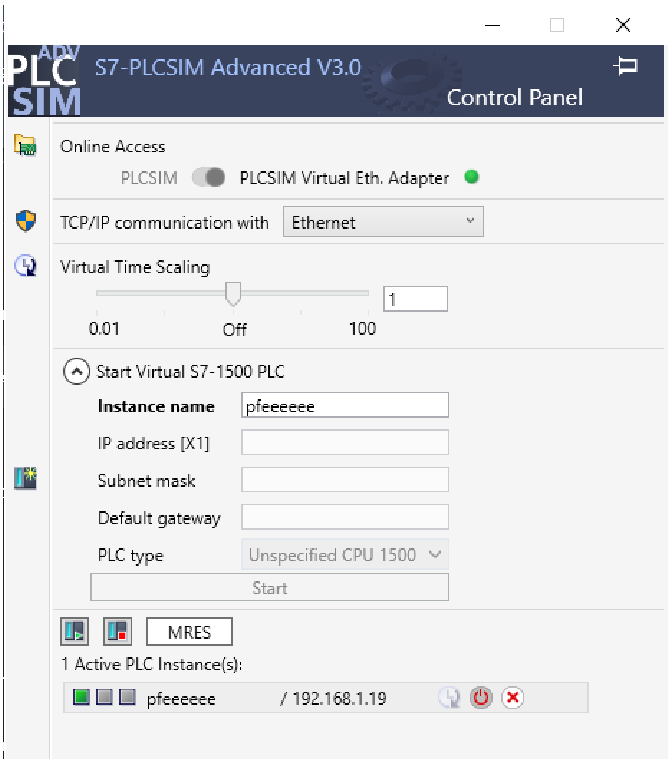


FIGURE 2.8: PLCSim Advanced software

The virtual commissioning of our S7-1500 safety PLC in our project was achieved using PLCSim Advanced software. This tool enabled us to create virtual controllers and effectively simulate the behavior of the PLC within a virtual environment. By utilizing PLCSim Advanced, we rigorously tested and validated our PLC program, ensuring its reliability and accuracy in real-world scenarios.

2.3.3 TIA Portal

The TIA Portal, also known as the Totally Integrated Automation Portal, serves as a comprehensive engineering framework that enables the implementation of automation solutions across various industries worldwide. It encompasses the entire process, from initial design and commissioning to operation, maintenance, and system upgrades. By utilizing the TIA Portal, engineers can significantly reduce the time, cost, and effort involved in these tasks.

Within the TIA Portal, one of the key software components is SIMATIC STEP 7. This powerful tool allows engineers to configure, program, test, and diagnose a wide range of modular and PC-based SIMATIC controllers. It offers a multitude of user-friendly functions that facilitate the automation development process.[18]

In addition to SIMATIC STEP 7, the TIA Portal also incorporates the WinCC Runtime, which is specifically designed for Human-Machine Interface (HMI) and SCADA (Supervisory Control and Data Acquisition) design. The WinCC Runtime enables engineers to create intuitive and visually appealing interfaces for monitoring and controlling automated systems. It enhances the overall functionality and user experience within the TIA Portal, providing a comprehensive solution for both control programming and HMI/SCADA design.

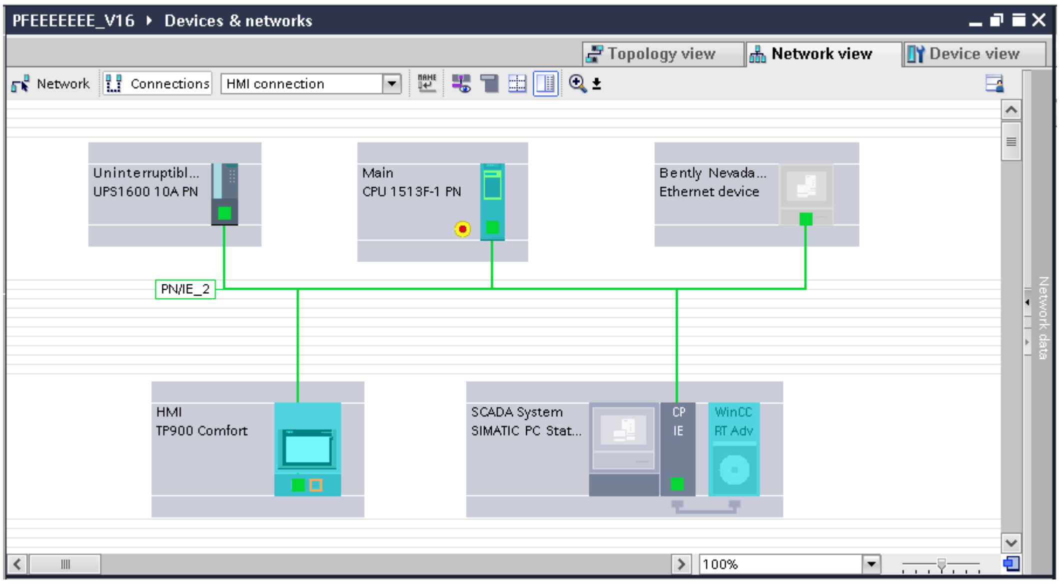


FIGURE 2.9: TIA Portal Devices and Networks view

2.3.3.1 SIMATIC STEP 7

SIMATIC STEP 7 played a pivotal role in the project by enabling hardware configuration and programming for the Gas Turbine Generator Set Protection System. In the upcoming subsection, we will explore in detail the functions and features of SIMATIC STEP 7 that were utilized in this context.

Modbus Data Reading Function

To gather data from the Bently Nevada 3500 system, including temperatures, vibrations, and the speed of the gas turbine generator set, we utilized the MB_Server Block in conjunction with Modbus TCP/IP communication.
This enabled seamless data exchange between our system and the Bently Nevada 3500 device.

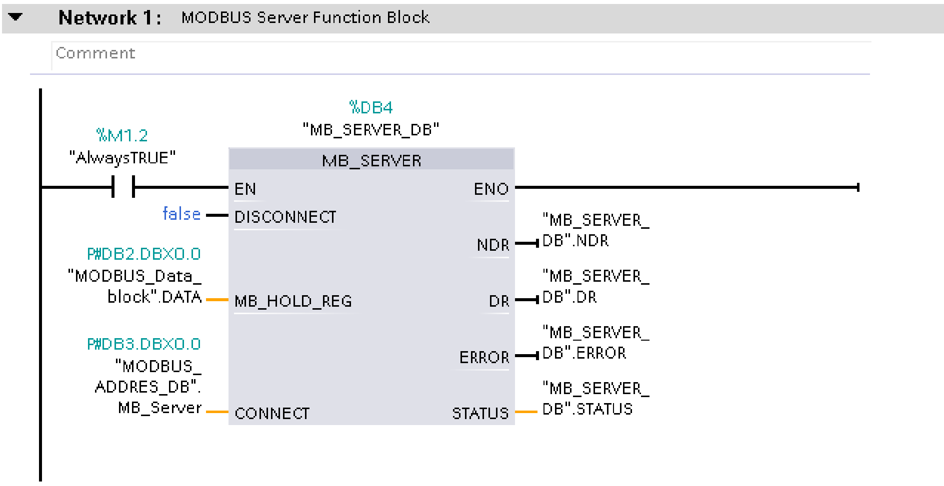
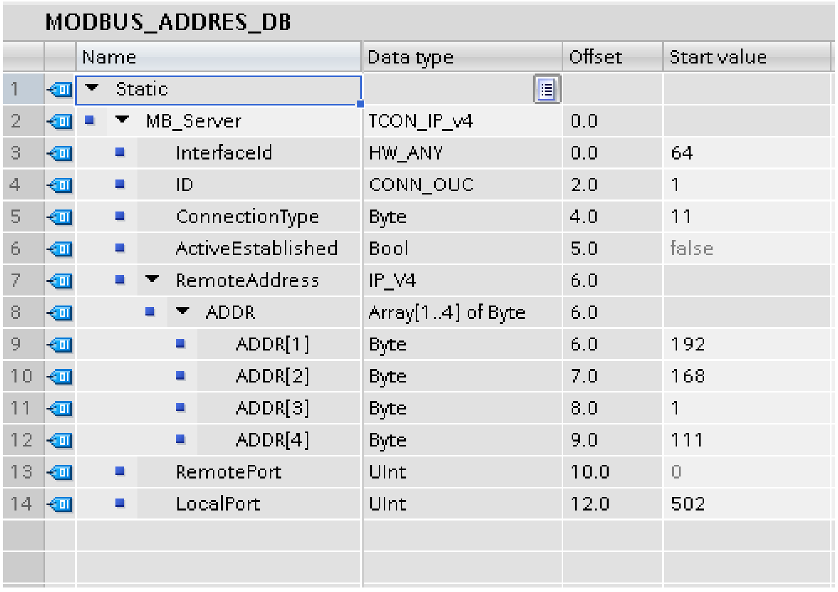


FIGURE 2.10: MB_SERVER Block

To configure the MB_Server Block, we delved into its settings and parameters. Through these configurations, we precisely specified the target device, ensuring accurate communication with the Bently Nevada 3500 system. Additionally, we identified register address associated with the desired data points, enabling us to retrieve the specific information we required.



MODBUS_ADDRES_DB

	Name	Data type	Offset	Start value
1	Static			
2	MB_Server	TCON_IP_v4	0.0	
3	InterfaceId	HW_ANY	0.0	64
4	ID	CONN_OUC	2.0	1
5	ConnectionType	Byte	4.0	11
6	ActiveEstablished	Bool	5.0	false
7	RemoteAddress	IP_V4	6.0	
8	ADDR	Array[1..4] of Byte	6.0	
9	ADDR[1]	Byte	6.0	192
10	ADDR[2]	Byte	7.0	168
11	ADDR[3]	Byte	8.0	1
12	ADDR[4]	Byte	9.0	111
13	RemotePort	UInt	10.0	0
14	LocalPort	UInt	12.0	502

FIGURE 2.11: MODBUS ADDRESS DataBlock

Rearrange Data Function

To enhance the setup and management of the gathered data from the Modbus server block, we utilized the MOVE_BLK function Block. Initially received as a single block, we employed the MOVE_BLK function to separate each parameter (vibration, speed, and temperature) into its own data block.

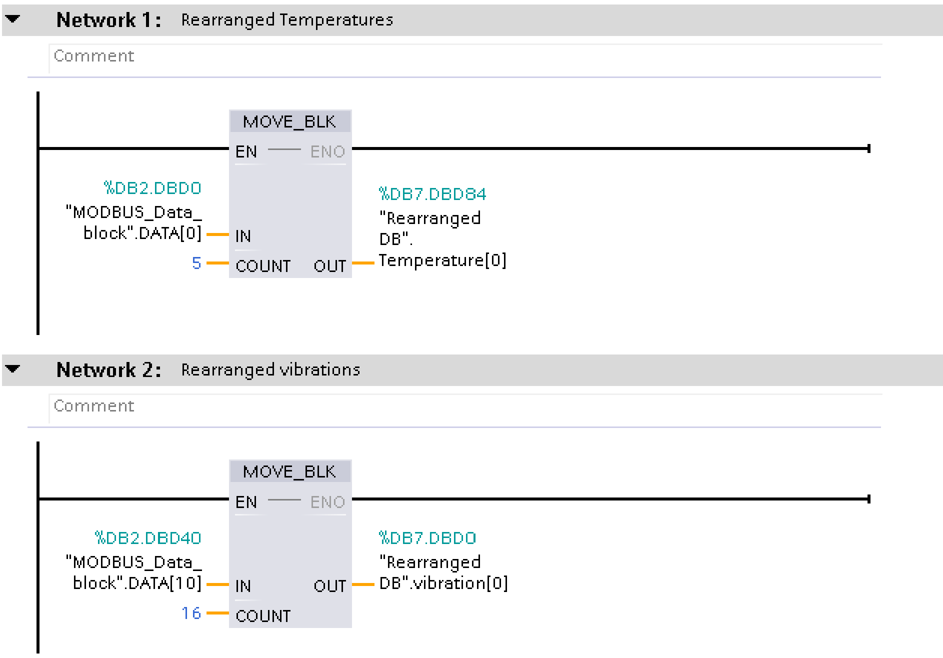


FIGURE 2.12: Rearrange Data Function

2.3.3.2 The Not Okay Function

The Not Okay function incorporates a fail-safe alarm generation mechanism to detect and communicate any instances where the rearranged data (vibration, speed, temperature) exceeds the high setpoints. These alarms are promptly displayed on the HMI and SCADA systems, providing operators with specific information to address abnormal conditions and ensure system safety.

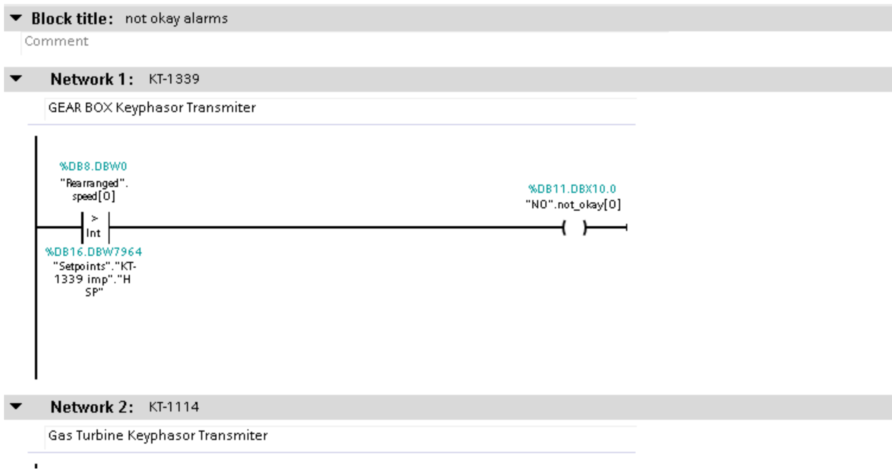


FIGURE 2.13: High threshold comparison Ladder Diagram in the Not Okay Function

The TRIP Function

The TRIP function serves as a fail-safe measure. When the data (vibration, speed, temperature) surpasses the high high setpoints, this function activates a TRIP alarm. It triggers an emergency shutdown through the PLC and displays detailed information on the HMI and SCADA systems, ensuring system safety in critical situations.

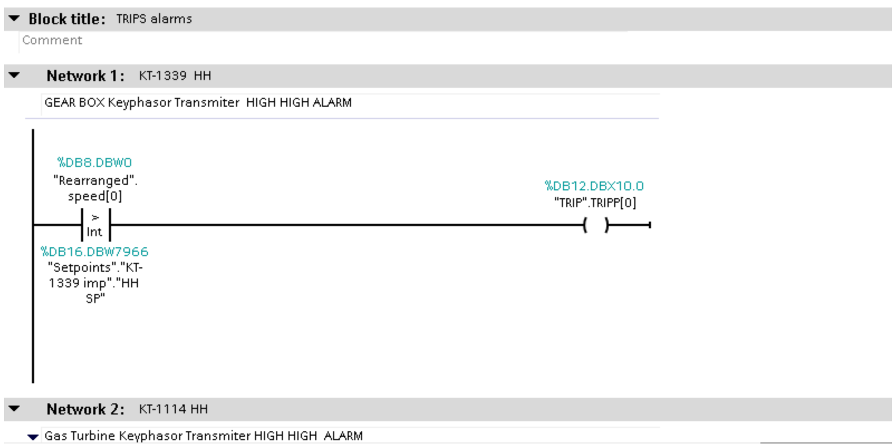


FIGURE 2.14: HighHigh threshold comparison Ladder Diagram in the TRIP function

Emergency Shutdow Function

The ESTOP1 function in STEP 7 Safety V16 provides a robust and configurable emergency shutdown capability, ensuring swift and safe cessation of operations in critical situations. It prioritizes the safety of personnel and equipment, making it an essential tool for implementing reliable emergency stop functionality in industrial automation systems.[19]

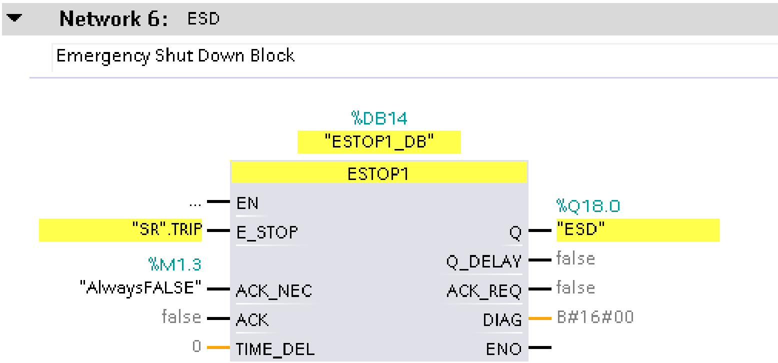


FIGURE 2.15: ESTOP1 Instruction for Emergency Shutdown FBD

In this part of my project, we utilized the ESTOP1 function in STEP 7 Safety V16 to ensure the safety of the gas turbine operation. The ESTOP function is triggered when either of two critical functions, Channels Trip and Modbus Trips, indicate the need for an emergency shutdown.

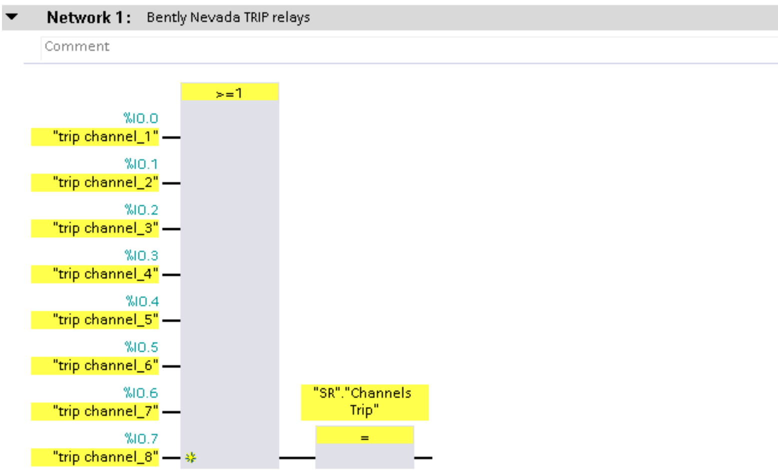


FIGURE 2.16: Relays TRIP Function Block Diagram

The Channels Trip function consists of eight digital inputs connected in an OR logic block. These inputs are linked to a Bently Nevada 3500 relay module, which detects when a HighHigh setpoint is exceeded. If any of these inputs indicate a critical condition, the Channels Trip function triggers the ESTO1P. The Modbus Trips function acts as a redundant safety measure, collecting real-time data from the Bently Nevada system via Modbus communication. It monitors the HighHigh setpoint and activates when the relay module fails to respond. In such cases, the Modbus Trips function takes over and initiates the ESTOP1 to trip the gas turbine.

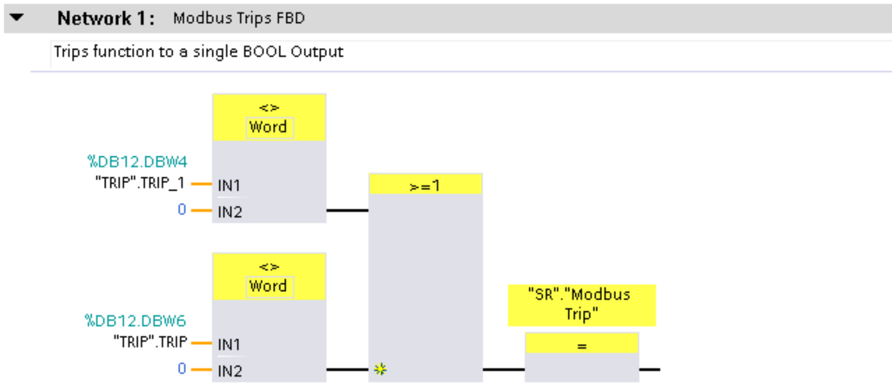


FIGURE 2.17: Modbus TRIP Function Block Diagram

Both the Channels Trip and Modbus Trips functions are connected in an OR logic block, ensuring that the ESTOP1 is triggered if either function detects a critical condition. The output of this logic block is connected to the Set (S) input of an SR (Set-Reset) block.

To reset the system after the trip condition is resolved, the Reset (R) input of the SR block is connected to a physical RESET pushbutton, which is connected to the PLC. Additionally, a SCADA Reset Memory is used to receive reset signals from the SCADA system. This dual reset mechanism allows for a comprehensive reset procedure.

The flowchart below serves as a valuable tool in enabling a comprehensive understanding of the structure and sequence of the Emergency Shutdown (ESD) procedure.

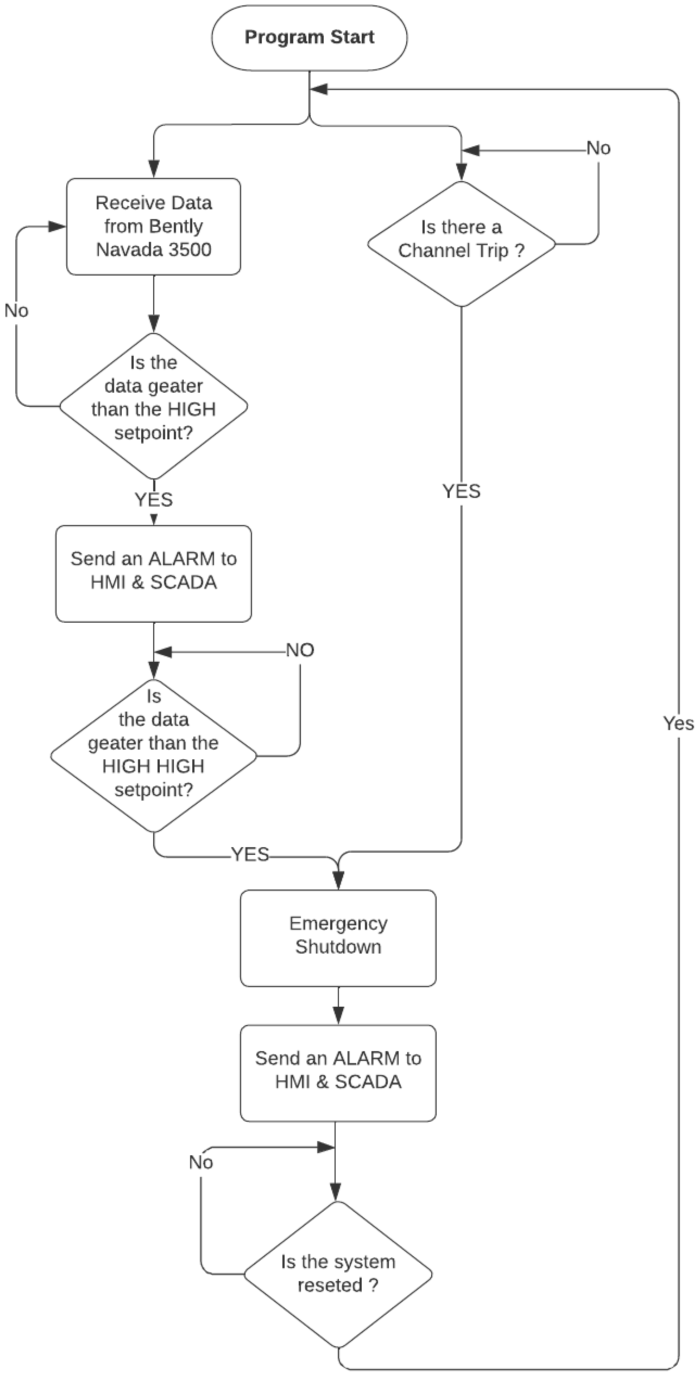


FIGURE 2.18: Flowchart of the Emergency Shutdown Procedure

2.3.3.3 WinCC Runtime Advanced

WinCC Runtime Advanced is an advanced software component within the TIA (Totally Integrated Automation) Portal that enables the design and implementation of powerful Human Machine Interface (HMI) and Supervisory Control and Data Acquisition (SCADA) systems. It provides a comprehensive platform for efficient visualization, control, and monitoring of industrial processes.[20]

In my project, we utilized WinCC Runtime Advanced to design and implement both an HMI (Human Machine Interface) and a SCADA (Supervisory Control and Data Acquisition) system.

The HMI system displays real-time data obtained from the Bently Nevada system. This data includes critical parameters such as temperatures, vibrations, and the speed of the gas turbine generator set. The HMI interface also incorporates alarm functionality, providing immediate visual alerts for high and high-high data values. This ensures that operators can promptly respond to any abnormal conditions. Furthermore, the SCADA

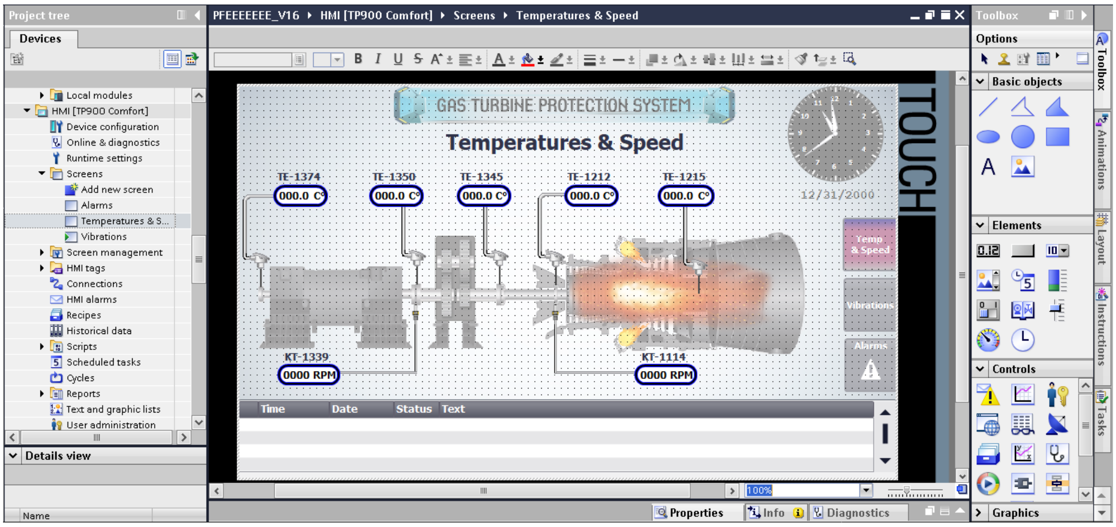


FIGURE 2.19: WinCC Runtime for HMI Design

system, built upon WinCC Runtime Advanced, offers enhanced capabilities beyond the HMI. It not only replicates the functionalities of the HMI but also provides additional features. One notable feature is the ability to modify the setpoints via the SCADA system, subject to appropriate authorization. This allows authorized personnel to make necessary adjustments to optimize the operation of the gas turbine system.

Additionally, the SCADA system presents trend displays for each transmitter, enabling operators and engineers to analyze historical data for monitoring and troubleshooting purposes. These trend displays provide valuable insights into the performance of the gas turbine system, aiding in identifying patterns and potential issues.

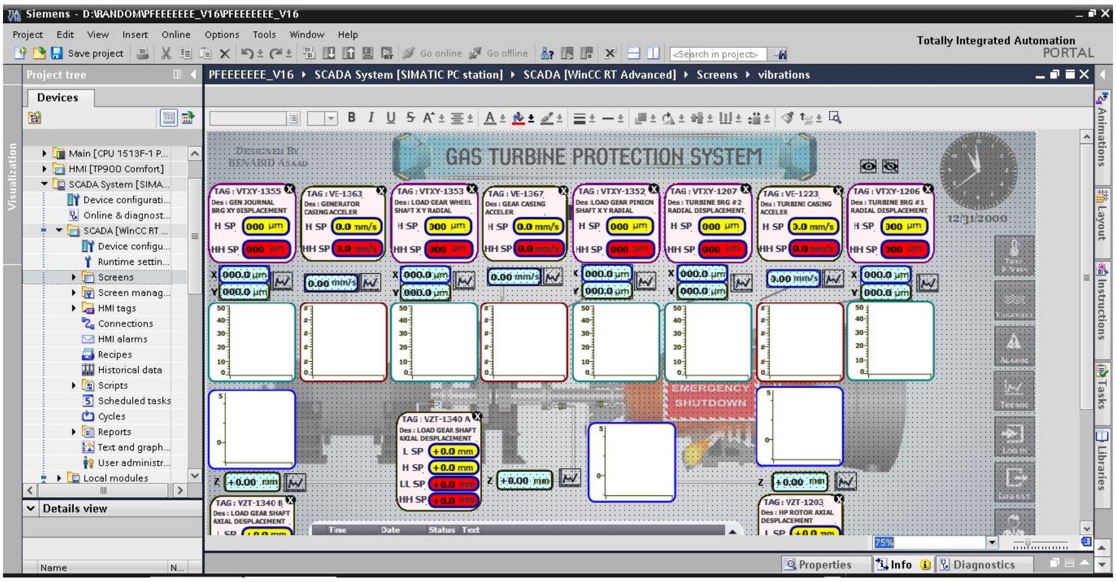


FIGURE 2.20: WinCC Runtime for SCADA Design

Overall, both the HMI and SCADA systems focus on user-friendliness. The interfaces are intuitive and easy to navigate, ensuring operators can efficiently interact with the systems. This user-centric design enhances operational control and monitoring, leading to improved efficiency and safety in the gas turbine environment.

2.3.4 Node-RED

Node-RED is an open source flow-based development tool designed to cater to the specific requirements of the Industrial Internet of Things (IIoT). IIoT involves the integration of industrial devices, sensors, and machines to enable advanced data collection, analysis, and automation in industrial settings. Developed by IBM Emerging Technology, Node-RED provides an intuitive visual programming interface that empowers developers to seamlessly connect and orchestrate diverse components within IIoT ecosystems. With its extensive library of pre-built nodes and support for various protocols, Node-RED simplifies the integration of industrial hardware devices, APIs, and online services, enabling efficient data exchange and communication between different industrial systems. This robust tool equips users with the capability to develop and deploy complex IIoT applications rapidly, enabling optimized monitoring, control, and automation of industrial processes. By harnessing Node-RED's capabilities, businesses can unlock the potential of IIoT, leveraging its benefits to improve operational efficiency, enhance predictive maintenance, and facilitate data-driven decision-making in industrial environments.[21]

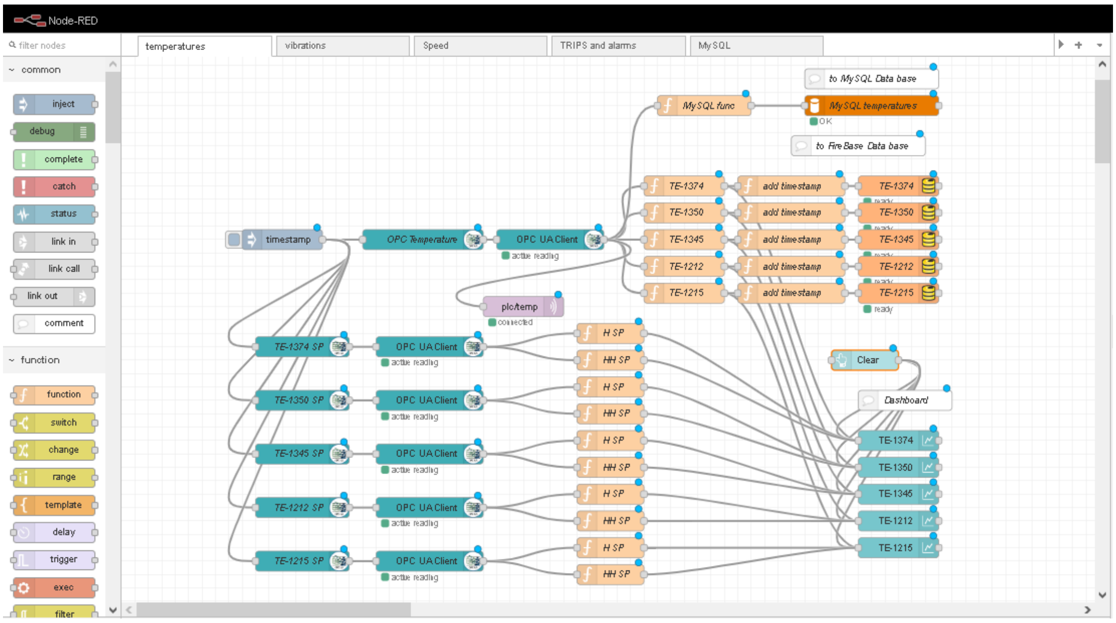


FIGURE 2.21: Node-RED

In my project,we utilized two Node-RED instances, each playing a crucial role in ensuring efficient data flow and processing. The first instance resides on my local PC. This local instance serves as the central hub, receiving real-time data from the S7-1500 safety PLC via the OPC UA protocol.

we deployed the second Node-RED instance in the cloud, running on a hosted server. This cloud-based Node-RED installation acts as the recipient, eagerly awaiting data from my local Node-RED instance. By establishing this cloud-based connection,we can effortlessly transmit data from my local environment to the cloud, opening the doors for seamless integration with additional services and systems.

Now, let's explore the details of these two Node-RED instances further to gain a comprehensive understanding of their functionalities and the vital roles they play in my project.

2.3.4.1 The Local Node-RED Instance

Real-Time Data Acquisition from S7-1500 PLC via OPC UA Protocol

OPC UA (OPC Unified Architecture) is a platform-independent standard series (IEC 62541) for communication of industrial automation devices and systems. The OPC Unified Architecture is an advanced communication technology for process control.[22]

Real-time data is acquired from the S7-1500 PLC through the utilization of the OPC UA protocol. The PLC is configured as an OPC UA server, and the desired data is set up within the server for transmission to the Node-RED instance acting as an OPC UA client.

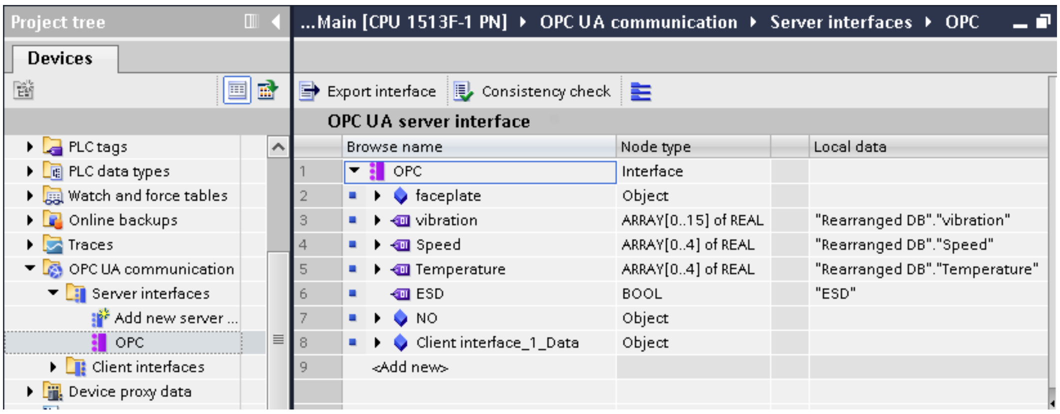


FIGURE 2.22: s7-1500 OPC UA Server interface

The OPC UA server, represented by the S7-1500 PLC, organizes the data into separate namespaces. Each element, such as temperature, has its own dedicated namespace, allowing for efficient data management and retrieval.

This Node-RED flow collects an array of temperature data from a gas turbine generator set. The data is retrieved from an S7-1500 PLC acting as the OPC server. The flow includes nodes to establish an OPC client connection, read the temperature data, trigger data retrieval at a one second interval, and define the OPC server's endpoint.The gathered temperature data from the gas turbine generator set will be processed and used for further analysis in the next subsections of the Node-RED flow.

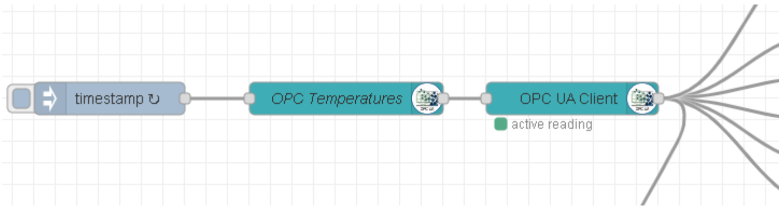


FIGURE 2.23: OPC UA temperatures DATA gathering each 1 second

Storing Data to Local MySQL Database

MySQL, an open-source relational database management system, plays a crucial role in the Local Node-RED Instance for storing and managing the acquired data. It provides a robust and scalable solution for efficient data storage and retrieval.[23]

In this project, XAMPP software is utilized as the development environment for MySQL. XAMPP is a popular cross-platform software package that includes MySQL, Apache web server, PHP, and other components necessary for building web applications.[24]

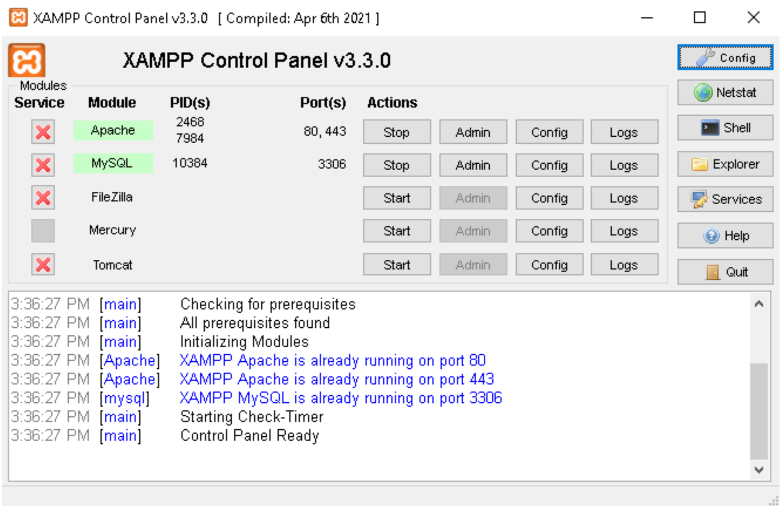


FIGURE 2.24: XAMPP Software

Within the MySQL database, specific columns are created to accommodate the data from each temperature sensor. Each column is assigned a unique tag to identify the corresponding sensor, allowing for organized and structured data storage. Additionally, a timestamp column is included to record the time at which each data point is received.

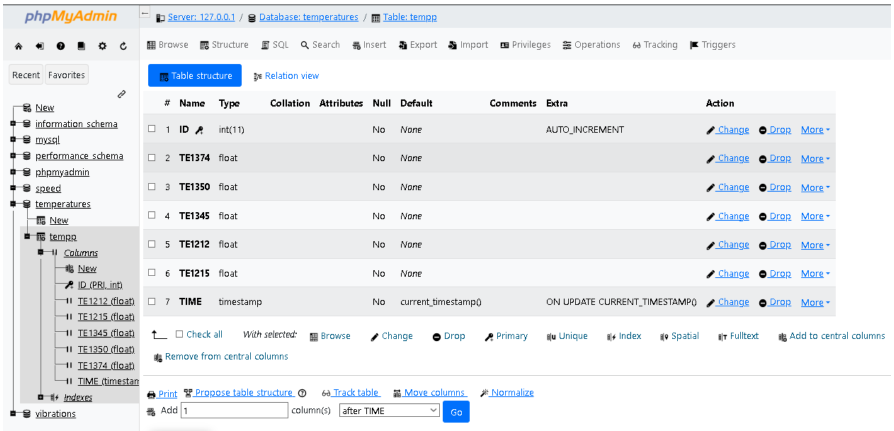


FIGURE 2.25: MySQL Temperatures Table

In the Local Node-RED Instance, a flow is implemented to store real-time temperature data from the OPC UA server to a local MySQL database. The flow consists of an OPC UA client that retrieves temperature data at regular intervals and a function node that processes and prepares the data for storage. Using SQL queries, the processed data is inserted into specific columns of the MySQL database. This approach ensures organized and structured storage of temperature data, enabling further analysis, visualization, and integration with other project functionalities.

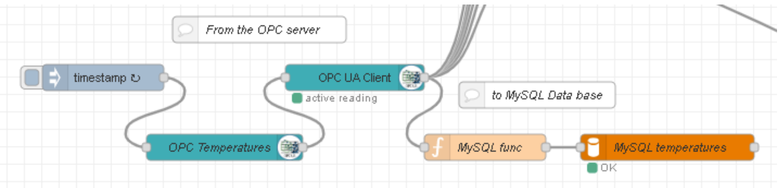


FIGURE 2.26: Storing Data to Local MySQL Database

Trend Dashboard

The Local Node-RED Instance incorporates a trend visualization dashboard to provide insightful and interactive visual representations of data collected from the temperature, vibration, and speed transmitters. This dashboard allows users to monitor and analyze trends in real-time, enabling effective decision-making and preventive maintenance.

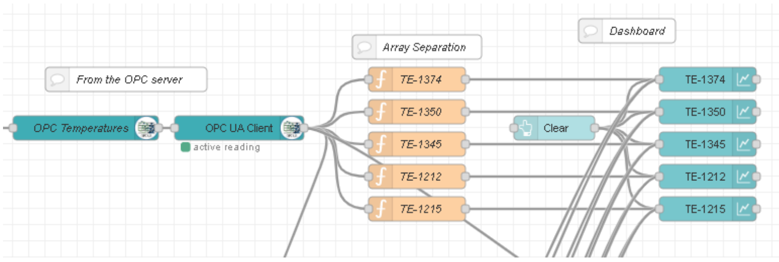


FIGURE 2.27: OPC Temperatures DATA transfer to Dashboard

Data Retrieval

In the context of data retrieval, both a dashboard and a Telegram bot offer specific commands that allow users to download the entire stored data from a MySQL database in CSV format. This feature facilitates in-depth data analysis, fault detection, and preventive maintenance strategies. Users can easly retrieve the data they need for analysis and gain insights, identify patterns and trends, and detect faults or anomalies within the system using the downloaded CSV files.

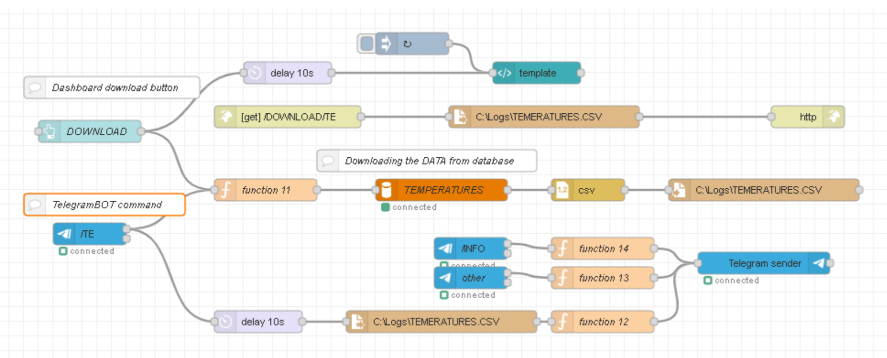


FIGURE 2.28: MySQL Database Retrieval by telegramBOT command or local Dashboard

Email and Telegram Notifications for Trip Events

The Local Node-RED Instance incorporates an email and Telegram notification system to instantly alert stakeholders in case of trip events. This feature ensures timely communication and enables quick response to critical situations. This proactive approach allows for swift corrective actions when trip events occur.

Real-Time Storing Data to Firebase Database

To enable seamless remote access to data, the Local Node-RED Instance integrates Firebase nodes to store data in a real-time database. This integration allows for convenient

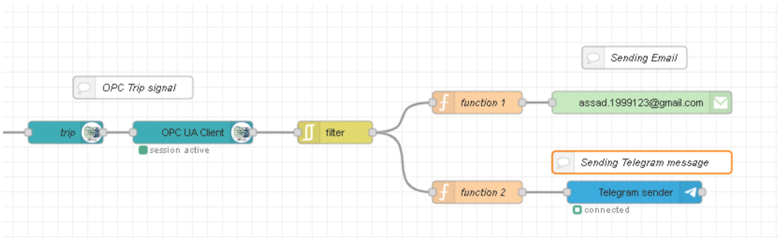


FIGURE 2.29: OPC Trip signal used to send Email and Telegram Notifications

access to the data from the Cloud-based Node-RED, regardless of the user's location, as long as an internet connection is available. By leveraging Firebase, the project ensures easy accessibility and enhances the flexibility of data retrieval and analysis from anywhere in the world.

Storing Data To The Real-Time Database

The Firebase Realtime Database is a NoSQL cloud-based database that syncs data across all clients in realtime, and provides offline functionality. Data is stored in the Realtime database as JSON, and all connected clients share one instance, automatically receiving updates with the newest data.[25]

In the context of our project, the data received from the Programmable Logic Controller (PLC) via OPC UA in the Local Node-RED instance serves as valuable information that may be required for remote access or retrieval by interested parties. To facilitate this, we utilize the Firebase Real-Time Database as a storage solution.

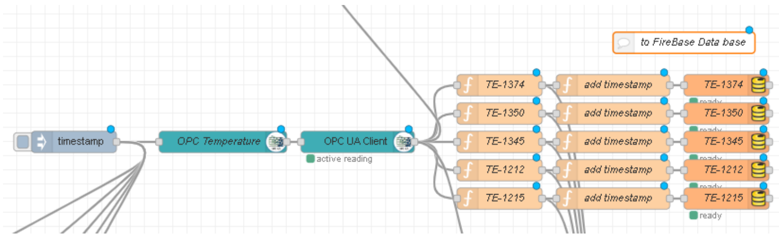


FIGURE 2.30: OPC temperatures data stored to Firebase real-time data base

The Local Node-RED instance acts as a bridge between the OPC UA data received from the PLC and the Firebase Real-Time Database. It securely sends the received data to the database, ensuring its availability for remote access and retrieval by authorized users.

By utilizing the cloud-based Node-RED instance, users can remotely access the Firebase Real-Time Database and retrieve the stored data as needed. This feature provides convenience and flexibility, enabling users to access the data from anywhere and at any time.

Furthermore, the storage of data in the Firebase Real-Time Database allows for seamless integration with other applications and services that may require access to the data. This enhances the overall functionality and usability of the monitoring system, enabling easy sharing and utilization of the collected data for various purposes.

Sending Real-Time Data to Cloud-Based Node-RED via HiveMQ MQTT Broker

In the project, the Local Node-RED Instance leverages the power of MQTT and integrates with HiveMQ MQTT Broker to seamlessly transmit real-time data to the Cloud-based Node-RED. By utilizing MQTT's lightweight nature, data is efficiently published from the Local Node-RED, while HiveMQ MQTT Broker acts as the intermediary, securely routing the data to the Cloud-based Node-RED.

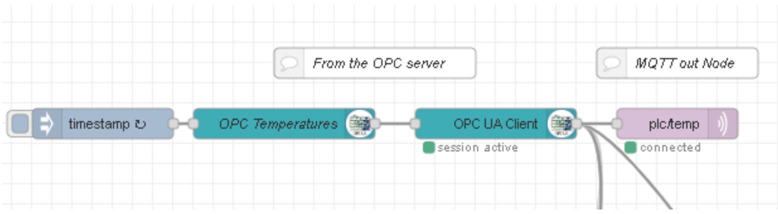


FIGURE 2.31: OPC temperatures data transfer via MQTT

This integration ensures fast and reliable transmission of data, facilitating real-time monitoring, analysis, and visualization of the data from anywhere in the world. The combination of MQTT and HiveMQ enables seamless connectivity and supports the continuous flow of data, bridging the gap between the Local and Cloud-based Node-RED instances.

2.3.4.2 The Cloud Based Node-RED Instance

Introduction to FlowForge

FlowForge is a DevOps platform for Node-RED application development and delivery. It allows users to sign up and start creating Node-RED instances without having to install and manage their own instance of FlowForge. FlowForge adds collaborative development, management of remote deployments, support for DevOps delivery pipelines, and the ability to host Node-RED applications on FlowForge, making it easy for remote monitoring. It helps Node-RED developers deliver applications in a more reliable, collaborative, and secure manner. The key features of FlowForge are team collaboration, remote deployment management, professional support for Node-RED deployments, and seamless remote monitoring capabilities.[26]

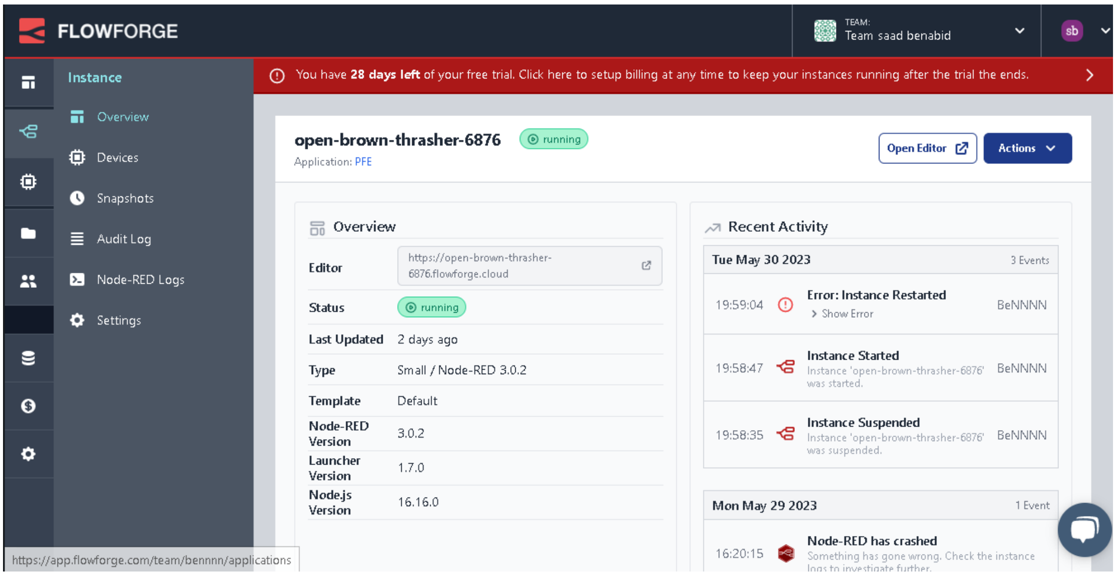


FIGURE 2.32: FlowForge web page

Real-Time MQTT Data Reception & Dynamic Dashboard Design for Monitoring

In this part of the project, we explore the methodology of real-time MQTT data reception and the creation of a dynamic dashboard for effective monitoring. The system utilizes the Cloud MQTT Broker, specifically HiveMQ, to receive data sent from the MQTT broker as shown in 2.31. the figure below illustrates the process of subscribing to the topic "plc/temp" to obtain the temperatures data.

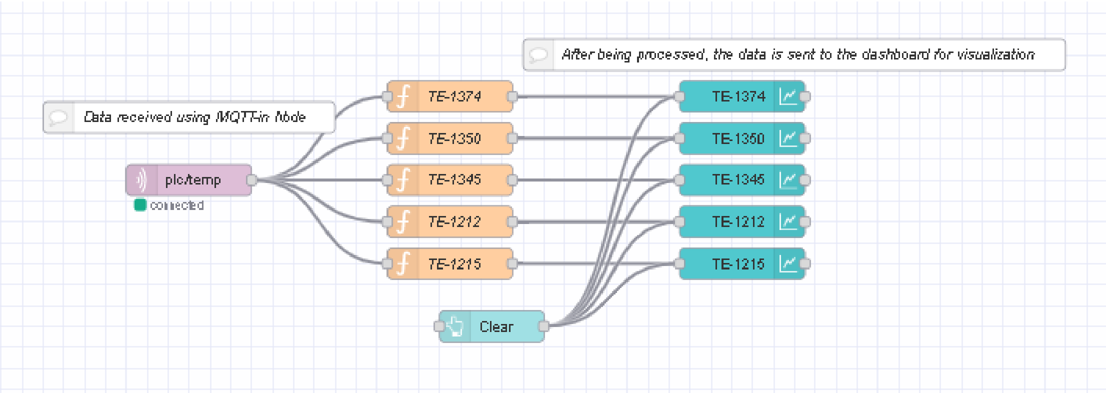


FIGURE 2.33: real-time MQTT data reception and dashboard creation nodes

To process and visualize the received temperature data, we employ "function" nodes and "ui_chart" nodes. Each "function" node corresponds to a specific temperature measurement, such as "TE-1374," "TE-1350," "TE-1345," "TE-1212," and "TE-1215." These nodes handle the processing of data associated with each temperature measurement.

Once the temperature data is processed, it is sent to the corresponding "ui_chart" node for real-time visualization on the dynamic dashboard. The dynamic dashboard is developed using Node-RED UI nodes, which include intuitive line charts for visualizing temperature variations across different components.

In addition to temperature monitoring, a similar approach is employed for tracking vibrations and speed. The system collects data related to vibrations and speed measurements from appropriate sources. This data is processed and visualized in a similar manner using dedicated "function" nodes and "ui_chart" nodes.

By employing this comprehensive monitoring solution, users can concurrently track and analyze temperature, vibrations, and speed variations. The real-time insights provided by the dashboard enable users to make informed decisions based on timely information.

Data Retrieval using Firebase

As discussed earlier, data is securely sent from the Local Node-RED instance to the Firebase Real-Time Database, as depicted in 2.30. Now, let's explore how data retrieval is performed in the Cloud-Based Node-RED environment.

In the Cloud-Based Node-RED instance, we utilize the power of Firebase to access the stored data in the real-time database. Specifically, we retrieve the database associated with each transmitter and save it in a CSV (Comma-Separated Values) file format. This retrieval process enables us to extract the data for further analysis and sharing purposes.

Using the appropriate Node-RED nodes and functions, we establish a connection with the Firebase Real-Time Database. By specifying the transmitter and relevant database within the cloud environment, we fetch the desired data in real-time.

Once the data is retrieved, we convert it into a CSV file format, which provides a widely compatible and easily accessible structure for data manipulation. The CSV file contains organized rows and columns, with each row representing a data entry and each column representing a specific attribute or measurement.

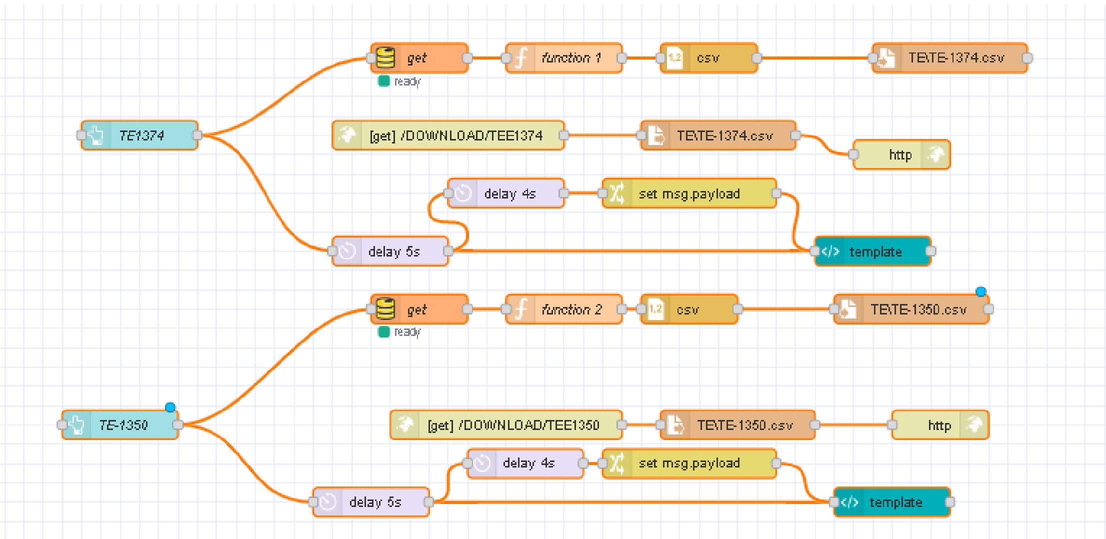


FIGURE 2.34: Remote Data Retrieval Nodes

To facilitate remote access and ease of data sharing, we enable users to download the CSV file directly from the remote dashboard. By incorporating user-friendly features, such as a download button or an export functionality, users can effortlessly retrieve the CSV file containing the desired data.

This approach empowers users with the ability to remotely access and analyze the collected data in a format that suits their requirements. Whether for further analysis, generating reports, or integrating the data with external tools or systems, the retrieved CSV file provides a convenient and versatile means of data utilization.

Chapter 3

Results & Discussion

3.1 Introduction

This chapter presents the results and discussion of the implemented gas turbine protection system, focusing on the utilization of TIA Portal, including its role in programming the S7-1500 safety PLC, as well as the design of the HMI and SCADA interfaces. Additionally, the chapter explores the integration of Node-RED as a data processing and visualization tool. TIA Portal served as the programming environment for the S7-1500 safety PLC, enabling real-time decision-making and system response, while also providing the means to design user-friendly HMI and SCADA interfaces for effective monitoring and control. Node-RED, on the other hand, facilitated data storage and processing, visualization, and remote access, enhancing the overall functionality and accessibility of the gas turbine protection system. Through a detailed analysis, we evaluate the performance, functionality, and integration capabilities of TIA Portal and Node-RED in the context of the gas turbine protection system, providing valuable insights for future industrial automation and IIoT. The results and discussions presented in this chapter highlight the successful implementation and effectiveness of TIA Portal and Node-RED, emphasizing their contributions to the advancement of gas turbine protection systems and data management practices in the industry.

3.2 TIA Portal

In this section, we will present the results achieved through the utilization of TIA Portal in our gas turbine protection system project. TIA Portal played a pivotal role in programming the S7-1500 safety PLC and designing user-friendly HMI and SCADA interfaces. To ensure accurate and efficient testing, we employed PLCSIM Advanced, a powerful simulation tool that allowed us to simulate the behavior of the S7-1500 PLC. By leveraging PLCSIM Advanced in conjunction with TIA Portal, we were able to validate and test the control logic and system behavior in the virtual commissioning.

3.2.1 Data Transfer Results

After setting the Modbus Data Reading Function in the previous chapter, the validation process was conducted to ensure the successful transfer of the simulated data from Modbus Poll to the S7-1500 Safety PLC.

This subsection focuses on the results of the validation, emphasizing the reliability and accuracy of the data transfer simulation. The data transfer setup involved establishing a seamless connection between Modbus Poll and the PLC, configuring communication settings, and ensuring compatibility between the software and the PLC.

The outcomes of the data transfer simulation showcased the successful transmission of the simulated data to the PLC, demonstrating its reliability and accuracy. Furthermore, an analysis was performed to assess the accuracy and reliability of the simulated data transfer by comparing the simulated values with the expected values and evaluating any discrepancies or variations.

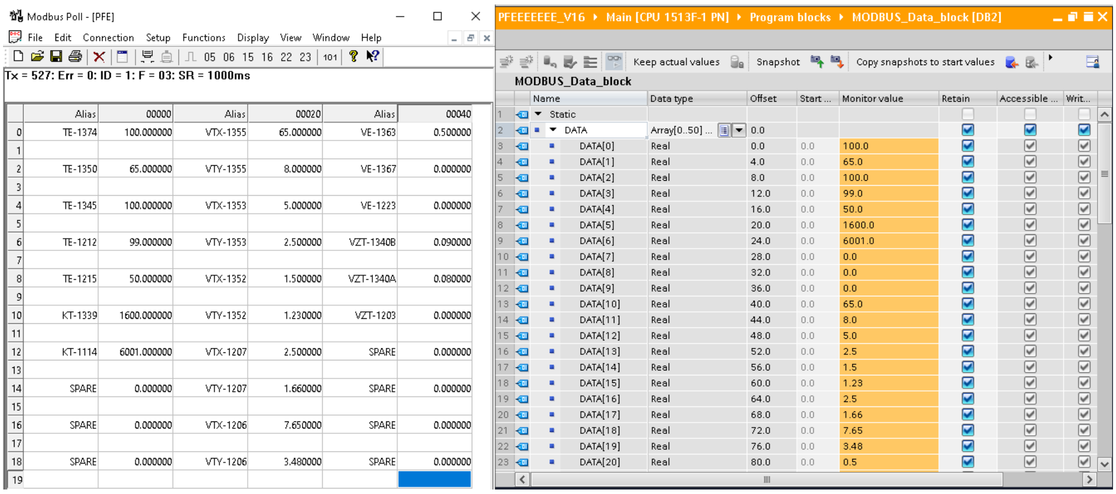


FIGURE 3.1: Virtual Commissioning of Modbus TCP/IP Data Transfer Between Bently nevada 3500 and S7-1500 Safety PLC

This analysis provides valuable insights into the reliability of the implemented data transfer mechanism, validating its effectiveness in accurately transferring the simulated data to the PLC.

3.2.2 Results and Success of Functions

TIA Portal was used as the programming environment for the PLC. To ensure the accuracy of the program, we performed online monitoring by going online and running the PLC from the PLCSim Advanced. This monitoring process allowed us to test the functionality of the program in real-time. The program consisted of two main functions: one for normal functions and the other for safety functions.

Through the monitoring process, we observed the successful execution of both functions, with the corresponding portions of the program displaying green color, indicating correct execution. This comprehensive monitoring approach provided valuable insights into the successful operation of the programmed functions for both normal and safety operations.

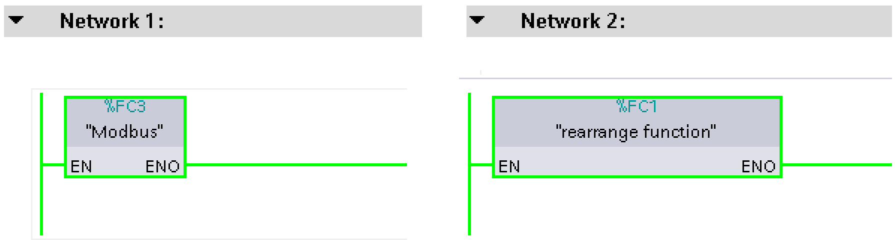


FIGURE 3.2: TIA Portal Main Block Running

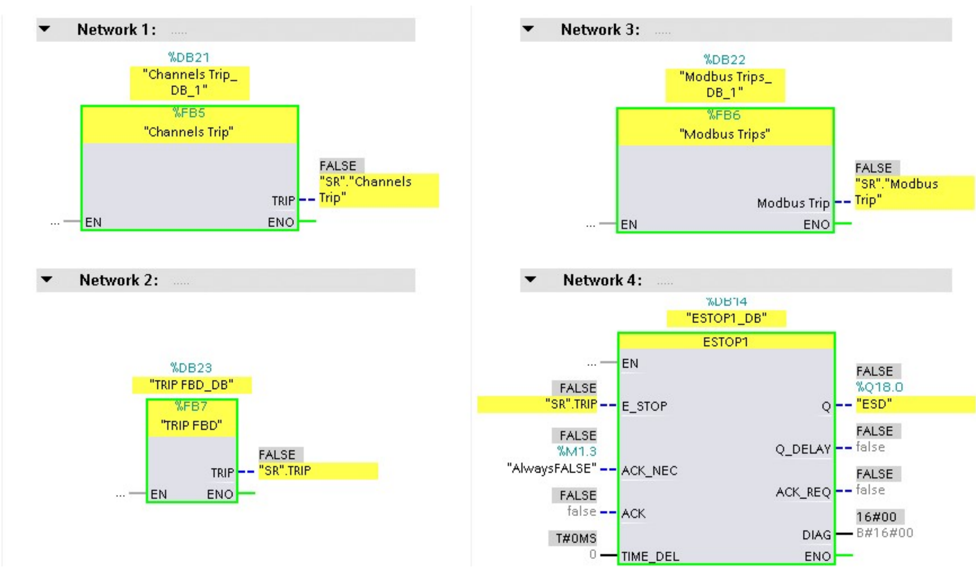


FIGURE 3.3: TIA Portal Main Safety Block Running

3.2.3 WinCC Runtime Advanced Results

3.2.3.1 HMI Results

The gas turbine protection system was equipped with a meticulously designed TP900 Comfort HMI panel, powered by WinCC runtime. This advanced HMI provided an intuitive and efficient interface for monitoring and controlling the system.

The TP900 Comfort HMI displayed real-time data obtained from the Bently Nevada system, offering operators a comprehensive overview of the gas turbine generator set. The placement of data on the HMI was strategically organized based on a detailed P&ID (Process and Instrumentation Diagram) provided by the Instrumentation Engineer from SONATRACH company.[27] This ensured optimal visibility and accessibility of critical information.

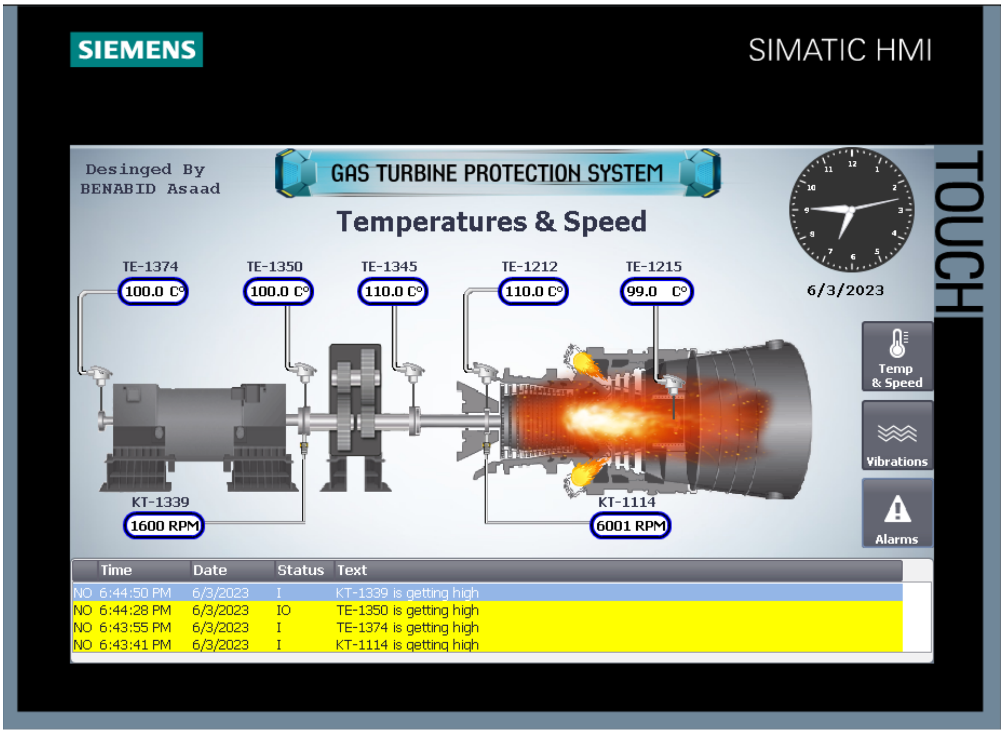


FIGURE 3.4: HMI Temperatures & Speed Screen

The HMI incorporated two main screens to facilitate effective monitoring. The first screen was dedicated to temperatures and speed, allowing operators to closely monitor these vital parameters. Each temperature and speed data had its specific tag, ensuring accurate and reliable readings for analysis.

The second screen focused on vibrations, presenting real-time vibration data to monitor the health of the system. Operators could quickly assess vibration levels, enabling early detection of any abnormal behavior or potential issues. Similar to the temperature and speed screen, each vibration data point was associated with a specific tag, facilitating precise monitoring and analysis.

To further enhance alarm management, an additional screen was designed to provide a more detailed view of alarms. This screen allowed operators to access comprehensive alarm information and take appropriate actions promptly.(For more detailes, please see Appendix C)

The figure 3.4 showcases the temperatures and speed screen of the TP900 Comfort HMI. It demonstrates the well-organized and user-friendly layout of temperature and speed data, each accompanied by its specific tag for easy identification and analysis.

The TP900 Comfort HMI panel, with its carefully crafted design and logical screen organization, empowered operators to monitor the gas turbine protection system effectively. It offered clear data visualization, alarm notifications, and easy access to key parameters, contributing to the overall safety and performance of the system.

3.2.3.2 SCADA Results

The gas turbine protection system incorporated a robust SCADA system designed using WinCC runtime. The SCADA system provided enhanced functionality and capabilities compared to the HMI, offering operators a comprehensive control and monitoring platform.

Similar to the HMI, the SCADA system facilitated real-time data visualization and control, but with additional features and advantages. It allowed authorized personnel to modify setpoints, ensuring flexibility in system operation. The setpoints, provided by the same Instrumentation Engineer, were readily accessible within the SCADA interface. (For more setpoints detailes, please see Appendix C)

One notable feature of the SCADA system was the inclusion of trend visualization for each transmitter. This enabled operators to analyze historical data trends and identify patterns or anomalies, aiding in the system's performance evaluation and troubleshooting.

The SCADA design prioritized user-friendliness, ensuring operators could navigate the system effortlessly. Multiple screens were implemented to accommodate various functionalities. These included screens dedicated to temperatures and speed monitoring, detailed alarms, comprehensive trends, and an administrative screen for access authorization management.

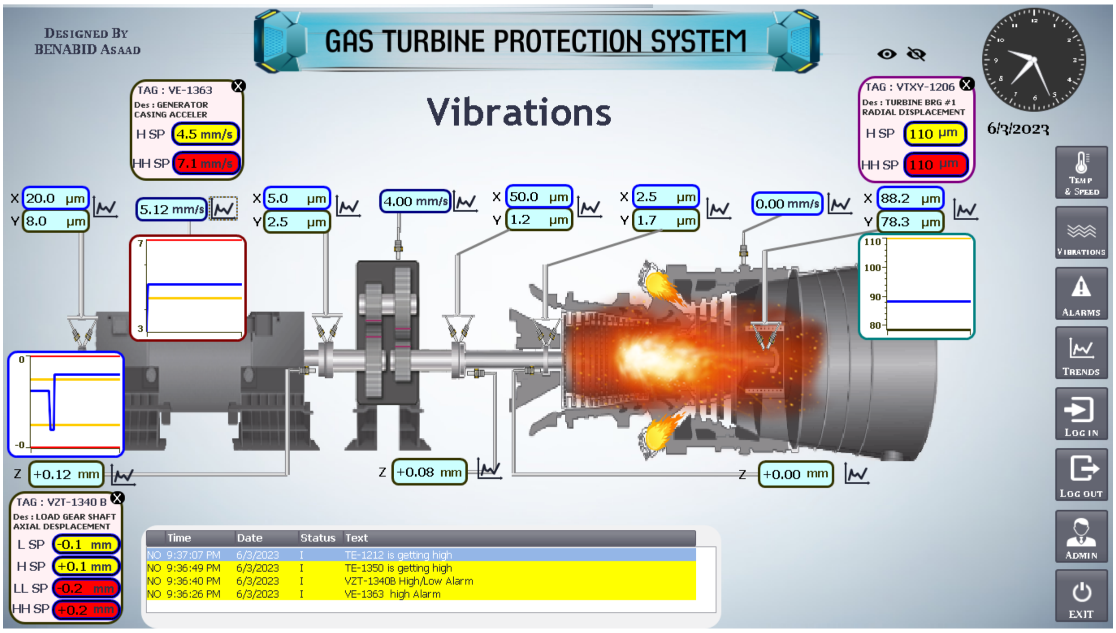


FIGURE 3.5: SCADA Vibrations Screen

The figure 3.7 highlights the Vibration screen within the SCADA system, showcasing a clear and intuitive visualization of different vibration parameters. It provided insights into radial vibrations (X and Y axes), axial vibrations (Z axis), and casing vibrations. Each vibration parameter was associated with a specific tag and description, facilitating easy identification and analysis.

Furthermore, the SCADA system offered an administrative screen that allowed authorized personnel to modify access authorizations and reset the system in the event of a trip occurrence, after resolving the underlying issue.(For more detailes, please see Appendix C)

The SCADA system, with its advanced functionalities, user-friendly design, and comprehensive data visualization capabilities, significantly contributed to the efficient and reliable operation of the gas turbine protection system. It empowered operators to monitor and control the system effectively, facilitating prompt decision-making and ensuring the overall safety and performance of the system.

3.2.4 Discussion of TIA Portal Results

The integration of the S7-1500 Safety PLC with SIL3 certification has played a crucial role in ensuring the reliable operation of the gas turbine protection system. The utilization of a safety PLC with a high safety integrity level provides an additional layer of protection against potential failures and risks. In the event of a trip or abnormal condition, the safety PLC promptly triggers predefined safety protocols, leading to the swift shutdown of the turbine. This integration enhances the overall reliability of the system and ensures compliance with stringent safety standards.

Furthermore, significant efforts were made to design a user-friendly Human Machine Interface (HMI) and Supervisory Control and Data Acquisition (SCADA) system. Traditional bargraphs used for transmitter monitoring were replaced with a more intuitive and visually appealing interface. The newly developed HMI and SCADA system offer operators effortless monitoring and clear visualization of the transmitter data. Through intuitive graphical representations, operators can easily analyze the data and pinpoint the location of specific transmitters. This user-friendly approach revolutionizes the monitoring experience, improving efficiency and facilitating informed decision-making.

The successful implementation of the TIA Portal, along with the integration of the S7-1500 Safety PLC and the user-friendly HMI and SCADA system, has significantly enhanced the monitoring and safety aspects of the gas turbine protection system. These results demonstrate the effectiveness of the chosen technologies and the meticulous design process. The combination of reliable hardware, intuitive interface, and comprehensive monitoring capabilities ensures a robust and efficient system operation while providing operators with the necessary tools to make informed decisions and respond promptly to potential risks or abnormalities.

3.3 Node-RED

In this section, we present the outcomes and implications of utilizing Node-RED in our gas turbine protection system. Node-RED played a pivotal role in facilitating efficient data flow, processing, and accessibility. By leveraging its capabilities, we implemented advanced data processing algorithms, real-time data storage, and intuitive dashboards for monitoring and analysis. In this section, we will discuss the specific results achieved, including data flow, database integration, dashboard design, trip notifications, cloud integration, and overall benefits of our IIoT solution. Through our experiences with Node-RED, we highlight its effectiveness in optimizing data handling, monitoring, and accessibility, ultimately enhancing the performance, safety, and efficiency of our gas turbine system.

3.3.1 Local Real-time Data Visualization and Access

After deploying the local Node-RED instance functions discussed in the previous chapter, we have successfully established a local dashboard that provides real-time data visualization and easy access to critical parameters from the gas turbine generator set. This section presents the outcomes of our efforts in achieving real-time data visualization with five screens, namely Temperatures, Radial Vibrations, Axial Vibrations, Casing Vibrations, and Speed, all designed to provide clear and comprehensive displays of the respective data.

The real-time data visualization capability offered by the dashboard allows for instant monitoring and analysis of the gas turbine system's vital parameters. Each screen is thoughtfully designed to present the data in a visually appealing and easily interpretable manner.

To further facilitate data access and monitoring, we have incorporated a convenient feature in each screen: a button that enables users to download the corresponding MySQL database in CSV format. For instance, the Temperatures screen provides a downloadable CSV file named Temperatures.CSV, as shown in the figure below. This functionality greatly enhances data accessibility, allowing users to retrieve historical data for in-depth analysis or seamless integration with other tools or systems.(For more detailes, please see Appendix D)

FIGURE 3.6: Local Temperatures Dashboard

The availability of these download buttons not only streamlines data access but also empowers users to easily monitor and analyze the gas turbine system's performance. By enabling effortless access to the data in a widely compatible format, the dashboard promotes informed decision-making and proactive response to any deviations or anomalies detected.

Overall, the real-time data visualization and easy access functionality within the local Node-RED dashboard significantly enhance the monitoring and analysis capabilities of our gas turbine protection system. The clear and comprehensive displays of temperatures, vibrations, and speed, coupled with the ability to download the corresponding MySQL databases, offer users a powerful toolset for efficient data analysis and informed decision-making.

3.3.2 Remote Real-time Data Visualization and Access

Following the successful deployment of the Flowforge Cloud-based Node-RED instance functions, as discussed in the previous chapter, we have now established a remote dashboard accessible from anywhere with proper authorization. The dashboard's URL is `https://open-brown-thrasher-6876.flowforge.cloud/ui`.

Similar to the previous subsection on Local Real-time Data Visualization and Access, this remote dashboard offers real-time data visualization for various parameters derived from the Gas Turbine Generator set. It consists of five screens, namely Temperatures, Radial Vibrations, Axial Vibrations, Casing Vibrations, and Speed, each providing a clear and intuitive display of the respective data.(For more detailes, please see Appendix D)

To further enhance data accessibility and analysis, we have incorporated a feature allowing the downloading of historical real-time data in CSV format. This data is stored in the Firebase Real-time Database. Users can conveniently access and download historical data for each transmitter by utilizing the provided buttons, as shown in the figure below.

FIGURE 3.7: Cloud-Based Axial vibrations Dashboard

This remote dashboard and its data access functionality enable stakeholders to easily monitor, analyze, and perform predictive maintenance on the Gas Turbine Generator set. By accessing the dashboard from anywhere in the world, authorized users gain valuable insights for efficient operations and proactive decision-making.

In summary, the deployment of the Flowforge Cloud-based Node-RED instance has enabled the implementation of an IIoT (Industrial Internet of Things) solution for remote real-time data visualization and access. This solution enhances operational efficiency, and facilitates informed decision-making for seamless management of the Gas Turbine Generator set.

3.3.3 Automatic trip Notifications

The integration of an email and Telegram notification system within the Local Node-RED Instance has yielded significant outcomes in terms of trip event management. The system provides instant alerts, ensuring timely communication and enabling swift responses to critical situations. Figure below showcases the results of the notification system, highlighting its effectiveness in facilitating proactive actions.

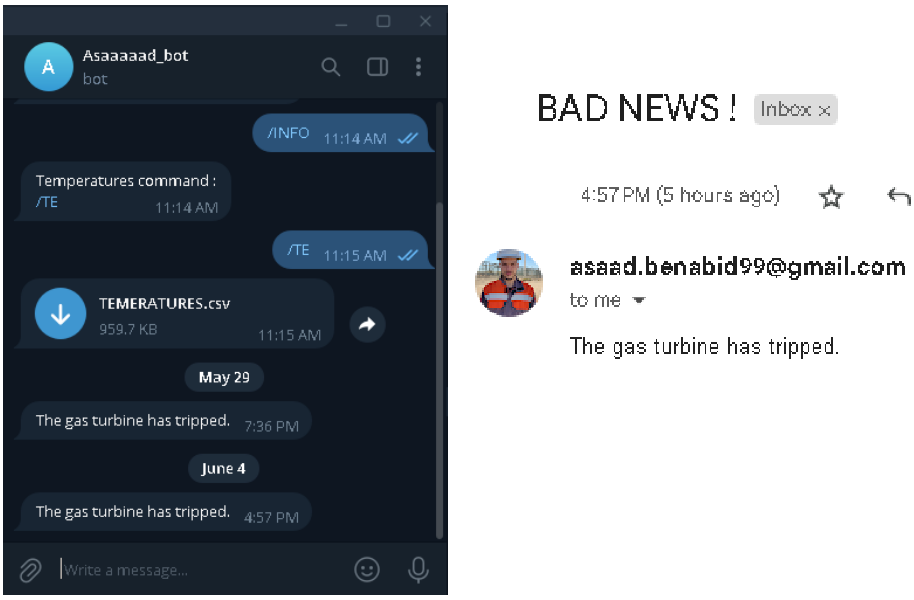


FIGURE 3.8: Automatic TelegramBOT and Email trip Notifications

3.3.4 Discussion and Evaluation of Node-RED Results

The integration of the IIoT solution using Node-RED for the gas turbine protection system has demonstrated several advantages compared to conventional systems:

Enhanced Data Processing and Storage: Node-RED plays a vital role in efficiently processing and storing real-time data received from the S7-1500 safety PLC via the OPC UA protocol. The data is processed and stored in a local MySQL database and a real-time database using Firebase. This ensures seamless data management, analysis, and storage for comprehensive monitoring and future insights.

Real-Time Data Visualization and Analysis: Node-RED's intuitive dashboard provides real-time data visualization and analysis capabilities. The dashboard presents key parameters such as vibrations, temperatures, and speeds in a user-friendly manner. This empowers operators with valuable insights into the gas turbine's performance and enables proactive decision-making for maintenance and optimization.

Remote Accessibility and Control: The IIoT nature of the solution allows for remote monitoring and control of the gas turbine. Node-RED hosted in the cloud receives data from the local Node-RED instance via MQTT, enabling access to real-time data from anywhere in the world. The cloud-based dashboard provides a simple and secure interface for users to monitor and analyze the turbine's operational parameters in real-time, facilitating prompt response and informed decision-making.

Data Availability and Download: Node-RED offers a convenient method to access and download the real-time data. Operators can easily retrieve the data in CSV format, facilitating further analysis, reporting, and integration with other systems. This feature enhances data availability and promotes collaborative efforts in system monitoring and predictive maintenance.

Overall, the incorporation of Node-RED as an IIoT solution has significantly improved the gas turbine protection system by enabling efficient data processing, real-time monitoring, remote accessibility, and data-driven decision-making capabilities.

Conclusion & Future Plans

In conclusion, the proposed gas turbine protection system integrated with an IIoT solution has successfully addressed the limitations of conventional approaches and achieved significant advancements in ensuring optimal turbine performance, reliability, and operator safety. The integration of an S7-1500 Safety PLC with SIL3 certification has provided a reliable system operation by swiftly activating safety protocols and shutting down the turbine during abnormal conditions. The user-friendly HMI and SCADA system have revolutionized monitoring capabilities, offering intuitive graphical representations for effortless data visualization and analysis. The advanced data acquisition and analytics capabilities have enabled comprehensive data collection and in-depth insights into turbine condition and potential faults. Furthermore, the IIoT-based solution has extended monitoring beyond local boundaries, allowing for remote monitoring and control, facilitating informed decision-making, and proactive maintenance actions.

Building on the accomplishments of the proposed system, there are several key future plans to further enhance its performance and capabilities. One important aspect is the implementation of redundant safety PLCs. By introducing redundancy, the system can ensure even higher levels of reliability and fault tolerance. Redundant safety PLCs will provide a backup mechanism in case of failure in one PLC, minimizing the risk of turbine failures and improving overall system resilience. Additionally, enhancing the security of the IIoT system is crucial. As the system expands to include remote monitoring and control, it becomes essential to strengthen the cybersecurity measures to protect against potential threats and unauthorized access. Implementing robust encryption protocols, intrusion detection systems, and regular security audits will be instrumental in safeguarding the system's integrity and maintaining the confidentiality of sensitive turbine data.

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APPENDICES

Appendix A: BRUSH Electric Generator Details

2 UNIT DETAILS

2.1 Machine Data

2.1.1 Generator Data

Power	:	25.882	kVA	Manufacturer	:	Brush Hma B.V.
Speed	:	1.500	Rpm	Type	:	DG 185ZL-04
Voltage	:	11.000	V	Machine N°	:	410019-03
Current	:	1.324	A	Standard	:	IEC 60034-1
P.F.	:	0,85		Altitude	:	Sea-Level
Phases / Frequency	:	3 / 50	~ / Hz	Protection	:	IP 55
Exc. Voltage	:	62	Vdc	Year of Manufacture	:	2005
Exc. Current	:	708	Adc	Duty	:	Continuous
Amb temperature	:	45	°C	Insul. cl. Stator/Rotor	:	F, temp rise to B
Customer's Unit N°	:	Unit 3				

2.1.2 Exciter Data

Power	:	44	kW	Type	:	DGBP 60/15
Voltage	:	62	Vdc	Machine N°	:	410019-03
Current	:	708	Adc	Speed	:	1.500 Rpm
Field voltage	:	44	Vdc	Phases / Frequency	:	3 / ~ / Hz
Field current	:	6,7	Adc			

2.1.3 PMG Data

Power (M.C.R.)	:	3.000	VA	Manufacturer	:	Newton Derby Ltd.
Phases / Frequency	:	1 / 250	~ / Hz	Type	:	540/40
Voltage	:	225	V	Machine N°	:	410019-03
Current	:	250	A			

Appendix B: Configuration DATA For Vibrations, Temperatures and Speed

MS5001 GAS TURBINE + GEARBOX + GENERATOR

2.2. RACK MONITOR CALIBRATION

2.2.1. Proximitor Monitor (or Proximitor/seismic)

Monitor Type	3500/40	3500/40	3500/40	3500/40	3500/40	3500/40	3500/40	3500/40
Monitor Slot Nr.	2	2	2	2	3	3	3	3
Channel Nr. (ex.:Ch.A; Ch.1)	1	2	3	4	1	2	3	4
Channel Name (Tag + Function)	VXT -1206 (XT-1X) TURBINE BRG.#1 RADIAL DISPLACEMENT	VYT -1206 (XT-1Y) TURBINE BRG.#1 RADIAL DISPLACEMENT	VXT -1355 (---) GENERATOR D.E. JOURNAL BRG. X DISPL.	VYT -1355 (---) GENERATOR D.E. JOURNAL BRG. Y DISPL.	VXT -1207 (XT-2X) TURBINE BRG.#2 RADIAL DISPLACEMENT	VYT -1207 (XT-2Y)TURBINE BRG.#2 RADIAL DISPLACEMENT	VXT -1352 (---)LOAD GEAR PINION N.D.E. SHAFT X RADIAL	VYT -1352 (---)LOAD GEAR PINION N.D.E. SHAFT Y RADIAL
Full Scale Range Direct	0-200 µ	0-200 µ	0-240 µ	0-240 µ	0-200 µ	0-200 µ	0-130 µ	0-130 µ
High Alarm (Set)	110µ	110µ	160µ	160µ	110µ	110µ	67 µ	67 µ
Very High Alarm (Trip Set)	NA	NA	240µ	240µ	NA	NA	126 µ	126 µ
Alert Mode	Not latched	Not latched	Not latched	Not latched	Not latched	Not latched	Not latched	Not latched
Danger Mode	Latched	Latched	Latched	Latched	Latched	Latched	Latched	Latched
Alert Delay	1s	1s	1s	1s	1s	1s	1s	1s
Danger Delay	100ms	100ms	100ms	100ms	100ms	100ms	100ms	100ms
Trip Multiply (1 to 3 steps of 0.25)	NA	NA	NA	NA	NA	NA	3X	3X
Barriers (None/Ext.Zener/ Isolator by BN)	MTL7096	MTL7096	MTL7096	MTL7096	MTL7096	MTL7096	MTL7096	MTL7096
Keyphasor Association	KT-1114	KT-1114	KT-1339	KT-1339	KT-1114	KT-1114	KT-1114	KT-1114
Corner Frequencies High Pass Filter	NA	NA	NA	NA	NA	NA	NA	NA
Corner Frequencies Low Pass Filter	NA	NA	NA	NA	NA	NA	NA	NA
Transducer Orient. (Deg. Left or Right)	45 right	45 left	45 right	45 left	45 right	45 left	45 right	45 left
Transducer Selection	3300 XL 8mm proximeter	3300 XL 8mm proximeter	3300 XL 8mm proximeter	3300 XL 8mm proximeter	3300 XL 8mm proximeter	3300 XL 8mm proximeter	3300 XL 8mm proximeter	3300 XL 8mm proximeter
Shaft Rotation	CW	CW	CW	CW	CW	CW	CW	CW
Shaft Speed	6100 rpm	6100 rpm	1500 rpm	1500 rpm	6100 rpm	6100 rpm	6100 rpm	6100 rpm

Nuovo Pignone

FIRENZE

Monitor Type	3500/40	3500/40	3500/40	3500/40	3500/40	3500/40	3500/40	3500/40
Monitor Slot Nr.	4	4	4	4	5	5	5	5
Channel Nr. (ex.:Ch.A; Ch.1)	1	2	3	4	1	2	3	4
Channel Name (Tag + Function)	VZT -1203 (XT-1) HP ROTOR AXIAL DISPLACEMENT	VZT -1340 B (---) LOAD GEAR PINION SHAFT AXIAL DISPLACEM.	VZT -1340 A (---) LOAD GEAR PINION SHAFT AXIAL DISPLACEM.	VE -1223 (39V-4A) TURBINE D.E. CASING ACCELER.	VE -1363 (39V-4A) GENERATOR D.E. CASING ACCELER.	VE -1367 (39V-5A) LOAD GEAR CASING ACCELER.	VXT -1353 (---) LOAD GEAR WHEEL N.G.E. SHAFT X RADIAL	VYT -1353 (---) LOAD GEAR WHEEL N.G.E. SHAFT Y RADIAL
Full Scale Range Direct	0-1 mm	0-1 mm	0-1 mm	0-8.1 mm/s	0-7.1 mm/s	0-8.1 mm/s	0-170μ	0-170μ
High Alarm (Set)	±0.6 mm	0.1 mm	0.1 mm	8.1 mm/s	4.5 mm/s	5.2 mm/s	88 μ	88 μ
Very High Alarm (Trip Set)	NA	0.2 mm	0.2 mm	8.1 mm/s	7.1 mm/s	8.1 mm/s	164μ	164μ
Alert Mode	Not latched	Not latched	Not latched	Not latched	Not latched	Not latched	Not latched	Not latched
Danger Mode	Latched	Latched	Latched	Latched	Latched	Latched	Latched	Latched
Alert Delay	1s	1s	1s	1s	1s	1s	1s	1s
Danger Delay	100ms	100ms	100ms	100ms	100ms	100ms	100ms	100ms
Trip Multiply (1 to 3 steps of 0.25)	NA	NA	NA	NA	NA	NA	3X	3X
Barriers (None/Ext.Zener/ Isolator by BN)	MTL7096	MTL7096	MTL7096	2 X (STAHL 9001/02-016-050-111)	2 X (STAHL 9001/02-016-050-111)	2 X (STAHL 9001/02-016-050-111)	MTL7096	MTL7096
Keyphasor Association	NA	NA	NA	NA	NA	NA	KT-1339	KT-1339
Corner Frequencies High Pass Filter	NA	NA	NA	(3-400) Hz	(3-400) Hz	(3-400) Hz	NA	NA
Corner Frequencies Low Pass Filter	NA	NA	NA	(40-5500) Hz	(40-5500) Hz	(40-5500) Hz	NA	NA
Transducer Orient. (Deg. Left or Right)	NA	NA	NA	NA	NA	NA	45 right	45 left
Transducer Selection	3300 XL 8mm proximeter	3300 XL 8mm proximeter	3300 XL 8mm proximeter	Velometer	Velometer	Velometer	3300 XL 8mm proximeter	3300 XL 8mm proximeter
Shaft Rotation	NA	NA	NA	NA	NA	NA	CW	CW
Shaft Speed	6100 rpm	1500 rpm	6100 rpm	NA	NA	NA	1500 rpm	1500 rpm

		ITEM
		N. SOM6620966 / 4
0	EMISSION - ISSUE	LINGUA-LANG. A / PAGINA-SHEET 6 / 7
REV	DESCRIZIONE - DESCRIPTION	

SOSTITUISCE IL - REPLACES

SOSTITUITO DA - REPLACED BY

Key Phasor Monitor

Monitor Type	3500/25	3500/25	3500/25	3500/25
Monitor Slot Nr.	11A	11A	11B	11B
Channel Nr. (ex.:Ch.A; Ch.1)	1	2	1	2
Channel Name (Tag)	KT -1114 (---)KEY PHASOR	SPARE	KT -1339 (---) LOAD GEAR WHEEL SHAFT	SPARE
Events per Revolution	1	---	1	---
Upper RPM Limit	6100rpm	---	1800rpm	---

Monitor Type (ex.: 3500/40)	3500/60	3500/60	3500/60	3500/60	3500/60	3500/60
Monitor Slot Nr.	6	6	6	6	6	6
Channel Nr. (ex.:Ch.A; Ch.1)	1	2	3	4	5	6
Channel Name (Tag + Function)	TE -1212 BEARING #2 METAL TEMP - TURBINE	TE -1350 LOAD GEAR WHEEL JOURNAL BRG	TE -1374 A (A26EG-2A) GENERATOR JOURNAL BEARING TEMP.	TE -1345 LOAD GEAR PINION THRUST BRG TEMP.	TE -1215 BEARING #1 METAL TEMP - TURBINE	SPARE
Channel type (Temp/Diff. Temp.)	Temperature	Temperature	Temperature	Temperature	Temperature	---
Slot Input/Output Module Type (TC/RTD)	RTD Pt100	RTD Pt100	RTD Pt100	RTD Pt100	RTD Pt100	---
Range	0-115 °C	0-110 °C	0-110 °C	0-110 °C	0-115 °C	---
Barriers (None/Ext.Zener/ Isolator by BN)	3X (STAHL9001/02-016-150-111)	3X (STAHL9001/02-016-150-111)	3X (STAHL9001/02-016-150-111)	3X (STAHL9001/02-016-150-111)	3X (STAHL9001/02-016-150-111)	---
Set Point Alarm (Deg C)	115 °C	95 °C	95 °C	95 °C	115 °C	---
Set Point Danger (Deg C)	115 °C	110 °C	110 °C	110 °C	115 °C	---

Appendix C: HMI & SCADA Results

HMI Vibrations Screen

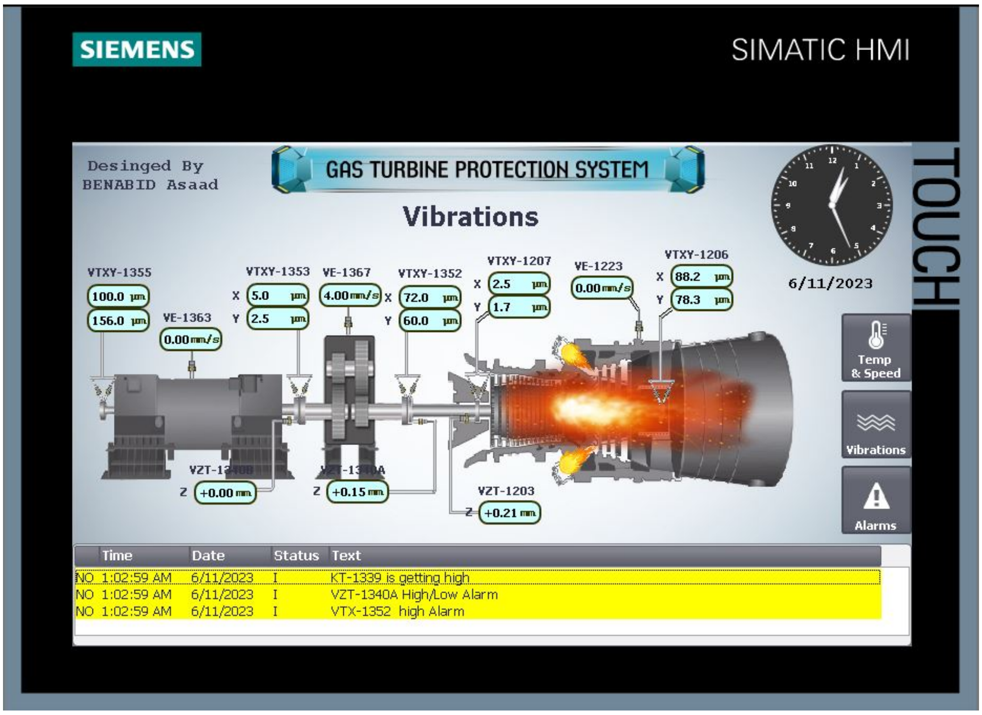


FIGURE C.1: HMI Vibrations Screen

HMI Alarms Screen

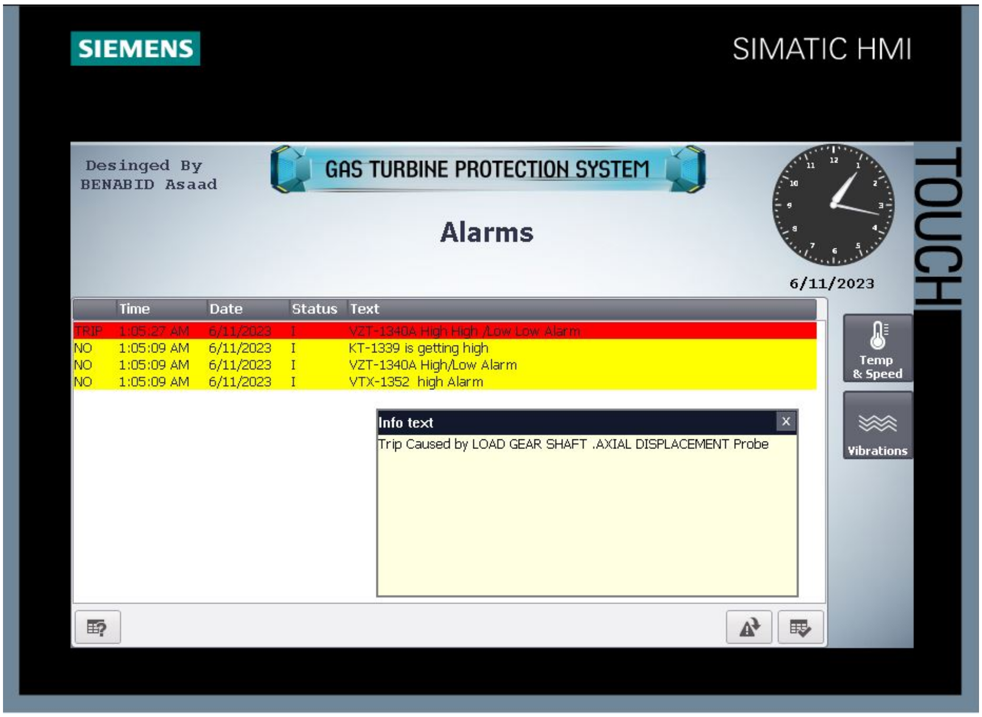


FIGURE C.2: HMI Alarms Screen

SCADA Temperatures Screen

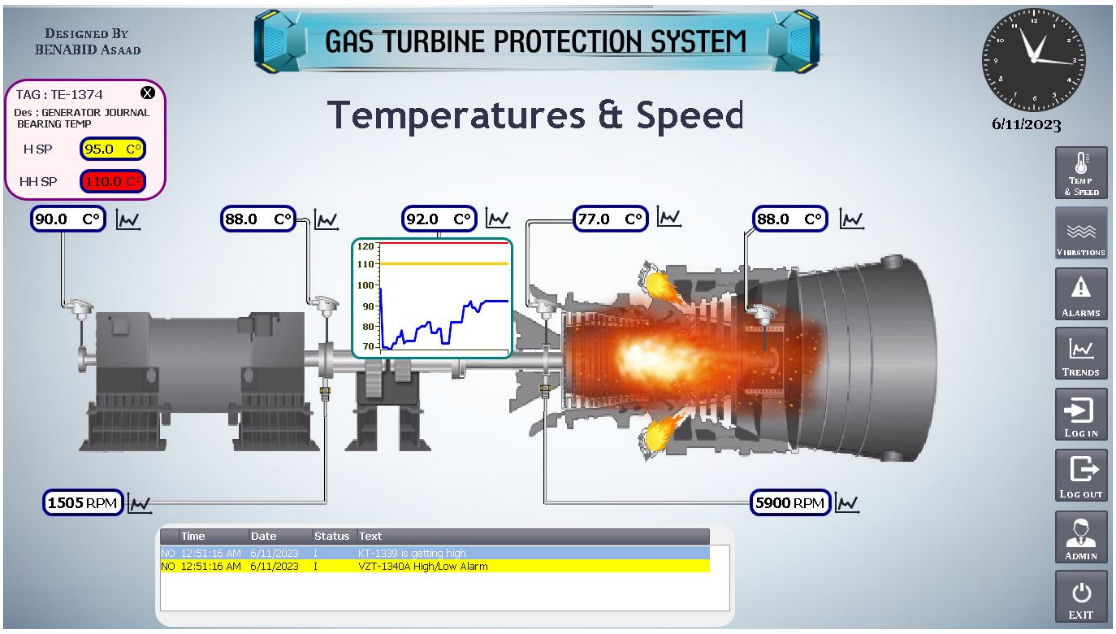


FIGURE C.3: SCADA Temperatures & Speed Screen

SCADA Emergency Shutdown

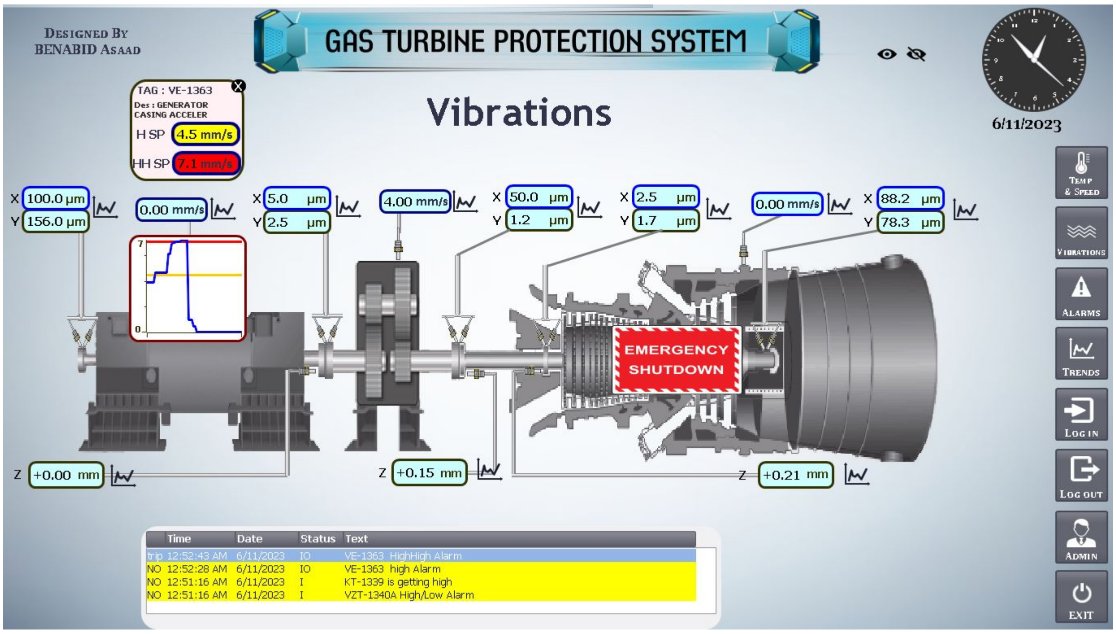


FIGURE C.4: Emergency Shutdown

SCADA Administration Screen

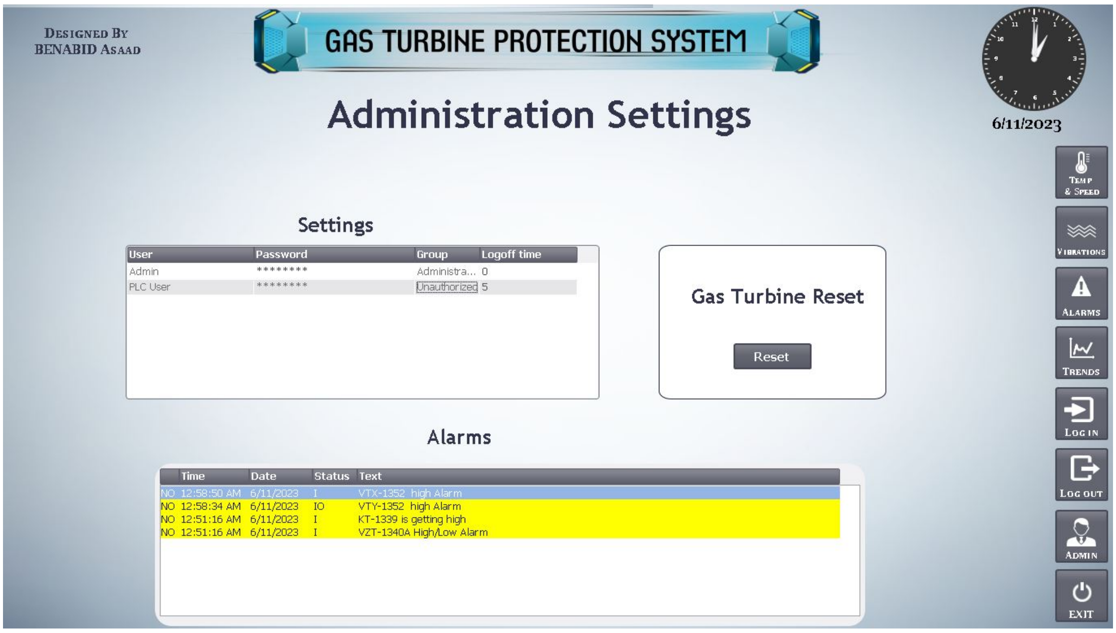


FIGURE C.5: Administration Screen

SCADA Trends Screen

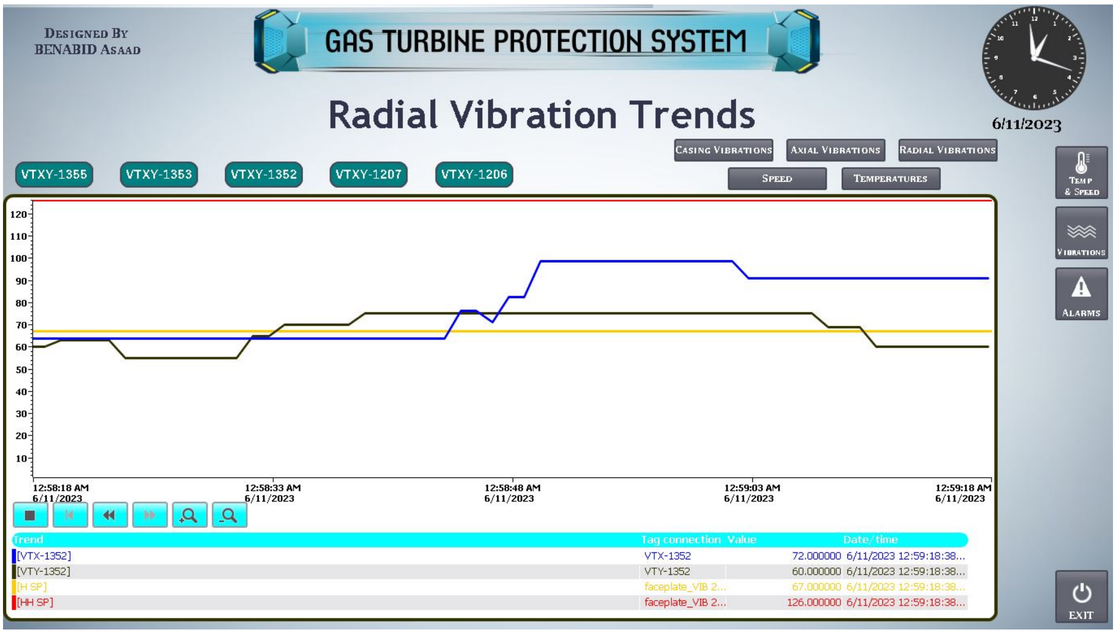


Figure C.6: SCADA Trends Screen

SCADA Admin Autorization for Setpoint Changes

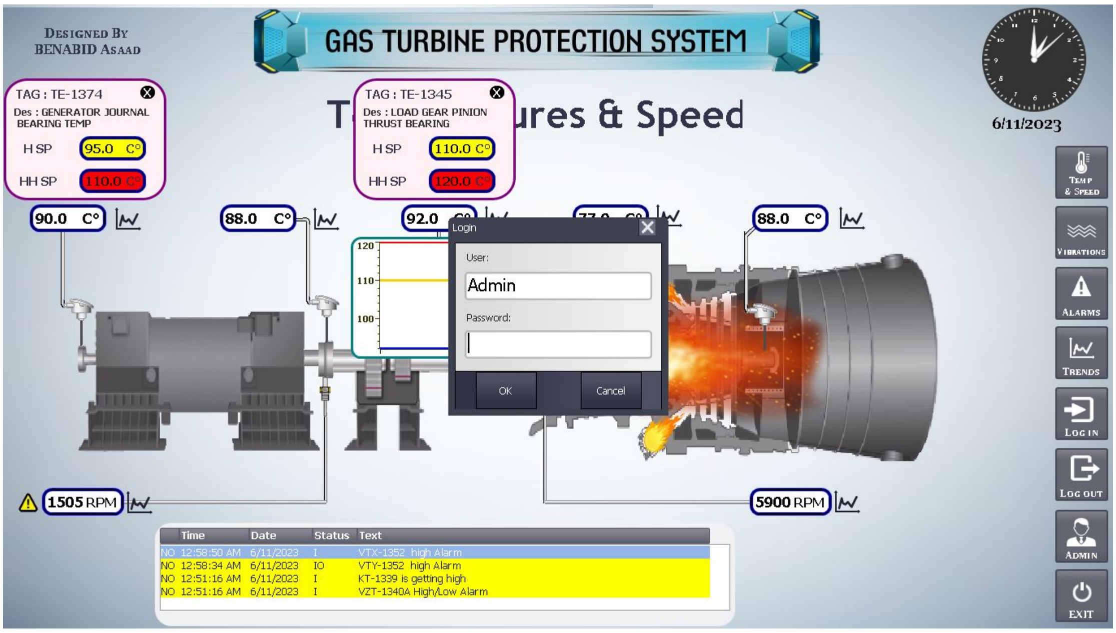


Figure C.7: Admin Autorization for Setpoint Changes

Appendix D: IIoT Results

Radial Vibrations Local Dashboard

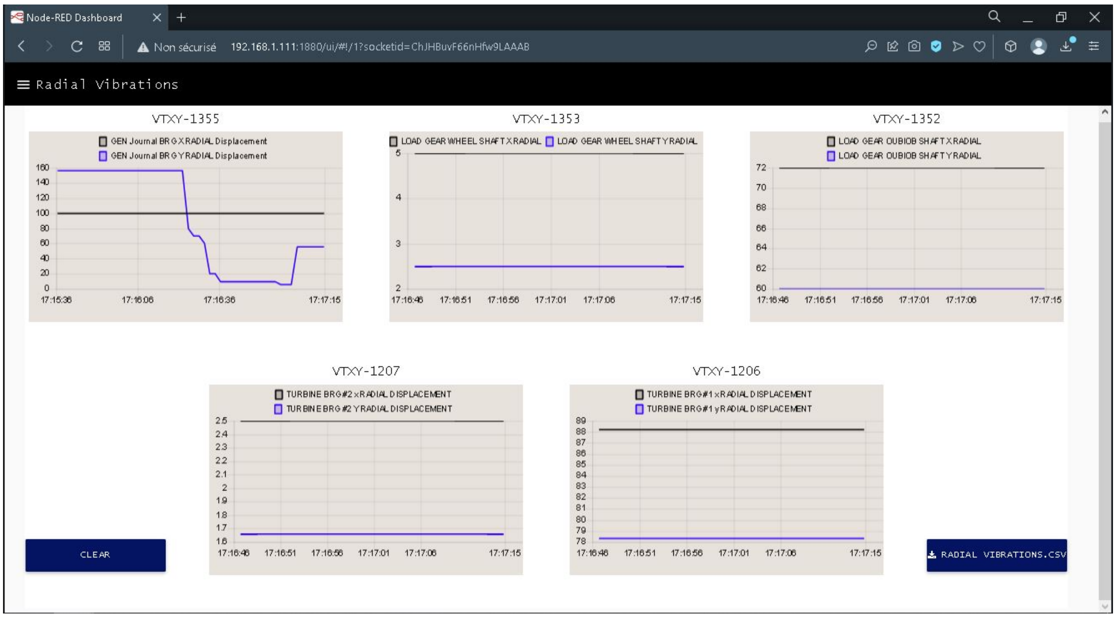


FIGURE D.1: Radial Vibrations Local Dashboard

Axial Vibrations Local Dashboard

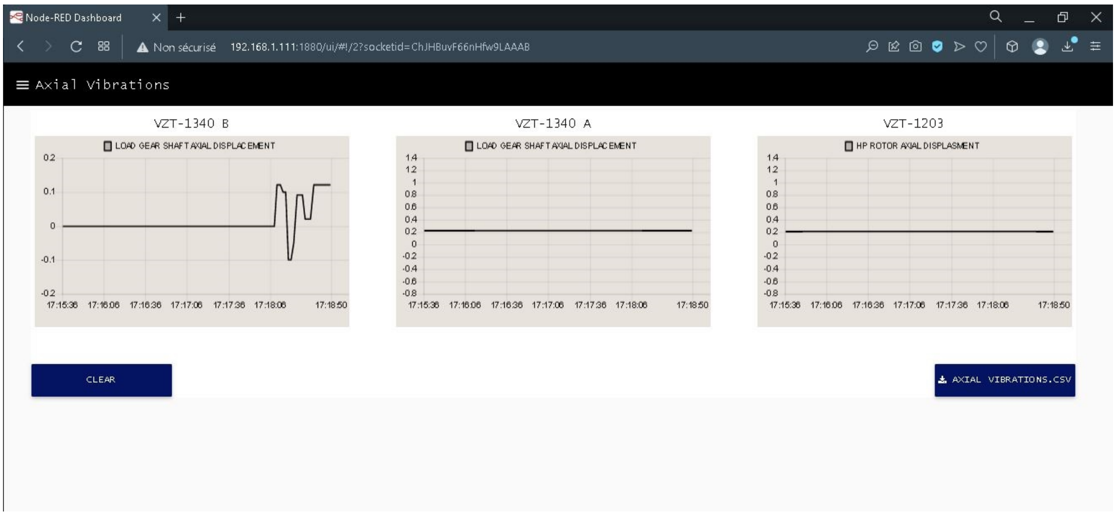


FIGURE D.2: Axial Vibrations Local Dashboard

Speed Local Dashboard

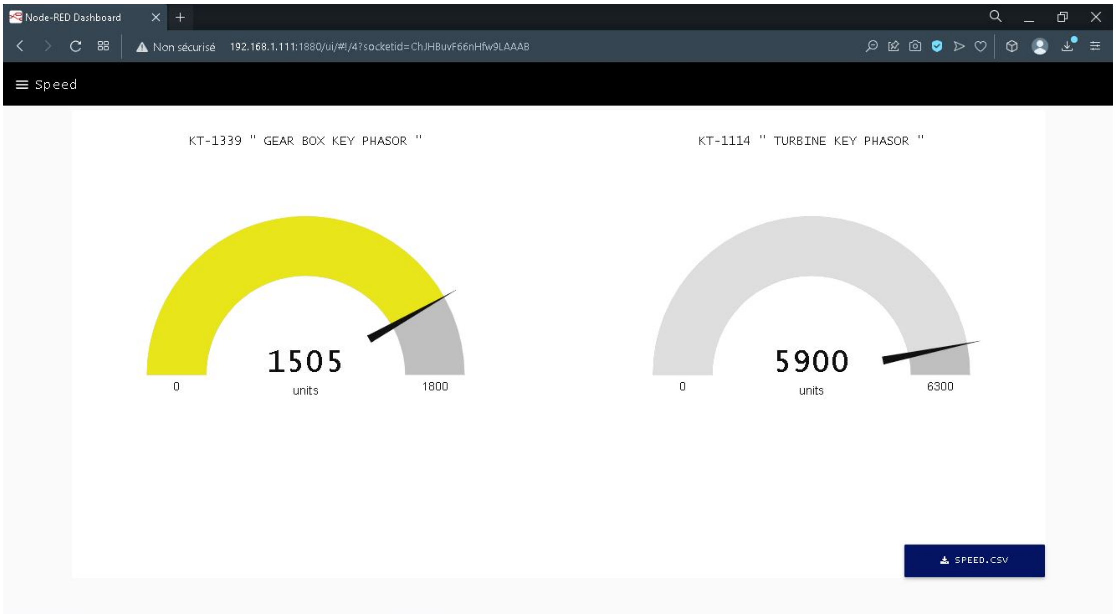
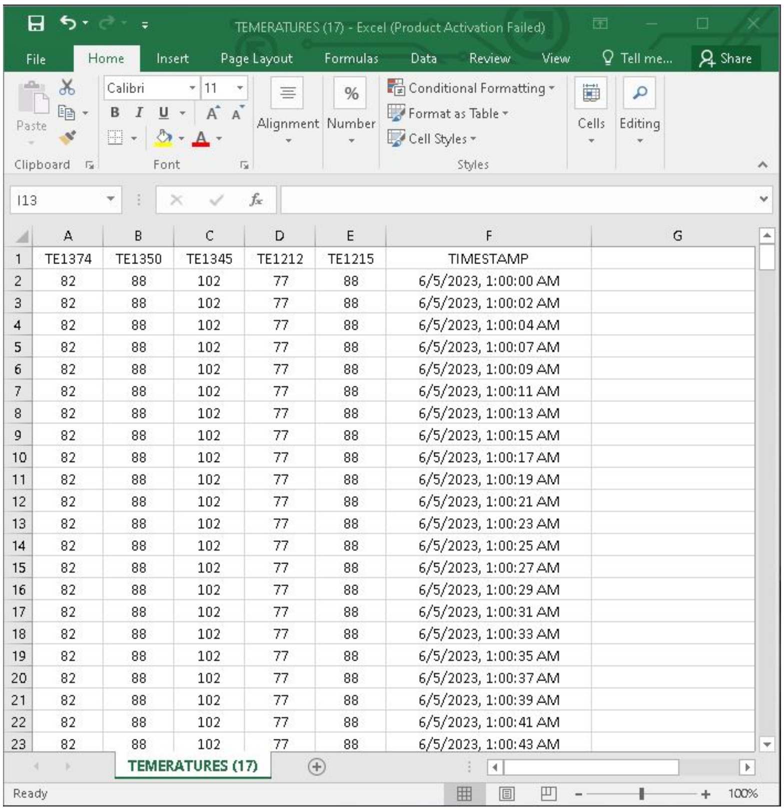


FIGURE D.3: Speed Local Dashboard

CSV File From The Local Dashboard (MySQL)



	A	B	C	D	E	F
1	TE1374	TE1350	TE1345	TE1212	TE1215	TIMESTAMP
2	82	88	102	77	88	6/5/2023, 1:00:00 AM
3	82	88	102	77	88	6/5/2023, 1:00:02 AM
4	82	88	102	77	88	6/5/2023, 1:00:04 AM
5	82	88	102	77	88	6/5/2023, 1:00:07 AM
6	82	88	102	77	88	6/5/2023, 1:00:09 AM
7	82	88	102	77	88	6/5/2023, 1:00:11 AM
8	82	88	102	77	88	6/5/2023, 1:00:13 AM
9	82	88	102	77	88	6/5/2023, 1:00:15 AM
10	82	88	102	77	88	6/5/2023, 1:00:17 AM
11	82	88	102	77	88	6/5/2023, 1:00:19 AM
12	82	88	102	77	88	6/5/2023, 1:00:21 AM
13	82	88	102	77	88	6/5/2023, 1:00:23 AM
14	82	88	102	77	88	6/5/2023, 1:00:25 AM
15	82	88	102	77	88	6/5/2023, 1:00:27 AM
16	82	88	102	77	88	6/5/2023, 1:00:29 AM
17	82	88	102	77	88	6/5/2023, 1:00:31 AM
18	82	88	102	77	88	6/5/2023, 1:00:33 AM
19	82	88	102	77	88	6/5/2023, 1:00:35 AM
20	82	88	102	77	88	6/5/2023, 1:00:37 AM
21	82	88	102	77	88	6/5/2023, 1:00:39 AM
22	82	88	102	77	88	6/5/2023, 1:00:41 AM
23	82	88	102	77	88	6/5/2023, 1:00:43 AM

FIGURE D.4: TEMPERATURES CSV File From The Cloud-Based Dashboard

Cloud-Based Dashboard Autorization

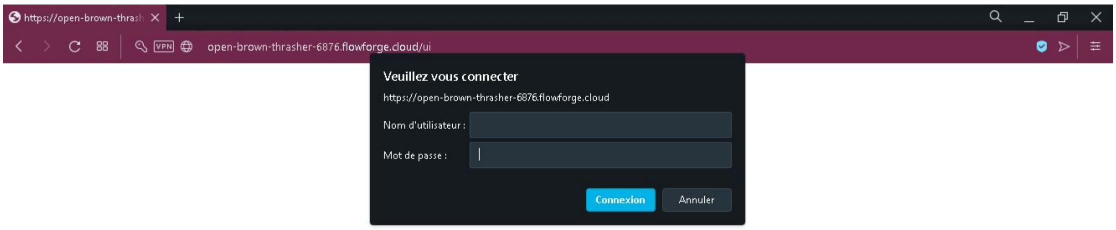


FIGURE D.5: Cloud-Based Dashboard Autorization

Cloud-Based Main Dashboard

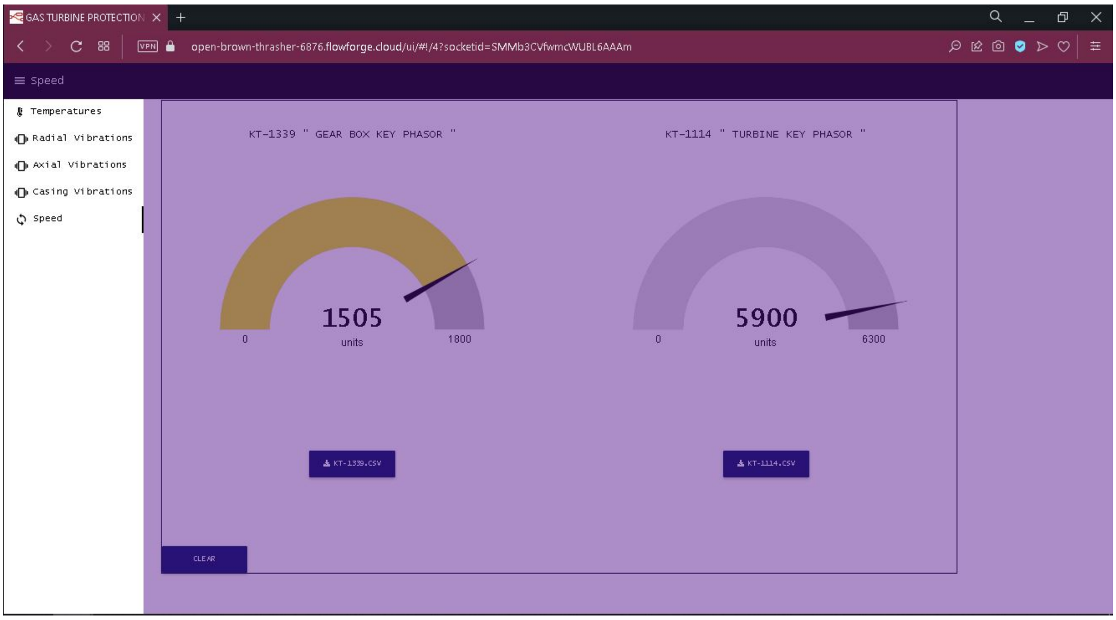


FIGURE D.6: Cloud-Based Main Dashboard

Remote-RED Android/IOS APP Dashboard

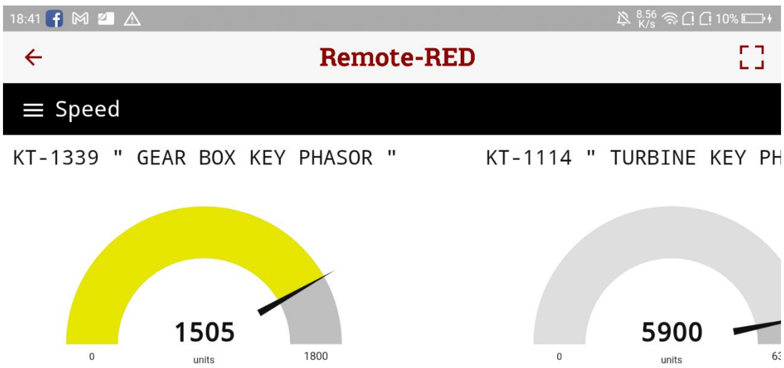


FIGURE D.7: Remote-RED Android/IOS APP Dashboard

Cloud-Based Temperatures Dashboard

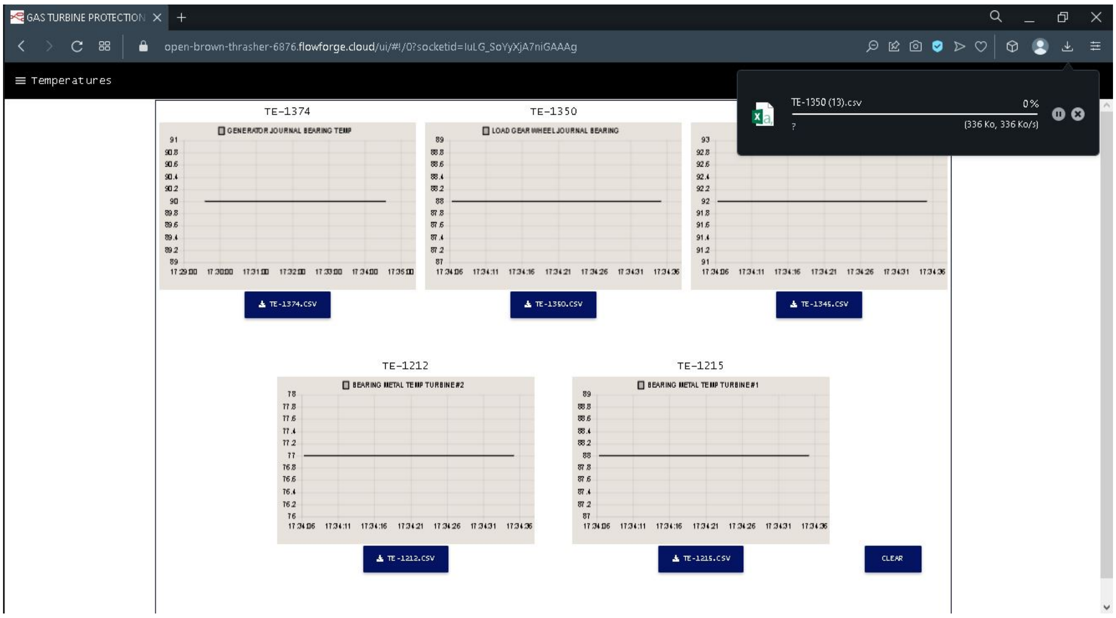


FIGURE D.8: Cloud-Based Temperatures Dashboard

CSV File From The Cloud-Based Dashboard (FireBase)

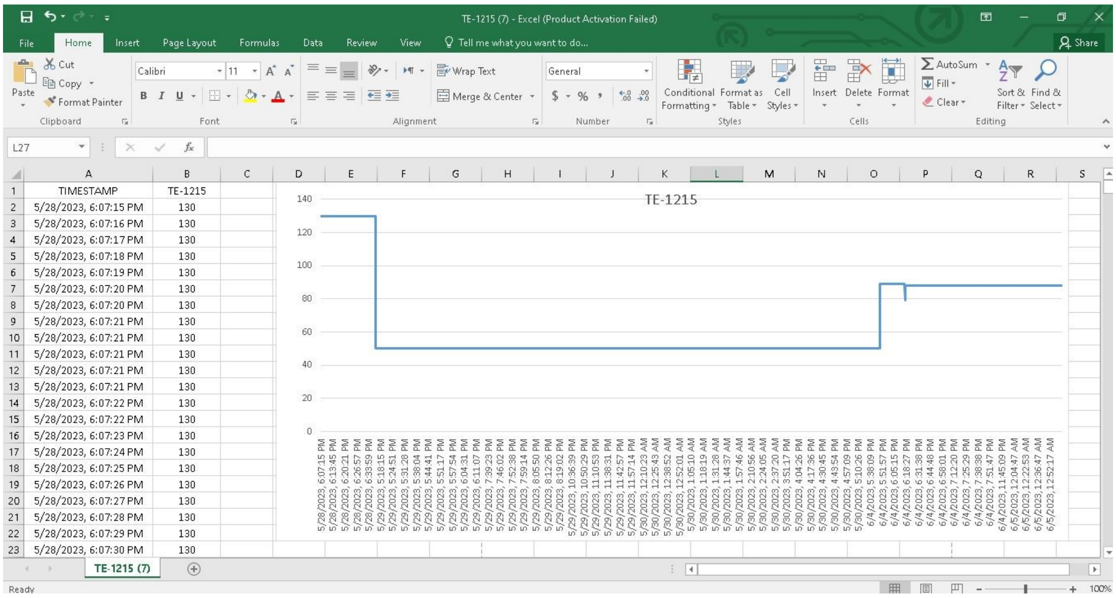


FIGURE D.9: TE-1215 CSV File From The Cloud-Based Dashboard