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# Feasibility Evaluation of a Microcontroller-Based SCADA Prototype as an Operational Traction Substation Monitoring System

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**ABSTRACT**

This study evaluates the feasibility of a microcontroller-based Supervisory Control and Data Acquisition (SCADA) prototype for railway traction substation monitoring. A quantitative evaluative approach is employed using experimental data, focusing on reliability, response time, accuracy, and communication performance. The system integrates Arduino-based controllers, electrical sensors, TCP/IP communication, and a computer-based Human Machine Interface (HMI). Results show that the system achieves an operational success rate above 90% with an average response time below 2 seconds, indicating adequate performance for basic monitoring and control functions. However, compared to industrial SCADA standards, the system exhibits limitations in reliability, security, and scalability. Therefore, the prototype is classified as having limited feasibility, suitable for educational and simulation purposes but not for direct operational deployment. This study provides a structured evaluation framework and highlights key gaps for future development of more robust SCADA systems. This study contributes by introducing a quantitative feasibility evaluation framework for low-cost SCADA systems in railway applications.

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## 1. INTRODUCTION

The rapid development of modern railway transportation systems demands high levels of reliability, efficiency, and operational safety, particularly in the traction power supply system. Traction substations play a critical role in converting high-voltage electrical energy into operational voltages (e.g., 25 kV or 27.5 kV AC) to supply electric trains through overhead catenary systems. Any disturbance in this system can significantly impact train operations, leading to service delays and economic losses [1].

To ensure reliable operation, real-time monitoring and control systems are required. Supervisory Control and Data Acquisition (SCADA) has become a key technology widely implemented in power systems and railway infrastructure due to its capability to provide centralized monitoring, remote control, and data acquisition [2]. In traction substations, SCADA enables operators to monitor electrical parameters such as voltage, current, and frequency, as well as control critical equipment such as circuit breakers and switchgear [3]. Industrial SCADA systems typically rely on Programmable Logic Controllers (PLCs) and Remote Terminal Units (RTUs), which offer high reliability, scalability, and robustness. However, these systems require substantial investment costs, complex infrastructure, and skilled human resources, making them less suitable for small-scale applications, research environments, or educational purposes [4]. In recent years, SCADA systems have evolved into cyber-physical systems integrated with smart grid technologies, enabling advanced monitoring, automation, and intelligent decision-making in power systems [7], [12]. Furthermore, the increasing interconnection of SCADA networks has introduced significant cybersecurity challenges, requiring robust protection mechanisms to ensure system integrity and resilience [9], [11].

As an alternative, microcontroller-based SCADA systems have been developed to provide a low-cost and flexible solution. Platforms such as Arduino allow easy integration with sensors, communication modules, and user interfaces, making them attractive for prototyping and learning applications [5]. Several studies have demonstrated that such systems can perform basic SCADA functions, including real-time monitoring and control [6]. Despite these advantages, most existing studies focus primarily on system design and implementation, with limited attention to evaluating system feasibility for real-world operational deployment. In contrast, industrial SCADA systems must meet stringent requirements, including reliability above 99%, response times below 1 second, high data accuracy, and robust cybersecurity and redundancy mechanisms [4]. These requirements present significant challenges for microcontroller-based systems, which are typically designed for small-scale applications. Although microcontroller-based systems offer flexibility and low cost, their limitations in handling large-scale distributed systems and real-time synchronization remain significant challenges compared to modern smart grid infrastructures [8], [10]. Despite extensive research on SCADA implementation, limited studies have quantitatively evaluated the feasibility of low-cost microcontroller-based SCADA systems against industrial standards, particularly in railway traction applications. This creates a critical gap in understanding their practical deployment limitations.

Therefore, this study aims to evaluate the feasibility of a microcontroller-based SCADA prototype for traction substation monitoring. The evaluation focuses on key performance parameters, including reliability, response time, accuracy, and communication stability, and compares the results with industrial SCADA standards. The outcome of this study is expected to provide a structured feasibility assessment framework and identify critical gaps between prototype systems and industrial implementations, thereby supporting the development of more reliable and scalable SCADA solutions for railway applications. This study differentiates itself by providing a structured feasibility evaluation framework, rather than focusing solely on system implementation, which remains limited in existing literature.

## 2. RESEARCH METHOD

### A. Research Approach

This study employs a quantitative evaluative approach to assess the feasibility of a microcontroller-based SCADA prototype for traction substation monitoring. Evaluative research is used to determine system performance based on predefined technical parameters and to compare the results with industrial SCADA standards. The quantitative approach is applied by analyzing numerical data obtained from system testing, such as response time, communication success rate, and data stability [1]. Unlike previous studies that focus on system design and implementation, this research emphasizes performance evaluation and feasibility assessment, providing a more practical perspective for real-world applications.

### B. System Description

The object of this study is a microcontroller-based SCADA prototype designed to simulate traction substation monitoring and control. The system consists of three substations, each equipped with electrical sensors, actuators, and communication modules. The prototype integrates:

1. Microcontrollers (Arduino Uno and Arduino Mega) as data processing units
2. Electrical sensors (PZEM-004T) for measuring voltage, current, power, and frequency
3. TCP/IP-based communication over Ethernet and fiber optic networks
4. A Human Machine Interface (HMI) developed using Visual Basic

5. A database system using Microsoft Access

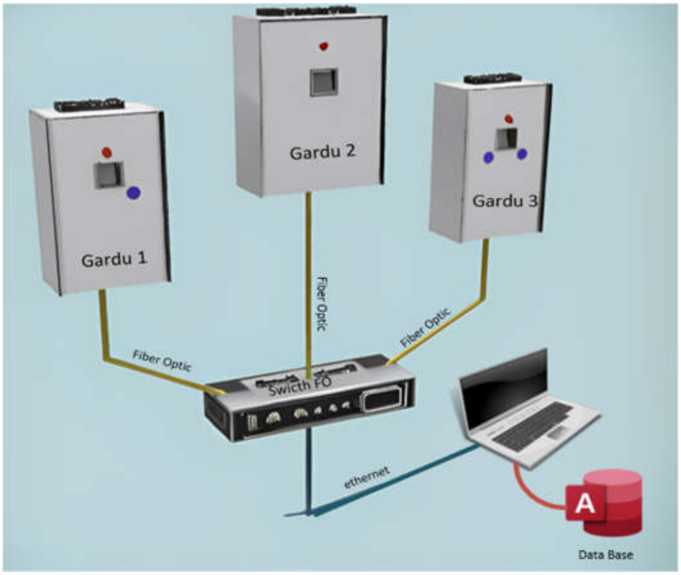
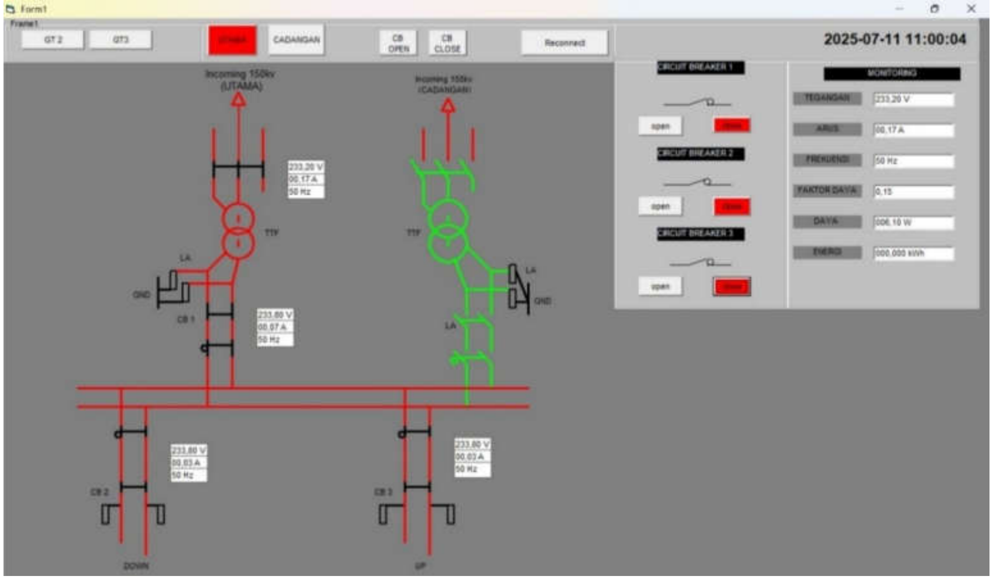


Figure 1. The evaluated SCADA system prototype



2025-07-11 11:00:04

233,20 V
00,17 A
50 Hz

233,80 V
00,07 A
50 Hz

233,80 V
00,03 A
50 Hz

233,80 V
00,03 A
50 Hz

TEGANGAN 233,20 V
ARUS 00,17 A
FREKUENSI 50 Hz
FAKTOR DAYA 0,15
DAYA 006,10 W
ENERGI 000,000 kWh

Figure 2 HMI Design for SCADA system

This architecture enables real-time monitoring and remote control of electrical parameters and switching devices, representing the fundamental functionality of SCADA systems [2].

C. Data Collection

The data used in this study are secondary data obtained from previous experimental testing of the SCADA prototype. The collected data include:

1. System response time
2. Communication success rate
3. Sensor measurement results
4. System stability during operation

Data collection is conducted through documentation review of experimental results and supported by literature studies related to SCADA performance standards and evaluation methods [3].

Table 1 System Integration Reliability Testing

| **No** | **Button** | **Substation 1** | | **Substation 2** | | **Substation 3** | | **Description** |
|---|---|---|---|---|---|---|---|---|
| | | **✓/ X** | **s** | **✓/ X** | **s** | **✓/ X** | **s** | |
| 1 | Main CB | ✓ | 0,62 | ✓ | 0,89 | ✓ | 0,72 | succes |
| 2 | CB 1 | ✓ | 0,42 | ✓ | 0,91 | ✓ | 0,71 | succes |
| 3 | CB2 | ✓ | 0,65 | ✓ | 1,69 | ✓ | 0,56 | succes |
| 4 | CB 3 | ✓ | 0,69 | ✓ | 10,20 | ✓ | 0,53 | succes |
| 5 | CB 4 | ✓ | 0,60 | ✓ | 0,89 | ✓ | 0,55 | succes |
| 6 | Main CB | ✓ | 0,69 | X | - | ✓ | 0,68 | succes |
| 7 | CB 1 | ✓ | 0,72 | ✓ | 0,82 | ✓ | 1,60 | succes |
| 8 | CB2 | ✓ | 0,92 | ✓ | 0,75 | ✓ | 0,52 | succes |
| 9 | CB 3 | ✓ | 0,54 | X | - | ✓ | 0,52 | succes |
| 10 | CB 4 | ✓ | 1,06 | V | 1,05 | ✓ | 0,54 | succes |

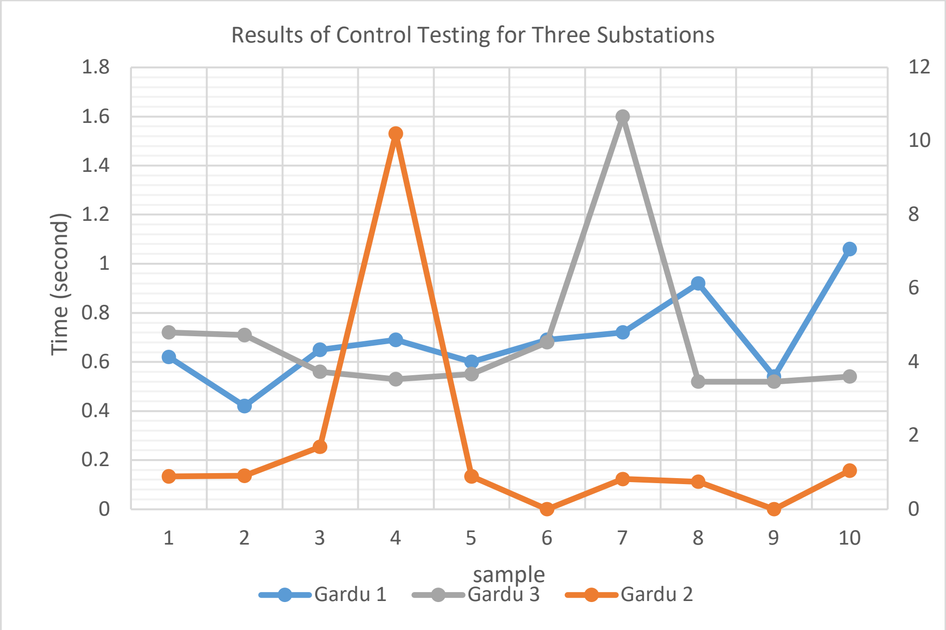


Figure 3 Results of Control Testing for Three Substations

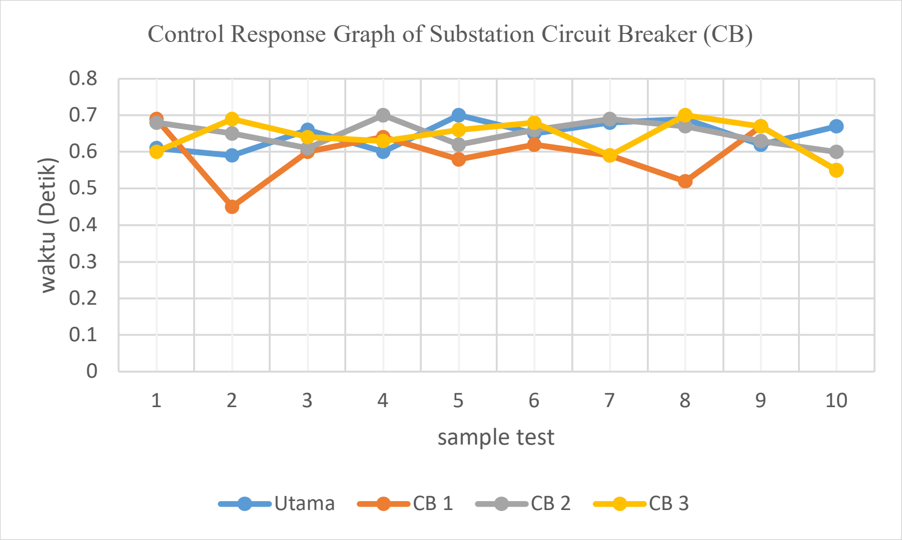


Figure 4 Control Response Graph of Substation Circuit Breaker (CB)

D. Performance Parameters

The feasibility evaluation is based on key SCADA performance parameters commonly used in industrial systems, including:

1. Reliability – the ability of the system to operate continuously without failure, Reliability is calculated as the ratio of successful operations to total test attempts, expressed as a percentage
2. Response Time – the time required for the system to respond to commands or changes
3. Accuracy – the degree of conformity between measured and actual values
4. Availability – the percentage of system uptime
5. Security – the ability to protect data and system access from disturbances

These parameters are widely recognized as essential criteria for SCADA system performance evaluation [4]. The selected evaluation parameters are aligned with performance indicators commonly used in smart grid and industrial control systems, particularly in cyber-physical system environments [12].

E. Data Analysis Method

The data analysis is conducted through the following stages:

1. Descriptive Analysis
   The system performance is analyzed based on average values, trends, and stability of the measured parameters.
2. Comparative Analysis
   The obtained results are compared with industrial SCADA standards, such as reliability (>99%) and response time (<1 second) [4].
3. Gap Analysis
   Differences between the prototype system and industrial SCADA systems are identified to determine performance limitations.
4. Feasibility Evaluation
   The system feasibility is classified into three categories:
   a. Feasible → meets industrial standards
   b. Limited feasibility → suitable for simulation/education
   c. Not feasible → requires significant improvement

This structured approach ensures that the evaluation not only measures system performance but also determines its readiness for real-world implementation.

## 3. RESULTS AND DISCUSSION

### A. Overall System Performance

The developed microcontroller-based SCADA prototype was tested to evaluate its capability in performing real-time monitoring and control of a simulated traction power system. The system successfully executed core SCADA functions, including real-time acquisition of electrical parameters (voltage, current, and frequency), remote switching control, and data logging. The Human Machine Interface (HMI) effectively visualized system status and enabled operator interaction. In addition, the database system recorded sensor data continuously without significant data loss, indicating stable integration between hardware and software components. These results demonstrate that the prototype is capable of representing fundamental SCADA functionality in a laboratory-scale environment.

### B. Reliability Analysis

Reliability is a critical parameter for SCADA systems, particularly in safety-critical applications such as railway traction power systems. Based on experimental results, the system achieved an overall operational success rate of above 90%. All substations were able to perform monitoring and control tasks under normal conditions.

However, during integrated system testing, communication failures were observed, particularly in one substation, resulting in intermittent disconnections. These failures reduced the reliability level compared to industrial SCADA systems, which typically require reliability above 99% [1]. The observed instability was mainly caused by communication conflicts and limited processing capability of the microcontroller. Therefore, while the system demonstrates acceptable reliability for simulation purposes, it does not meet the reliability requirements for operational deployment. The observed reliability limitations are consistent with previous studies indicating that low-cost embedded systems often struggle to achieve industrial-grade reliability required in smart grid applications [8].

The reliability of each substation was quantitatively evaluated based on the success rate of control operations. Substations 1 and 3 achieved a reliability of 100%, while Substation 2 showed a lower reliability of 80%, indicating a 20% performance gap. When compared to industrial SCADA requirements (>99% reliability), the prototype system exhibits a deviation of approximately 9–19%. This deviation highlights that the system does not yet meet the reliability standards required for mission-critical railway operations. The system performed a total of 30 control operations across three substations, of which 27 operations were successful, resulting in an overall success rate of 90%. Substations 1 and 3 achieved 100% reliability (10/10 operations), while Substation 2 achieved 80% (8/10 operations), indicating a 20% performance gap.

### C. Response Time Analysis

In general, the system demonstrates relatively stable response performance, particularly under normal communication conditions. However, occasional delays exceeding 1 second were observed, especially during communication disturbances or network congestion. Compared to industrial SCADA systems, which typically require response times below 1 second for critical control applications [2], the prototype performance is considered insufficient for time-critical operations. Nevertheless, it remains acceptable for monitoring applications and non-critical control scenarios. A total of 30 response time measurements were recorded. The average response time was approximately 0.85 seconds under normal operating conditions, with a minimum value of 0.42 seconds and a maximum value of 10.2 seconds during communication failure scenarios. The results indicate moderate variability, suggesting that system performance is sensitive to communication disturbances.

The measured response time ranged from 0.4 s to 2 s, with an average value of approximately 0.7–1.0 s under normal operating conditions. However, extreme delays were observed, reaching up to 10.2 s during communication failures. Compared to industrial SCADA standards, which typically require response times below 1 s, the prototype system exceeds the acceptable limit by up to 900% under worst-case conditions. This significant deviation indicates that system performance is highly dependent on communication stability.

D. Accuracy and Data Stability

The accuracy of the system is related to the ability of the sensors and processing units to produce measurements that reflect actual electrical conditions. Based on experimental observations, the measured data remained stable with no significant fluctuations, indicating consistent system performance during operation However, the system utilizes non-industrial-grade sensors without standardized calibration procedures. In contrast, industrial SCADA systems employ calibrated Current Transformers (CTs) and Voltage Transformers (VTs) to ensure high measurement precision [1]. The measured values remained within an estimated variation range of less than ±5% during normal operation, indicating stable system performance. However, due to the absence of calibration using industrial-standard instruments, the absolute measurement error cannot be quantitatively verified.

This limitation introduces uncertainty in measurement accuracy, which may affect system reliability in critical applications. Therefore, although the prototype demonstrates acceptable stability for simulation purposes, it does not yet meet the accuracy requirements of industrial SCADA systems.

E. Communication System Analysis

The communication recovery time was measured at approximately 10 seconds on average, which is significantly higher than industrial SCADA systems that typically achieve recovery within milliseconds to a few seconds. This represents a performance gap of more than 5–10 times, indicating that the current system lacks fast fault recovery mechanisms required in real-time control systems. The communication system utilizes TCP/IP protocol over Ethernet and fiber optic networks, enabling real-time data exchange between substations and the central control system. This approach provides flexibility and ease of integration with standard computer networks. Despite these advantages, the system lacks several key features required in industrial SCADA communication, including:

a. Redundant communication paths
b. Error detection and correction mechanisms
c. Data encryption and cybersecurity protection

These limitations significantly affect system robustness and reliability, especially under network disturbances. Industrial SCADA systems typically employ standardized protocols such as IEC 60870-5-104 or DNP3, along with secure communication mechanisms [4]. The absence of secure communication mechanisms increases vulnerability to cyber threats, which is a critical concern in modern SCADA systems as highlighted in recent cybersecurity studies [9], [11].

F. Comparison with Industrial SCADA Systems

A comparative analysis between the developed prototype and industrial SCADA systems highlights several performance gaps. The prototype shows acceptable performance in basic functionality but falls short in key aspects such as reliability, security, scalability, and redundancy. Industrial SCADA systems are designed to operate under strict performance requirements, including high availability, fault tolerance, and cybersecurity protection. In contrast, the prototype system is limited by hardware constraints and simplified system architecture.

Tabel 1 Comparison Between Prototype and Industrial SCADA Systems

| Parameter | Prototype SCADA | Industrial SCADA |
|---|---|---|
| **Reliability** | >90% | >99% |
| **Response Time** | <2 s | <1 s |
| **Accuracy** | Moderate | High (calibrated) |
| **Security** | Not available | High |
| **Redundancy** | Not available | Available |
| **Scalability** | Limited | High |

The comparison indicates that the prototype system still has significant limitations, particularly in reliability, security, and scalability. These gaps highlight the challenges in deploying low-cost SCADA systems in real-world railway applications.

### G. Feasibility Evaluation

Based on the evaluation of performance parameters, the feasibility of the system can be classified as follows:

1. Reliability: Below industrial standard (>99%) → limited feasibility
2. Response Time: Acceptable for monitoring → not suitable for critical control
3. Accuracy: Adequate for simulation → not suitable for operational systems
4. Security and Redundancy: Not available → not suitable for deployment

Therefore, the system is categorized as having limited feasibility, meaning it is suitable for educational and laboratory applications but not for direct implementation in operational traction substations.

### H. Gap Analysis and Future Development

The identified gaps between the prototype and industrial SCADA systems include the absence of redundancy, lack of cybersecurity mechanisms, insufficient reliability, and limited scalability. To address these limitations, several improvements are recommended:

1. Integration of a hybrid architecture (microcontroller and PLC) to enhance reliability
2. Implementation of redundant communication networks
3. Adoption of industrial communication protocols (IEC 60870-5-104 or Modbus TCP)
4. Enhancement of cybersecurity through encryption and authentication
5. Calibration of sensors to improve measurement accuracy

These improvements are essential to enhance system performance and enable future deployment in real-world railway applications. These limitations indicate that the proposed system has not yet achieved the characteristics of a cyber-physical system, which requires tight integration between computation, communication, and control layers [12].

The observed performance limitations suggest that system reliability is strongly influenced by communication architecture and processing constraints of the microcontroller. In distributed SCADA systems, communication instability can propagate delays and reduce overall system performance. This aligns with previous studies indicating that low-cost embedded systems often face challenges in achieving industrial-grade performance due to limited processing capability and lack of redundancy mechanisms.

## 4. CONCLUSION

This study evaluated the feasibility of a microcontroller-based SCADA prototype for monitoring and controlling a railway traction substation system. The results demonstrate that the system is capable of performing fundamental SCADA functions, including real-time data acquisition, remote control, and data logging, with an operational success rate exceeding 90% and an average response time below 2 seconds. However, when compared to industrial SCADA standards, the system exhibits significant limitations in terms of reliability, response time, accuracy, security, and scalability. In particular, the absence of redundancy and cybersecurity mechanisms, along with performance inconsistencies in communication, prevents the system from meeting the requirements for critical operational environments. Therefore, the proposed system is classified as having limited feasibility, meaning it is suitable for educational and simulation purposes but not for direct implementation in operational traction substations. Future work should focus on integrating industrial-grade components, enhancing system reliability and security, and adopting standardized communication protocols to improve system readiness for real-world deployment.

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