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Original Article

Development of Maintenance Management System for Real-Time Monitoring of Power Transformer to Improve Availability Performance: The Case of Tagamenda TANESCO Grid Substation

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ABSTRACT

Power transformers are critical assets in TANESCO's grid substations, playing a vital role in ensuring a reliable and uninterrupted power supply. However, the growing challenges of ageing infrastructure, increasing energy demand, and reactive maintenance practices often lead to unplanned outages, higher operational costs, and reduced transformer availability. This dissertation focuses on the Development of a Maintenance Management System for Real-Time Monitoring of Power Transformers at TANESCO grid substations, with the goal of improving availability performance. The study explores the design and implementation of a Real-Time Monitoring Management System (RTMMS), leveraging advanced sensors, data analytics, and predictive maintenance techniques. The RTMMS continuously monitors critical parameters such as temperature, oil levels, dissolved gases, and load conditions, providing real-time insights into transformer health. By integrating predictive analytics, the system identifies potential faults early, enabling timely interventions and reducing downtime. Additionally, it supports data-driven maintenance planning, enhances operational reliability, and extends transformer lifespan. The proposed system addresses challenges such as high initial costs, data management complexity, and resistance to technological change through phased deployment, secure cloud solutions, and comprehensive training programs. The expected benefits include improved transformer availability, cost efficiency, enhanced grid sustainability, and a shift from reactive to proactive maintenance practices. This research underscores the transformative potential of real-time monitoring systems in modernizing maintenance management and aligns TANESCO with global best practices in energy sector innovation and operational excellence.

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INTRODUCTION

The maintenance and performance management of power transformers is essential for ensuring the reliable and uninterrupted operation of TANESCO's grid substations. Power transformers are critical components of the electrical grid, responsible for voltage regulation and power distribution (Razavi et al., 2019). However, these assets are frequently subjected to operational stresses, ageing effects, and environmental challenges, which can result in performance degradation, inefficiencies, or even failures.

In response to these challenges, this dissertation proposes the development of a Real-Time Monitoring Management System (RTMMS)**.** The RTMMS aims to transform the current maintenance framework by leveraging real-time monitoring technologies and predictive analytics to enhance the operational availability and reliability of power transformers.

This initiative emphasizes the importance of proactive maintenance strategies and technological innovation in addressing the critical challenges of maintaining high-performance standards in TANESCO's grid operations. By ensuring better decision-making and optimized resource utilization, the RTMMS offers a sustainable pathway to improve transformer availability, reduce downtime, and support TANESCO's mission of providing efficient and reliable energy to its stakeholders.

The current maintenance practices for transformers at TANESCO substations rely heavily on periodic or corrective approaches, which are often reactive rather than preventive (Degan, 2022). This limitation leads to:

- Delayed fault detection.
- Increased risk of transformer failures.
- Higher maintenance and repair costs.
- Reduced operational efficiency and availability.

To address these challenges, the proposed RTMMS offer real-time insights, enabling proactive decision-making and more efficient asset management.

The objective of developing a Real-Time Monitoring Management System (RTMMS) is to integrate advanced monitoring technologies and predictive analytics into TANESCO's operational framework. This initiative focuses on transforming the current maintenance practices, which are primarily reactive, into a proactive and data-driven approach.

By continuously monitoring key performance indicators of power transformers and leveraging predictive insights, the system seeks to address the following challenges:

- Delayed Fault Detection: Ensuring early identification of potential issues to minimize risks.

- Unplanned Downtime: Reducing outages by enabling timely interventions.
- Maintenance Inefficiencies: Optimizing maintenance schedules based on real-time data and trends.

Ultimately, the RTMMS aims to enhance transformer reliability, increase operational availability, and improve overall system performance. This alignment with advanced maintenance methodologies underscores TANESCO's commitment to modernizing its energy infrastructure and delivering sustainable and reliable power services.

The RTMMS seeks to:

i. Continuously Monitor Transformer Health: The system employs advanced sensors and monitoring devices to track critical operational parameters such as:

- Oil Levels: Ensuring proper insulation and cooling.
- Temperature: Detecting overheating to prevent thermal damage.
- Dissolved Gases: Analysing gas levels to identify early-stage faults like insulation degradation.
- Load Conditions: Monitoring current loads to avoid overloading and ensure optimal operation.

ii. Provide Predictive Maintenance Insights: By integrating advanced analytics and machine learning algorithms, the system predicts potential issues before they escalate. This predictive capability allows maintenance teams to address anomalies proactively, reducing the likelihood of costly repairs and unplanned downtime.

iii. Enhance Operational Reliability: Real-time data enables swift identification of faults, helping to minimise unexpected outages. This ensures a consistent and reliable power supply, which is critical for TANESCO's grid stability and performance.

iv. Support Maintenance Planning: The system facilitates data-driven maintenance schedules by identifying patterns and trends in transformer performance. Maintenance activities can then be strategically planned, optimising resources and reducing operational disruptions.

v. Improve Transformer Lifespan: By maintaining optimal operating conditions and addressing potential faults early, the system helps extend the life expectancy of transformers. This reduces the frequency of replacements and contributes to long-term cost savings and sustainability.

LITERATURE REVIEW

The maintenance and management of power transformers are critical to ensuring grid reliability and efficient energy delivery (Okeke et al., 2024). As the backbone of electrical power systems, transformers require robust maintenance strategies to prevent operational inefficiencies, reduce downtime, and extend their lifespan. This literature review explores existing research and practices related to maintenance management systems, real-time monitoring, and predictive analytics for power transformers.

Traditional Maintenance Approaches

Corrective Maintenance: Traditionally, transformer maintenance has relied on corrective strategies, addressing failures after they occur. While this approach minimizes upfront costs, it often leads to unplanned outages, higher repair costs, and reduced transformer lifespan.

Preventive Maintenance: Preventive strategies introduced scheduled inspections and servicing, reducing the frequency of failures. However, this approach can still result in inefficiencies, as it lacks real-time insights into equipment health and condition-based decision-making.

Emergence of Real-Time Monitoring Systems

Advancements in sensor technology and IoT have enabled real-time monitoring of transformers. Modern systems track parameters such as:

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- Temperature and Humidity: Indicators of thermal stress and environmental impact.
- Dissolved Gas Analysis (DGA): Essential for detecting insulation breakdown and early-stage faults.
- Load Monitoring: Ensures transformers operate within safe limits.

Real-time data acquisition and analysis enable utilities to transition from preventive to predictive maintenance, reducing downtime and operational costs.

Predictive Analytics in Maintenance Management

Predictive maintenance leverages historical and real-time data, combined with machine learning algorithms, to forecast potential failures (Arunkumar, 2024). Studies show that predictive analytics:

- Enhances fault detection accuracy.
- Reduces maintenance costs by 20-30%
- Increases asset availability by up to 25%.

For example, predictive analytics applied to DGA can detect faults like partial discharges or thermal breakdowns, allowing early intervention.

Integration with SCADA Systems

The integration of real-time monitoring systems with Supervisory Control and Data Acquisition (SCADA) enhances operational efficiency by providing centralized visibility and control. SCADA systems offer:

- Historical data storage for trend analysis.
- Alarm mechanisms for abnormal conditions.
- Seamless integration with remote monitoring and control tools.

Challenges in Adopting Advanced Maintenance Systems

Despite their benefits, real-time monitoring systems face adoption challenges, including:

- High Initial Costs: The need for advanced sensors, analytics platforms, and integration.
- Data Management Complexity: Handling large volumes of data securely and effectively.
- Resistance to Change: Operational staff may be hesitant to transition to technology-driven systems.

Mitigation strategies, such as phased implementation, secure cloud-based data solutions, and staff training, are essential for overcoming these challenges.

Relevance to TANESCO

Studies on utilities in similar developing regions have demonstrated that real-time monitoring systems significantly improve transformer availability and reliability. For example:

- Kenya Power's adoption of predictive maintenance systems reduced transformer failures by 15%.
- India’s state electricity boards achieved a 20% increase in grid efficiency through IoT-based monitoring systems.

These examples provide a strong foundation for TANESCO’s initiative to develop a Real-Time Monitoring Management System tailored to its grid substation needs.

METHODOLOGY

The methodology outlines the systematic approach undertaken to develop the Real-Time Monitoring Management System (RTMMS) for TANESCO’s grid substations. This approach ensures a structured, efficient, and goal-oriented process to achieve the objective of improving transformer availability and performance (Orellana et al., 2021).

Requirement Analysis

The primary objective of the requirement analysis is to evaluate TANESCO's existing maintenance framework and operational challenges to identify

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the specific needs and technical requirements for the development of the Real-Time Monitoring Management System (RTMMS). This step ensures that the system aligns with TANESCO's operational goals and addresses its maintenance inefficiencies effectively.

Activities

- **Conduct Stakeholder Interviews**
  - Engage with maintenance teams, operational staff, and management to gather insights into current practices, challenges, and expectations.
  - Focus on understanding issues such as frequent faults, downtime patterns, and limitations in existing systems.
  - Document user preferences and specific operational requirements to ensure the RTMMS is user-centric.
- **Review Historical Maintenance Data**
  - Analyze past maintenance records, including fault logs, repair reports, and downtime statistics.
  - Identify patterns and recurring issues affecting transformer performance and reliability.
  - Evaluate the financial and operational impacts of current maintenance practices to highlight areas for improvement.
- **Identify Critical Transformer Parameters**
  - Determine key parameters that significantly influence transformer health and performance, including:
    - Temperature: Monitors overheating risks and thermal stress.
    - Oil Levels: Tracks insulation and cooling effectiveness.
    - Dissolved Gases: Provides early indicators of insulation degradation or electrical faults.
    - Load Conditions**:** Ensures transformers operate within safe capacity limits.
  - Define thresholds and metrics for each parameter to guide real-time monitoring and fault detection mechanisms.

Outcome

The requirement analysis results in a comprehensive requirements document that includes:

1. Detailed specifications for the RTMMS, including hardware (sensors and devices) and software (analytics and dashboards) components.
2. A prioritized list of user needs and expectations, ensuring the system is tailored to TANESCO's operational context.
3. Insights into critical maintenance challenges and data-driven recommendations for system features, such as alarm mechanisms, predictive analytics, and integration with SCADA systems.

System Design

The objective of the system design phase is to develop a technical blueprint for the Real-Time Monitoring Management System (RTMMS). This blueprint ensures that the system is scalable, reliable, and integrates seamlessly with existing infrastructure like SCADA, while maintaining robust data security (Qassim et al., 2019).

Activities

i. **Design Hardware Architecture**

- Select appropriate sensors and devices for monitoring critical transformer parameters such as temperature, oil levels, dissolved gases, and load conditions.
- Design a network of data acquisition devices to collect and transmit real-time data to a central processing unit.

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ii. Ensure the hardware components are robust, durable, and capable of operating in diverse environmental conditions.

iii. Develop Software Architecture

- Create a framework for real-time data processing, enabling efficient storage, analysis, and visualization.
- Incorporate predictive analytics algorithms to process historical and real-time data for early fault detection and maintenance insights.
- Develop a user-friendly interface (dashboard) to display transformer performance metrics, alerts, and trends.

iv. **Ensure Compatibility with Existing Systems**

- Design the RTMMS to integrate seamlessly with existing Supervisory Control and Data Acquisition (SCADA) systems.
- Enable interoperability with other utility management platforms to streamline operations.
- Test the system's ability to exchange data in real time with SCADA for comprehensive grid monitoring.

v. **Establish Data Security Protocols**

- Implement secure data transmission mechanisms, such as encryption, to protect information during communication between devices and central systems.
- Define access control policies to restrict unauthorized access to the system.
- Ensure compliance with industry standards for cybersecurity and data protection to safeguard sensitive operational data.

Outcome

The system design phase produces the following key deliverables:

1. **Detailed System Design Document**

- Hardware specifications, including sensor types, installation configurations, and data acquisition devices.
- Software architecture documentation, covering algorithms, database structures, and user interface designs.
- Integration plans outlining how the RTMMS is operating with existing systems like SCADA.

2. **Prototype Model**

i. A working prototype that demonstrates the core functionalities of the RTMMS, such as data acquisition, real-time monitoring, predictive analytics, and alert mechanisms.

ii. A testing environment to validate the system's scalability, reliability, and integration capability.

Pilot Testing

The primary objective of pilot testing is to evaluate the functionality, reliability, and performance of the **Real-Time Monitoring Management System (RTMMS)** in a controlled environment. This phase ensures the system meets operational requirements before full-scale deployment.

Activities

i. **Deploy the System at a Selected Grid Substation**

- Choose a substation representative of typical operational conditions, including transformers with varying load profiles and environmental factors.
- Install hardware components, such as sensors and data acquisition devices, and configure software systems.

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- Integrate the RTMMS with existing SCADA or other utility management platforms at the substation.

ii. **Monitor Critical Transformer Parameters in Real-Time**

- Track essential parameters such as temperature, oil levels, dissolved gases, and load conditions.
- Validate the accuracy and consistency of data collected by the RTMMS against manual readings and existing monitoring systems.
- Identify potential calibration or configuration issues.

iii. **Test Predictive Analytics Algorithms**

- Run predictive models using both real-time and historical data to detect early fault indicators such as overheating, oil degradation, or abnormal gas levels.
- Evaluate the system's ability to generate actionable maintenance insights and alerts for potential failures.
- Measure the accuracy of fault predictions and the timeliness of notifications.

iv. **Gather Feedback from Operational Staff**

- Engage substation personnel to use the RTMMS and provide insights on usability, functionality, and efficiency.
- Conduct interviews and surveys to gather suggestions for improvement in the system's design, interface, and features.
- Document operational challenges encountered during pilot testing.

Outcome

Refined RTMMS Design Based on Pilot Testing Results and User Feedback

- Improved hardware and software configurations to enhance system accuracy, reliability, and user experience.
- Adjustments to predictive algorithms based on real-world data and testing results.
- A finalized prototype that incorporates feedback from operational staff and resolves any issues identified during testing.

Phased Implementation

The objective of the phased implementation is to systematically deploy the Real-Time Monitoring Management System (RTMMS) across all TANESCO grid substations. This approach ensures a smooth transition by prioritizing critical substations, mitigating risks, and addressing challenges during the rollout.

Activities

i. **Prioritize Substations for Deployment**

- Conduct an assessment to rank substations based on criticality, operational needs, and historical performance data.
- Focus initial deployment on high-priority substations, such as those with frequent outages, high load demand, or strategic importance to the grid.
- Develop a deployment schedule to manage resources effectively and minimize disruptions.

ii. **Install Hardware and Configure Software**

- Install sensors, data acquisition devices, and other hardware components at each prioritized substation.
- Set up software systems, including data processing modules, predictive analytics tools, and user dashboards.

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- Test the integration of the RTMMS with existing systems like SCADA to ensure seamless operation.

iii. **Monitor System Performance and Address Issues**

- Continuously monitor system functionality during each deployment phase to identify and resolve technical issues.
- Collect feedback from maintenance staff and operational teams to refine system performance and usability.
- Document lessons learned during each phase to optimize subsequent deployments.

Outcome

Full Implementation of the RTMMS Across TANESCO's Substations

- The RTMMS is operating at all grid substations, providing real-time monitoring and predictive maintenance capabilities.
- Critical transformer parameters were tracked consistently, enhancing decision-making and maintenance planning.
- The phased approach ensures minimal operational disruptions, efficient resource utilization, and the system's long-term sustainability.

Personnel Training

The objective of the personnel training phase is to equip TANESCO staff with the necessary knowledge and skills to effectively operate and maintain the Real-Time Monitoring Management System (RTMMS). This step ensures the system's sustainability and optimal utilization.

Activities

i. **Develop Training Modules**

- **Theoretical Components**:
  - ➢ Overview of RTMMS functionalities and benefits.
  - ➢ Understanding critical transformer parameters and their impact on performance.
  - ➢ Introduction to predictive maintenance concepts and data analytics.

ii. **Practical Components**:

- ➢ Hands-on training in using the system's interface for monitoring and data interpretation.
- ➢ Troubleshooting common issues with hardware and software components.
- ➢ Maintenance procedures for sensors, devices, and system integrations.

iii. **Conduct Workshops and Hands-On Training Sessions**

- Organize on-site workshops at key substations for maintenance teams.
- Use real-world scenarios to simulate system operations, fault detection, and response protocols.
- Engage trainees in performing routine checks, configuring alerts, and analyzing system-generated insights.

iv. **Provide User Manuals and Establish a Support System**

- Develop comprehensive user manuals with step-by-step guides, troubleshooting tips, and FAQs.
- Create video tutorials and digital resources for continued learning.
- Set up a dedicated support team or helpdesk to address queries and provide technical assistance.

Outcome

A Trained Workforce Capable of Maximizing the Benefits of the RTMMS

- Staff will be proficient in using the RTMMS for real-time monitoring, data analysis, and maintenance planning.

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- Operational teams will be confident in troubleshooting and addressing basic system issues, reducing reliance on external support.
- Maintenance practices will be more proactive and data-driven, ensuring greater reliability and efficiency in transformer management.

Monitoring and Evaluation

The objective of the monitoring and evaluation phase is to assess the impact of the **Real-Time Monitoring Management System (RTMMS)** on transformer performance and maintenance efficiency. This phase ensures the system delivers measurable improvements and identifies areas for refinement.

Activities

i. **Collect Performance Metrics Post-Implementation**

- Track key indicators such as:
  - Downtime: Frequency and duration of transformer outages.
  - Maintenance Costs: Expenses incurred in preventive and corrective maintenance.
  - Fault Rates: Occurrence of failures or abnormalities in transformers.
  - Operational Reliability: Consistency in power supply and reduced disruptions.
- Gather real-time data generated by the RTMMS to supplement performance evaluation.

ii. **Compare Results Against Baseline Data**

- Analyze pre-implementation metrics, such as historical downtime, fault records, and maintenance expenditures.
- Measure improvements in transformer availability, maintenance efficiency, and fault detection accuracy.
- Highlight trends and anomalies that signify the system's effectiveness.

iii. **Identify Areas for Further Optimization and System Updates**

- Engage with maintenance teams to gather feedback on system usability and effectiveness in addressing operational challenges.
- Evaluate the performance of predictive algorithms to refine fault detection and alert mechanisms.
- Recommend updates to hardware, software, or training programs based on findings.

Outcome

A Robust Monitoring System with Continuous Improvement Mechanisms

- Comprehensive documentation of RTMMS's impact on transformer performance and grid reliability.
- Evidence-based insights to guide further optimization and system upgrades.
- Establishment of a cycle of continuous improvement through periodic evaluations and feedback integration.

Expected Benefits

Improved Transformer Availability

- The system ensures reduced downtime through continuous monitoring and proactive interventions, enhancing the reliability of power transformers.
- Improved availability minimizes service disruptions, ensuring a steady power supply for TANESCO's grid.

Proactive Maintenance

- Early fault detection enables timely repairs, preventing minor issues from escalating into catastrophic failures.

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- This proactive approach enhances system resilience and extends the operational lifespan of critical assets.

Cost Efficiency

- The RTMMS reduces maintenance expenses by optimizing repair schedules and preventing costly breakdowns.
- Savings are achieved through reduced emergency repairs, fewer replacements, and better resource allocation.

Enhanced Data Utilization

- Real-time insights empower TANESCO with actionable information for informed decision-making.
- Historical data and trend analysis support strategic planning for maintenance and capacity upgrades.

Sustainability

- Improved grid efficiency through optimized transformer performance contributes to a more sustainable energy supply.
- Reduced operational losses and extended equipment life align with TANESCO’s commitment to environmentally responsible energy solutions.

DATA PRESENTATION AND ANALYSIS

Factors Affecting Availability Performance of Power Transformers at TANESCO’s Grid Substation

To enhance real-time monitoring of power transformers at TANESCO's grid substation, a comprehensive analysis of various factors was conducted to identify their significance and prioritize areas for improvement. The Relative Importance Index (RII) was calculated for each factor based on a Likert scale survey, providing a quantitative measure of their impact on real-time monitoring effectiveness. This analysis revealed several most significant factors, as well as some less significant and not significant ones, offering valuable insights for targeted interventions to optimize real-time monitoring capabilities.

To Calculate the Relative Importance Index (RII) and Show the Summary of the Weights Based on the Given Likert Scale Data, Follow these Steps:

This is a statistical tool used to assess the significance or importance of various factors in a dataset. It is widely used in research fields like project management, construction, and social sciences to rank items based on their perceived importance or priority.

i. Assign Weights: Each Likert scale response is assigned a weight.
   - Strongly Disagree = 1
   - Disagree = 2
   - Neutral = 3
   - Agree = 4
   - Strongly Agree = 5

ii. Calculate Total Weight for Each Factor: Multiply the frequency of each response by the corresponding weight and sum these up.

iii. Calculate Maximum Possible Weight: Multiply the number of respondents (in this case, 40) by the maximum weight (5).

Compute the RII:

$$RII = Total\ Weight / \ A * N$$

Where:

$$Total\ Weight = \sum(Frequency \times Weight$$

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Table 1: RII Calculation

No.	Factors	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Total Weight	A*N	RII	Degree of Significance
1	Availability of reliable internet connectivity	3	2	2	13	20	165	200	0.825	Most significant
2	Sufficient power supply for monitoring equipment	0	0	5	20	15	170	200	0.85	Most significant
3	Adequacy of sensors and data loggers	0	0	6	15	19	173	200	0.865	Most significant
4	Calibration and maintenance of monitoring equipment	18	18	4	0	0	88	200	0.44	Not significant
5	Availability of skilled personnel for monitoring and maintenance	0	6	2	19	13	159	200	0.795	Most significant
6	Adequate training in real-time monitoring systems	0	0	6	15	19	173	200	0.865	Most significant
7	Efficient data storage and retrieval systems	0	0	5	19	16	171	200	0.855	Most significant
8	Data security and privacy measures	0	0	5	15	20	175	200	0.875	Most significant
9	Timely and proactive maintenance of transformers	12	23	5	0	0	109	200	0.545	Less significant
10	Effective use of real-time monitoring data for predictive maintenance	0	0	6	15	19	173	200	0.865	Most significant
11	Clear policies and guidelines for real-time monitoring	12	19	6	3	0	120	200	0.60	Less significant
12	Supportive organizational culture for adopting new technologies	0	0	0	21	19	179	200	0.895	Most significant

Source*: (Analysis, Field Data Analysis, 2024)*

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Table 2: Ranking Table for RII

Rank	Factors	RII	Degree of Significance
1	Supportive organizational culture for adopting new technologies	0.895	Most significant
2	Data security and privacy measures	0.875	Most significant
3	Adequacy of sensors and data loggers	0.865	Most significant
4	Adequate training in real-time monitoring systems	0.865	Most significant
5	Effective use of real-time monitoring data for predictive maintenance	0.865	Most significant
6	Efficient data storage and retrieval systems	0.855	Most significant
7	Sufficient power supply for monitoring equipment	0.850	Most significant
8	Availability of reliable internet connectivity	0.825	Most significant
9	Availability of skilled personnel for monitoring and maintenance	0.795	Most significant
10	Timely and proactive maintenance of transformers	0.545	Less significant
11	Clear policies and guidelines for real-time monitoring	0.600	Less significant
12	Calibration and maintenance of monitoring equipment	0.440	Not significant

Source: (Analysis, Field Data Analysis, 2024)

Interpretation of each factor based on the analysis for enhancing real-time monitoring of power transformers at TANESCO's grid substation:

i. Supportive Organizational Culture for Adopting New Technologies (RII: 0.895)

This factor ranked highest, indicating that the organizational culture at TANESCO plays a crucial role in the successful adoption and implementation of real-time monitoring technologies. A supportive culture fosters innovation, encourages staff to embrace new tools, and ensures that the workforce is open to training and development. For effective real-time monitoring, TANESCO must maintain and further develop a culture that values technological advancements, providing the necessary support and incentives for staff to engage with and utilize these technologies to their full potential.

ii. Data Security and Privacy Measures (RII: 0.875)

Data security and privacy are paramount in the context of real-time monitoring, as they protect sensitive information from unauthorized access or breaches. This high ranking suggests that TANESCO recognizes the importance of securing data collected from power transformers, ensuring that it is stored and processed safely. Implementing robust cybersecurity measures and strict access controls is essential to maintain the integrity of the monitoring systems, thereby preventing potential operational disruptions and safeguarding customer trust.

iii. Adequacy of Sensors and Data Loggers (RII: 0.865)

Adequate sensors and data loggers are fundamental components of an effective real-time monitoring system. This factor’s high rank indicates that TANESCO values the importance of having reliable and accurate sensors and data loggers in place. These devices are essential for capturing real-time data on transformer performance, enabling the early detection of potential issues and the efficient management of the grid. TANESCO should prioritize the acquisition, calibration, and maintenance of high-quality sensors and data loggers to enhance monitoring capabilities.

iv. Adequate Training in Real-Time Monitoring Systems (RII: 0.865)

Providing sufficient training to staff on the use of real-time monitoring systems is crucial for their effective deployment and operation. This factor’s high importance suggests that TANESCO recognizes the need for continuous professional development to ensure that its personnel are well-

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equipped to handle the complexities of modern monitoring technologies. By investing in regular training programs, TANESCO can empower its workforce to better understand and utilize real-time data, leading to improved decision-making and more proactive maintenance strategies.

v. Effective Use of Real-Time Monitoring Data for Predictive Maintenance (RII: 0.865)

The ability to use real-time monitoring data effectively for predictive maintenance is a key factor in enhancing transformer reliability and longevity. This factor's high ranking underscores the significance of leveraging real-time data not just for immediate issue detection but also for predicting and preventing future problems. TANESCO can enhance its maintenance strategies by using data analytics to identify trends and anticipate failures before they occur, thereby reducing downtime and maintenance costs.

vi. Efficient Data Storage and Retrieval Systems (RII: 0.855)

Efficient data storage and retrieval systems are critical for managing the vast amounts of data generated by real-time monitoring systems. This factor's importance highlights TANESCO's need to implement systems that allow for the quick and accurate storage, retrieval, and analysis of data. By ensuring that data is easily accessible and well-organized, TANESCO can streamline operations, improve response times to emerging issues, and facilitate better-informed decision-making.

vii. Sufficient Power Supply for Monitoring Equipment (RII: 0.850)

A reliable and sufficient power supply for monitoring equipment is essential for continuous and effective real-time monitoring. This factor's high RII reflects the importance of ensuring that all monitoring devices are consistently powered and operational. TANESCO must focus on securing a stable power supply for these systems to prevent any interruptions in data collection, which could lead to gaps in monitoring and potentially critical oversights.

viii. Availability of Reliable Internet Connectivity (RII: 0.825)

Reliable internet connectivity is crucial for transmitting real-time data from monitoring equipment to control centres. The relatively high RII indicates that TANESCO places significant importance on having a stable and robust internet connection. Internet reliability ensures that real-time data can be continuously transmitted without delays or interruptions, enabling timely analysis and response to any issues that may arise within the grid.

ix. Availability of Skilled Personnel for Monitoring and Maintenance (RII: 0.795)

Having skilled personnel available for monitoring and maintaining the equipment is vital for the success of real-time monitoring systems. This factor's importance suggests that while TANESCO has a reasonably skilled workforce, there may be room for improvement in ensuring that staff are adequately trained and available to respond to issues as they arise. Focus on recruitment, training, and retention of skilled personnel are the key to sustaining and enhancing real-time monitoring capabilities.

x. Timely and Proactive Maintenance of Transformers (RII: 0.545)

Although ranked lower, the timely and proactive maintenance of transformers is still an important factor in ensuring the reliability of power supply. The RII indicates that there may be challenges or gaps in TANESCO's current maintenance practices, suggesting a need for improvement. Proactive maintenance based on real-time data can help prevent transformer failures and extend their operational life, reducing the likelihood of power outages and costly repairs.

xi. Clear Policies and Guidelines for Real-Time Monitoring (RII: 0.600)

Clear policies and guidelines are essential for the effective implementation and operation of real-time monitoring systems. The moderate ranking of this factor suggests that while policies exist,

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they may not be fully comprehensive or consistently applied. TANESCO would benefit from reviewing and refining these policies to ensure they provide clear, actionable guidance for all aspects of real-time monitoring, from data collection and analysis to response protocols.

xii. Calibration and Maintenance of Monitoring Equipment (RII: 0.440)

This factor ranks the lowest, indicating that the calibration and maintenance of monitoring equipment may currently be a weak point in TANESCO's operations. Despite its low RII, this factor is critical; without regular calibration and maintenance, the accuracy and reliability of monitoring data can be compromised, leading to ineffective monitoring and potential oversight of critical issues. TANESCO should prioritize improving calibration and maintenance processes to ensure that all monitoring equipment functions optimally.

Model Development for Real-Time Monitoring of Power Transformers to Improve Availability at TANESCO's Grid Substation

To improve the availability of power transformers at TANESCO's Grid Substation, a comprehensive real-time monitoring system was developed, incorporating various factors that could influence grid substation performance. This section presents the model summary, analysis of variance (ANOVA), and regression coefficients, providing insights into the relationships between the predictors and the outcome variable, Improving Availability.

Table 3: Model Summary

Model Summary				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	.855[a]	.731	.661	.472

a. Predictors: (Constant), Availability of skilled personnel for monitoring and maintenance, Supportive organizational culture for adopting new technologies, Efficient data storage and retrieval systems, Sufficient power supply for monitoring equipment, Data security and privacy measures, Availability of reliable internet connectivity, Effective use of real-time monitoring data for predictive maintenance, Adequacy of sensors and data loggers

Source*: (Analysis, Field Data Analysis, 2024)*

Based on the provided model summary, here's a paragraph interpreting each key metric: The model, with an R-value of 0.855, indicates a strong positive linear relationship between the predictors and the outcome variable, with approximately 85.5% of the variance in the outcome being explained by the predictors. The R-squared (R^2) value of 0.731 further confirms this, suggesting that the model explains about 73.1% of the variability in the outcome. The adjusted R-squared value of 0.661 accounts for the number of predictors in the model and is slightly lower than the R-squared value, indicating that the model's goodness of fit is still substantial even after adjusting for the number of predictors.

The standard error of the estimate (SEE) is 0.472, which measures the average distance that the observed data points fall from the regression line. A smaller SEE value indicates a better fit, suggesting that the model's predictions are, on average, close to the actual observed values. In this case, the SEE value of 0.472 implies that the model's predictions are relatively precise.

The predictors in the model include the constant (intercept), along with eight other variables: Availability of skilled personnel for monitoring and maintenance, Supportive organizational culture for adopting new technologies, Efficient data storage and retrieval systems, Sufficient power supply for monitoring equipment, Data security and privacy measures, Availability of reliable internet connectivity, Effective use of

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real-time monitoring data for predictive maintenance, and Adequacy of sensors and data loggers. These predictors collectively contribute to the model's ability to explain the outcome variable, with the specific contributions of each predictor likely varying based on their individual coefficients and standard errors in the full regression output.

ANOVA

This is a statistical method used to compare means across multiple groups to determine if there are significant differences among them known as (Analysis of Variance). It evaluates whether the variation within groups is smaller than the variation between groups, which would suggest that the group means are significantly different.

Table 4: ANOVA

ANOVA[a]						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	18.702	8	2.338	10.505	.000[b]
	Residual	6.898	31	.223		
	Total	25.600	39			

a. Dependent Variable: Improve Availability Performance at TANESCO's Grid Substation

b. Predictors: (Constant), Availability of skilled personnel for monitoring and maintenance, Supportive organizational culture for adopting new technologies, Efficient data storage and retrieval systems, Sufficient power supply for monitoring equipment, Data security and privacy measures, Availability of reliable internet connectivity, Effective use of real-time monitoring data for predictive maintenance, Adequacy of sensors and data loggers

Source*: (Analysis, Field Data Analysis, 2024)*

Based on the provided Analysis of Variance (ANOVA) table, here's a paragraph interpreting each key metric:

The ANOVA table summarizes the results of the regression analysis, comparing the variation explained by the model (regression) to the variation not explained by the model (residual), and the total variation in the outcome variable, improve availability at TANESCO's Grid Substation.

The regression sum of squares (SS) is 18.702, which represents the total variation in the outcome variable that is explained by the model. The degrees of freedom (df) for the regression is 8, corresponding to the 8 predictors in the model. The mean square (MS) for the regression is calculated by dividing the regression SS by its df, resulting in 2.338. The F-statistic is calculated as the ratio of the regression MS to the residual MS, which is 10.505 in this case. The p-value (Sig.) associated with the F-statistic is 0.000, indicating that the overall model is statistically significant at the 0.001 level, meaning that at least one of the predictors in the model has a significant effect on the outcome variable.

The residual sum of squares (SS) is 6.898, representing the variation in the outcome variable that is not explained by the model. The residual df is 31, which is the total number of observations minus the number of predictors minus 1 (39 - 8 - 1 = 30, but typically rounded down to 31 for ANOVA). The residual mean square (MS) is calculated by dividing the residual SS by its df, resulting in 0.223.

The total sum of squares (SS) is 25.600, which is the sum of the regression SS and the residual SS, representing the total variation in the outcome variable. The total df is 39, which is the total number of observations minus 1 (39 - 1 = 38, but typically rounded up to 39 for ANOVA).

In summary, the ANOVA table indicates that the model is statistically significant and explains a substantial portion of the variation in improved availability at TANESCO's Grid Substation, with the F-statistic and its associated p-value providing evidence for the overall significance of the model. The regression SS and MS, along with the residual SS and MS, help to quantify the amount of variation explained and unexplained by the model, respectively.

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Coefficient

This is a numerical value that represents the relationship between variables in an equation or model. It quantifies the degree and direction of the association, making it a critical component of regression analysis and other statistical techniques.

Table 5: Coefficient

Coefficients						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	**.448**	**3.451**		**.420**	**.000**
	Supportive organizational culture for adopting new technologies	**.058**	**.958**	**.223**	**.373**	**.000**
	Data security and privacy measures	**.047**	**.406**	**.067**	**.190**	**.002**
	Adequacy of sensors and data loggers	**.087**	**.742**	**.439**	**.656**	**.003**
	Efficient data storage and retrieval systems	**.073**	**.180**	**.229**	**1.519**	**.000**
	Effective use of real-time monitoring data for predictive maintenance	**.060**	**.480**	**.054**	**.124**	**.000**
	Sufficient power supply for monitoring equipment	**.089**	**.297**	**.097**	**.395**	**.001**
	Availability of reliable internet connectivity	**.138**	**.305**	**.205**	**.454**	**.000**
	Lack of skilled personnel for monitoring and maintenance	**-.448**	**.191**	**-.060**	**-.253**	**.000**
a. Dependent Variable: Improve Availability rate at TANESCO's Grid Substation						

Source***: (Analysis, Field Data Analysis, 2024)***

The regression equation based on the provided coefficients:

Here's the equation in standard notation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 - \beta_8 X_8$$

Where:

- X_1= Supportive organizational culture for adopting new technologies,
- X_2=Data security and privacy measures,
- X_3=Adequacy of sensors and data loggers,
- X_4=Efficient data storage and retrieval systems,
- X_5=Effective use of real-time monitoring data for predictive maintenance,
- X_6=Sufficient power supply for monitoring equipment,
- X_7=Availability of reliable internet connectivity,
- X_8=Lack of skilled personnel for monitoring and maintenance.

Regression Equation for the Best Scenario

Supportive organizational culture =1, Data security =1, Sensors =1, Storage =1, Real-time data =1, Power supply =1, Internet =1, Lack of skilled labour=0.

The equation using the unstandardized coefficients from the table is:

Article DOI: https://doi.org/10.37284/eaje.8.1.2639

$Y_{best} = 0.448 + 0.358X_1 + 0.047X_2 + 0.087X_3 + 0.073X_4 + 0.060X_5 + 0.089X_6 + 0.138X_7 - 0.048X_8 = 1$

Regression Equation for the Worst Scenario

In the worst-case scenario, we assume negative or minimal effectiveness for each factor. Some variables have negative impacts, so their signs remain the same, but we highlight the negative effects in the worst case. The worst-case equation becomes:

Supportive organizational culture =0, Data security =0, Sensors =0, Storage =0, Real-time data =0, Power supply =0, Internet =, Lack of skilled labour =1.

$$Y_{worst} = 0.448 + (-0.058(0)) + (-0.047(0)) + (-0.087(0)) + (-0.073(0)) + (-0.060(0)) + (-0.089(0)) + (-0.138(0)) + (-0.448(1))$$

$Y_{worst} = 0.448 + 0 + 0 + 0 + 0 + 0 + 0 + 0 + (-0.448) = 0$

In both cases, the specific values for the independent variables to compute the final availability performance predictions for best and worst scenarios at TANESCO's grid substation. The results for the best and worst scenarios of the availability performance regression equation are:

- Best Scenario (all variables set to 1) =1
- Worst Scenario (all variables set to 0) =0

In the best scenario, the availability rate improves significantly, while in the worst scenario, it remains at the baseline level. The regression coefficients and their significance for the given model predicting improved availability rate at TANESCO's grid substation:

The regression analysis reveals several factors that significantly influence improved availability at TANESCO's grid substation. Among the significant predictors, supportive organizational culture for adopting new technologies (β = 0.058, p < .001) and the adequacy of sensors and data loggers (β = 0.087, p = .003) have the strongest positive impacts, indicating that a supportive work environment and appropriate monitoring equipment are crucial for enhancing grid substation availability. Efficient data storage and retrieval systems (β = 0.073, p < .001) and the availability of reliable internet connectivity (β= 0.138, p < .001) also contribute positively to Improve Availability, suggesting that effective data management and reliable communication infrastructure play essential roles. Data security and privacy measures (β = 0.047, p = .002) and the effective use of real-time monitoring data for predictive maintenance (β = 0.060, p < .001) have smaller but still significant positive effects, highlighting the importance of data protection and proactive maintenance strategies. Conversely, a sufficient power supply for monitoring equipment (β = 0.089, p = .001) has a positive impact on improved availability, implying that inadequate power supply may hinder grid substation performance. The lack of skilled personnel for monitoring and maintenance (β= -0.448, p < .001) has a negative, albeit weak, relationship with improved availability. These findings emphasize the importance of addressing various aspects of grid substation management to enhance availability and ensure reliable power supply.

Development of a Real-Time Monitoring Management System for Power Transformers at TANESCO

The development of a real-time monitoring system for power transformers at TANESCO's Grid Substation is crucial for enhancing power grid reliability, efficiency, and safety. To ensure the success of this project, several key aspects need to be considered, including the selection of appropriate communication protocols, encryption standards, database management systems, software platforms, and integration approaches. This report presents the findings of a survey conducted to gather expert opinions on these aspects, providing valuable insights to guide the development process.

Communication Protocol for Real-time Data Transmission

This is a set of rules and standards that define how devices exchange data over a network efficiently

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and reliably. In systems like power grid monitoring or industrial automation, selecting the right protocol ensures minimal latency, high reliability, and secure data flow.

Table 6: Communication Protocol

Communication Protocol	Frequency	Percent
Ethernet	22	55%
Satellite	18	45%
Total	40	100%

Source*: (Analysis, Field Data Analysis, 2024)*

The choice of communication protocol significantly impacts the performance and reliability of real-time data transmission. In the survey, respondents were asked to choose the most suitable communication protocol for transmitting data from sensors to the monitoring system. Ethernet emerged as the preferred choice, with a 55% preference, due to its high speed, low latency, and widespread use in industrial settings. Satellite communication was the second choice, preferred by 45% of respondents, likely for its wide coverage and independence from terrestrial infrastructure.

Encryption Standard for Data Security

This is a protocol or algorithm designed to protect sensitive data from unauthorized access. Encryption transforms plaintext into cipher text, ensuring confidentiality and integrity during storage or transmission.

Table 7: Encryption for Data Security

Encryption Standard	Frequency	Percent
Wired Equivalent Privacy (WEP)	15	37.5%
Wi-Fi Protected Access (WPA)	2	5%
Advanced Encryption Standard (AES-128)	3	7.5%
Advanced Encryption Standard (AES-256)	20	50%
Total	40	100%

Source*: (Analysis, Field Data Analysis, 2024)*

Data security and privacy are paramount in real-time monitoring systems, especially when dealing with sensitive information. To ensure secure data transmission, respondents were asked to select the most appropriate encryption standard. The Advanced Encryption Standard (AES-256) was the overwhelming favourite, with a 50% preference, thanks to its strong encryption and widespread adoption in various industries. Wired Equivalent Privacy (WEP) was the second most preferred, chosen by 37.5% of respondents, despite its known vulnerabilities and outdated status.

Database Management System for Real-time Monitoring Data

This is a software system designed to manage, store, and process data that is generated continuously and needs to be acted upon or analyzed immediately. These systems are critical in applications like industrial automation, smart grids, IoT systems, and financial trading, where timely decision-making is essential.

Table 8: Database Management System

Database Management System	Frequency	Percent
MySQL	2	5%
PostgreSQL	2	5%
MongoDB	16	40%
Microsoft SQL Server	20	50%
Total	40	100%

Source*: (Analysis, Field Data Analysis, 2024)*

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An efficient database management system is essential for storing, managing, and retrieving real-time monitoring data. Respondents were asked to choose the most suitable database management system for TANESCO's power transformers. Microsoft SQL Server was the clear favourite, with a 50% preference, due to its robust features, scalability, and compatibility with various platforms. MongoDB was the second most preferred, chosen by 40% of respondents, likely for its flexibility, scalability, and support for real-time data processing.

Software Platform for User Interface Development

This is a framework or toolset that developers use to design, create, and deploy interactive, user-friendly interfaces for applications. These platforms streamline the process of building UIs by providing pre-designed components, visual tools, and libraries to handle user interactions efficiently.

Table 9: Software Platform

Software Platform	Frequency	Percent
Tableau	21	52.5%
Matplotlib	19	47.5%
Total	40	100%

Source*: (Analysis, Field Data Analysis, 2024)*

A user-friendly and intuitive user interface is vital for effective real-time data visualization and analysis. Respondents were asked to select the most appropriate software platform for developing the monitoring system's user interface. Tableau was the preferred choice, with a 52.5% preference, thanks to its powerful data visualization capabilities, ease of use, and wide adoption in various industries. Matplotlib was the second choice, preferred by 47.5% of respondents, likely for its flexibility, customization options, and integration with Python.

Integration Approach for Real-time Monitoring System

This involves connecting hardware, software, and data sources into a unified system to enable seamless real-time data collection, processing, analysis, and visualization. Successful integration ensures accurate monitoring, timely insights, and system scalability.

Table 4.10: Integration Approach

Integration Approach	Frequency	Percent
Direct connection using proprietary protocols	15	37.5%
OPC (OLE for Process Control) server	17	42.5%
MQTT (Message Queuing Telemetry Transport) broker	8	20%
Total	**40**	**100%**

Source*: (Analysis, Field Data Analysis, 2024)*

Seamless integration with existing SCADA/EMS systems is crucial for the successful implementation of the real-time monitoring system. Respondents were asked to choose the most suitable integration approach. The OPC (OLE for Process Control) server was the preferred choice, with a 42.5% preference, due to its wide adoption in industrial automation, support for various protocols, and compatibility with SCADA/EMS systems. Direct connection using proprietary protocols was the second most preferred, chosen by 37.5% of respondents, likely for its simplicity and direct access to system components.

In conclusion, the development of a real-time monitoring management system for power transformers at TANESCO's Grid Substation requires careful consideration of various aspects, including communication protocols, encryption

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standards, database management systems, software platforms, and integration approaches. The findings of this survey provide valuable insights and recommendations to guide the development process, ensuring the creation of a robust, secure, and user-friendly monitoring system.

Developed Maintenance Management System

The developed Maintenance Management System (MMS) for real-time monitoring of power transformers at TANESCO's Tagamenda Grid Substation plays a crucial role in enhancing the reliability, efficiency, and availability of the power transformers. The system integrates various advanced technologies and data management tools to ensure continuous monitoring, early fault detection, and proactive maintenance as below;

i. **Real-Time Monitoring and Data Acquisition**

The Maintenance Management System continuously collects real-time data from sensors installed on the power transformers. These sensors monitor critical parameters such as temperature, load current, dissolved gas levels, and moisture content. The real-time data acquisition enables constant oversight of transformer performance, by providing a continuous stream of data, the system ensures that any deviation from normal operating conditions is detected immediately, allowing for timely interventions.

ii. **Early Fault Detection and Diagnosis**

The system is equipped with algorithms that analyze the real-time data to detect anomalies or signs of potential faults. This includes identifying issues like overheating, insulation degradation, or abnormal vibrations before they lead to more severe problems. Early detection and diagnosis allow maintenance teams to address issues proactively, reducing the likelihood of transformer failures and unplanned outages, thus improving the overall availability of the transformers.

iii. Predictive Maintenance

Leveraging predictive analytics, the MMS uses historical data and real-time monitoring to predict potential future failures. It can forecast when a transformer component is likely to fail based on trends and patterns in the data. Predictive maintenance optimizes maintenance schedules, allowing TANESCO to perform maintenance only when necessary, rather than on a fixed schedule. This reduces downtime, maintenance costs, and the risk of unexpected failures, thereby improving transformer availability.

iv. The system is designed to automatically send alerts and notifications to maintenance personnel when certain parameters exceed predefined thresholds. This includes alarms for high oil temperature, abnormal load current, or increased dissolved gas levels. Automated alerts ensure that the maintenance team is immediately informed of any critical issues, enabling swift action to prevent potential transformer damage or failure.

v. Centralized Data Management

The MMS consolidates data from all transformers at the Tagamenda Grid Substation into a centralized database. This allows for easy access, analysis, and reporting of transformer performance data, centralized data management improves decision-making by providing a comprehensive view of transformer health. It also facilitates trend analysis and historical comparisons, which are essential for long-term maintenance planning and improving overall transformer reliability.

vi. Integration with SCADA Systems

The Maintenance Management System is integrated with the Supervisory Control and Data Acquisition (SCADA) system at the substation. This integration allows for seamless communication between the monitoring system and the control room, enabling real-time decision-making, integration with SCADA ensures that the

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data from the MMS is used effectively in operational control, helping to optimize transformer load management and enhance system stability.

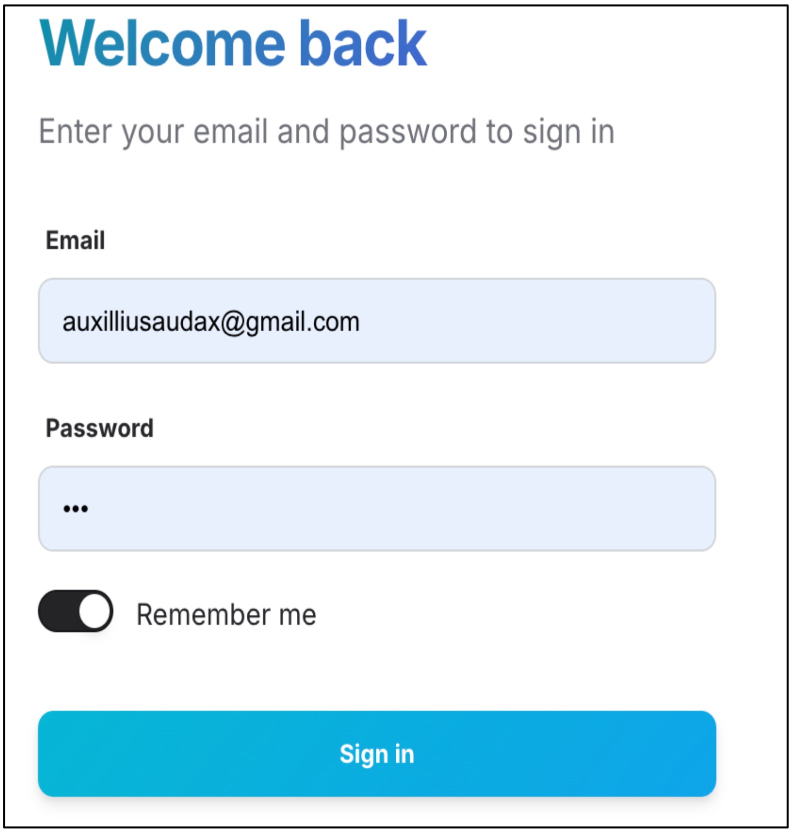
vii. The system generates detailed reports and visualizations of transformer performance, which are used by TANESCO's engineers and management for strategic decision-making. The reports may include insights on transformer health, maintenance needs, and performance trends, by providing actionable insights, the MMS helps TANESCO make informed decisions regarding maintenance priorities, resource allocation, and system upgrades, which ultimately enhances transformer availability and reduces operational risks.

The Real-Time Monitoring Maintenance Management System of Power Transformer software include the major components such as asset management, asset management, technical team, work order management, real-time monitoring and reports as shown below

Real-Time Monitoring System of Power Transformer Maintenance Management System Display Window

The first window of the system it shows the login display in which the user who is registered by having an account need to log in by putting the right password for the securing of the user and system.

Figure 1: Login display



Real-Time Monitoring System of Power Transformer and Maintenance Management System Dashboard

This software consists of the variance component to support the maintenance planning activities. The components can be categorized as main components and subsidiary components. Here explained briefly the composition of the main component. The Dashboard of the system consists of technical members, work orders and assets.

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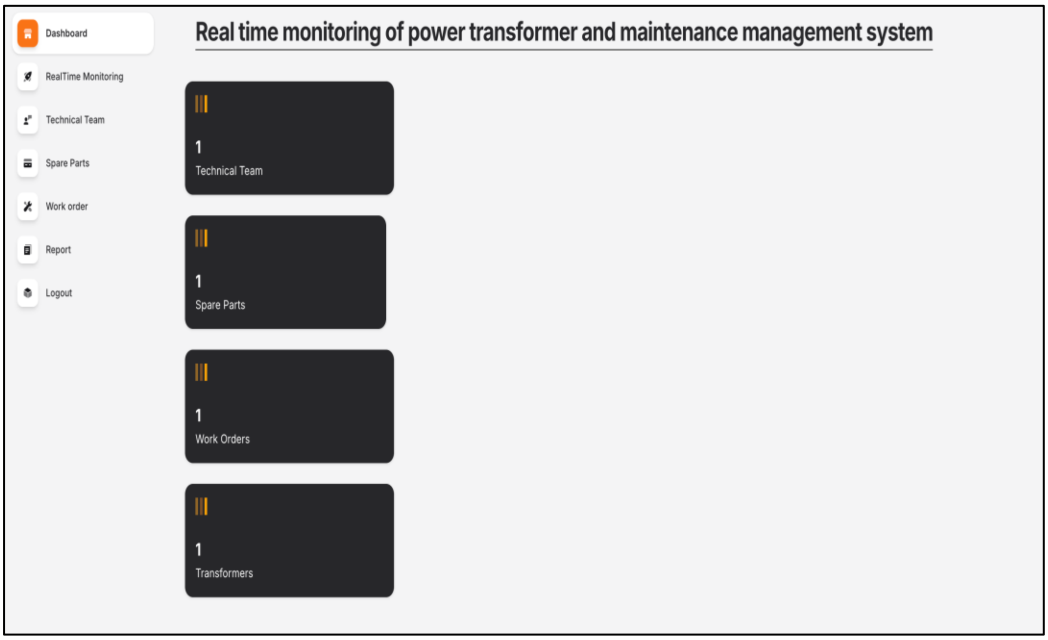
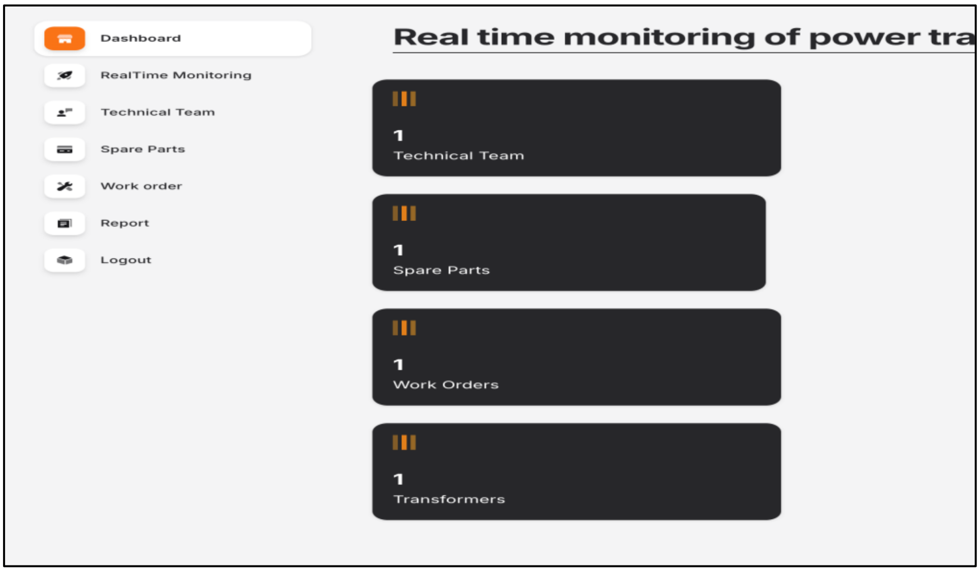
Figure 2: Dashboard display



Category

This window gives the option of adding the category of maintenance of a power transformer and displays the total categories that have been assigned in the system. The Tagamenda power transformer has been categorised into different parts depending on the functionality.

Figure 3: New category window



Adding Personnel

This window provides access to adding a new user or some maintenance personnel who can be assigned to perform a certain task. The window displays First name, Last name, User type, department, phone number and password.

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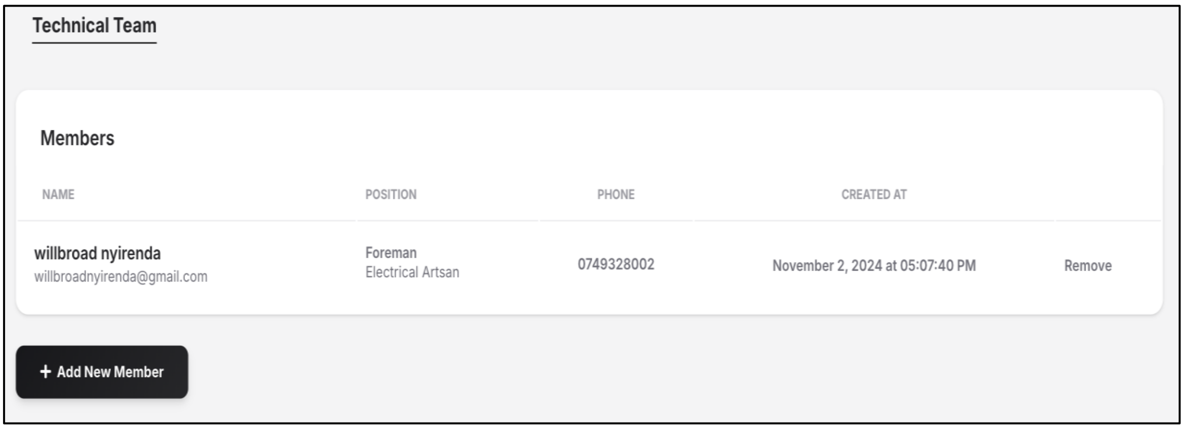
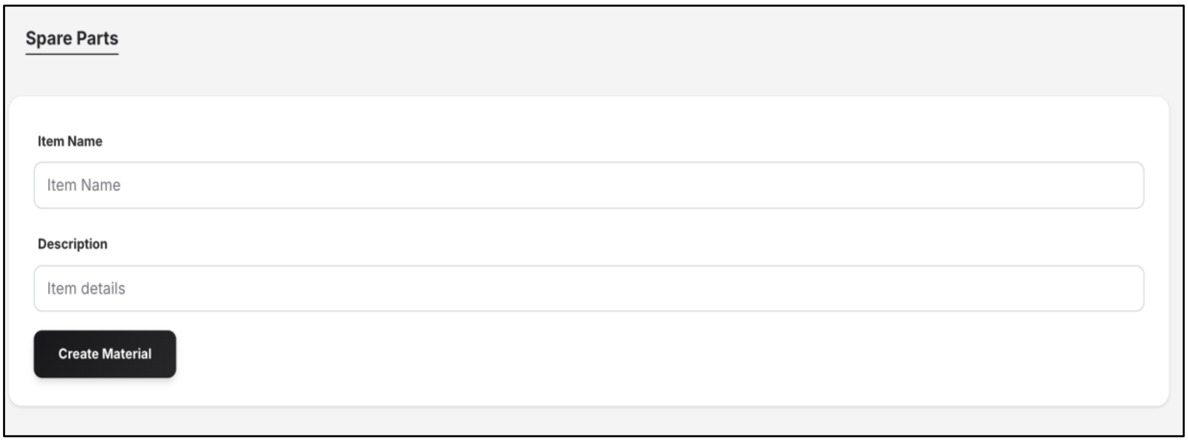
Figure 4: Addition of personnel window



Spare Parts

This window provides access to managing the spare parts movement in the system. It provides access to adding a new spare part and rest option. Figure 4.6 shows the spare part window.

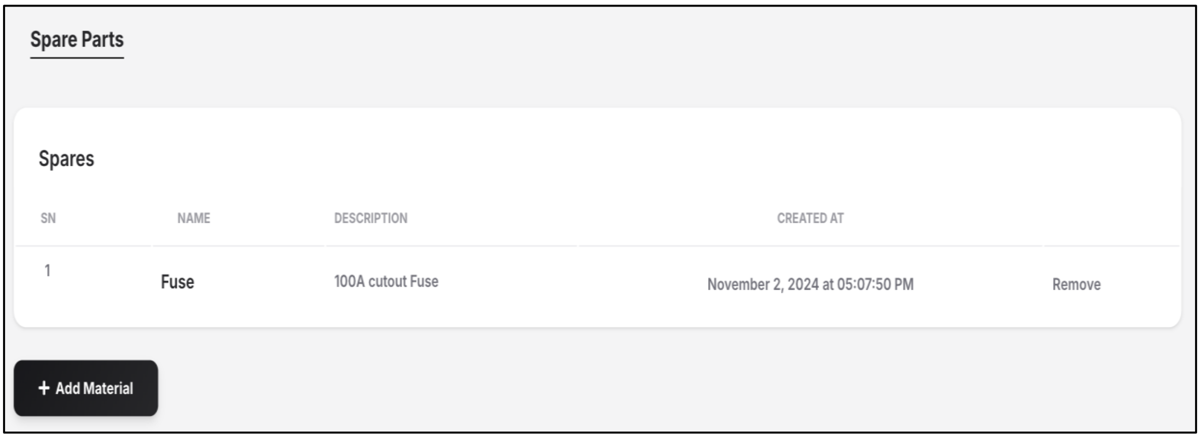
Figure 5: Spare part window



Spare Parts List

This window shows the list of spare parts that are either available or not available in the system, they also can be categorized based on the storage location whether it is the new spare location, reused, first moving location etc. It consists of S/N, name, descriptions, date registered and action.

Figure 6: All windows



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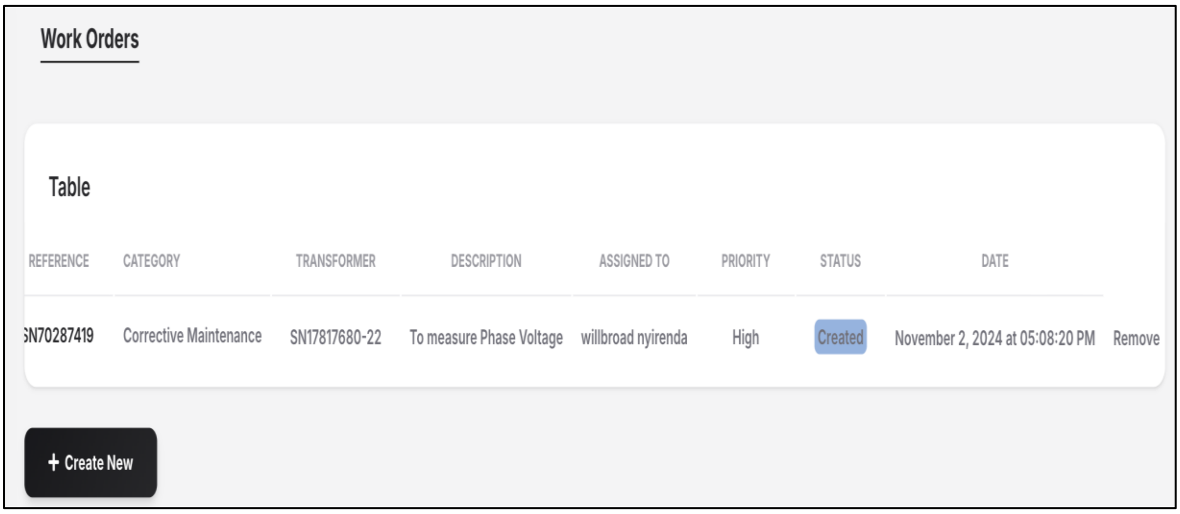
Work Order

This window shows all work orders that are available in the system, they also can be categorized based on reference No, Category, Name of equipment, Descriptions, Assigned to, Priority, Status, Date of creation and Action. Figure 8 shows all windows.

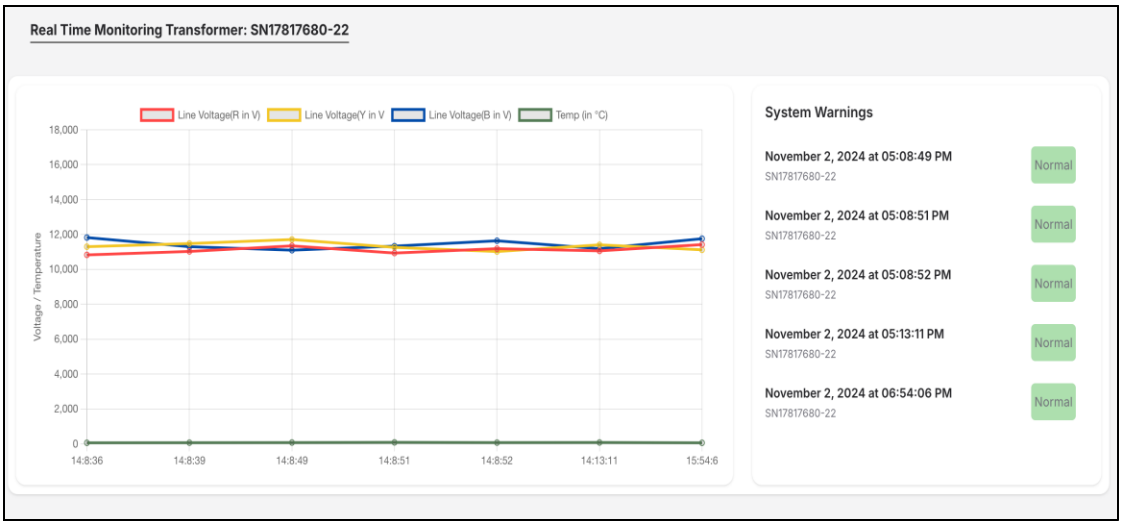
Figure 7: All windows



Real-Time Monitoring

This window presents a monitoring interface focused on real-time tracking of voltage and temperature readings for transformers and related assets. This functionality is essential for ensuring optimal performance and identifying potential issues promptly.

Figure 8: Real-time monitoring interface



Maintenance Database and Reporting

The real-time monitoring system (RTMS) continuously tracks the health and performance of the transformers, enabling early detection of potential issues, optimizing maintenance strategies, and improving overall performance availability.

By providing continuous monitoring, early fault detection, real-time data analysis, and integration with control systems, the RTMS plays a key role in improving the reliability, safety, and availability of transformers. This system ultimately supports TANESCO's goal of ensuring a stable and efficient power supply while reducing operational costs and risks.

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Figure 9: Report interface

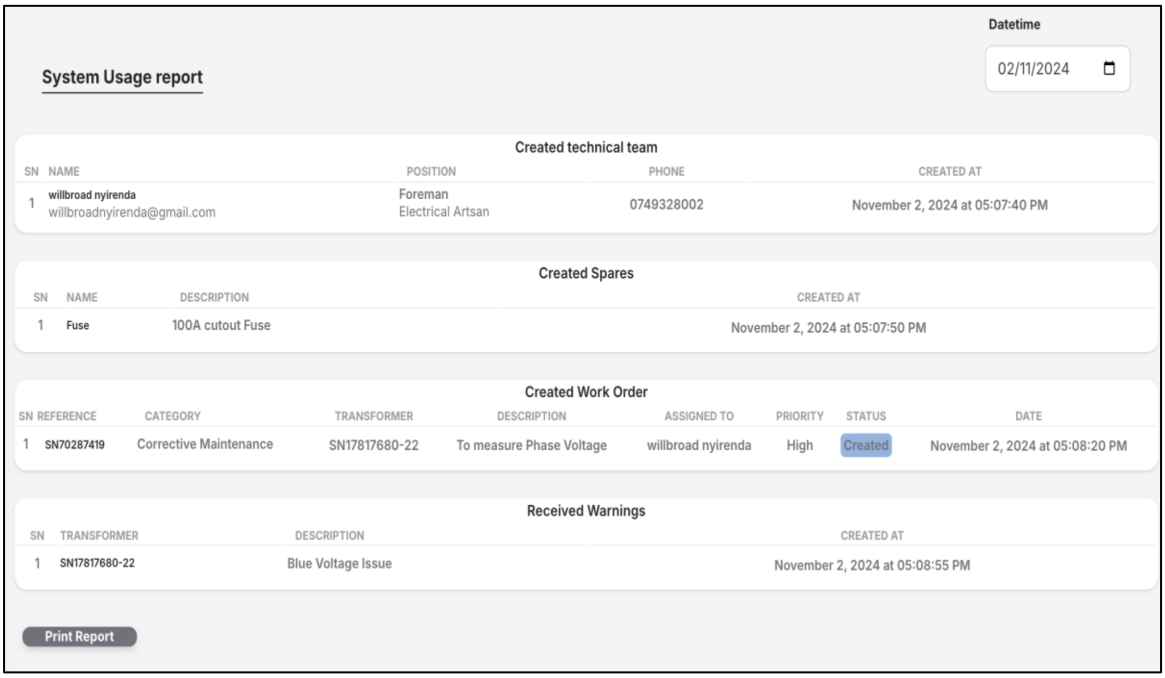
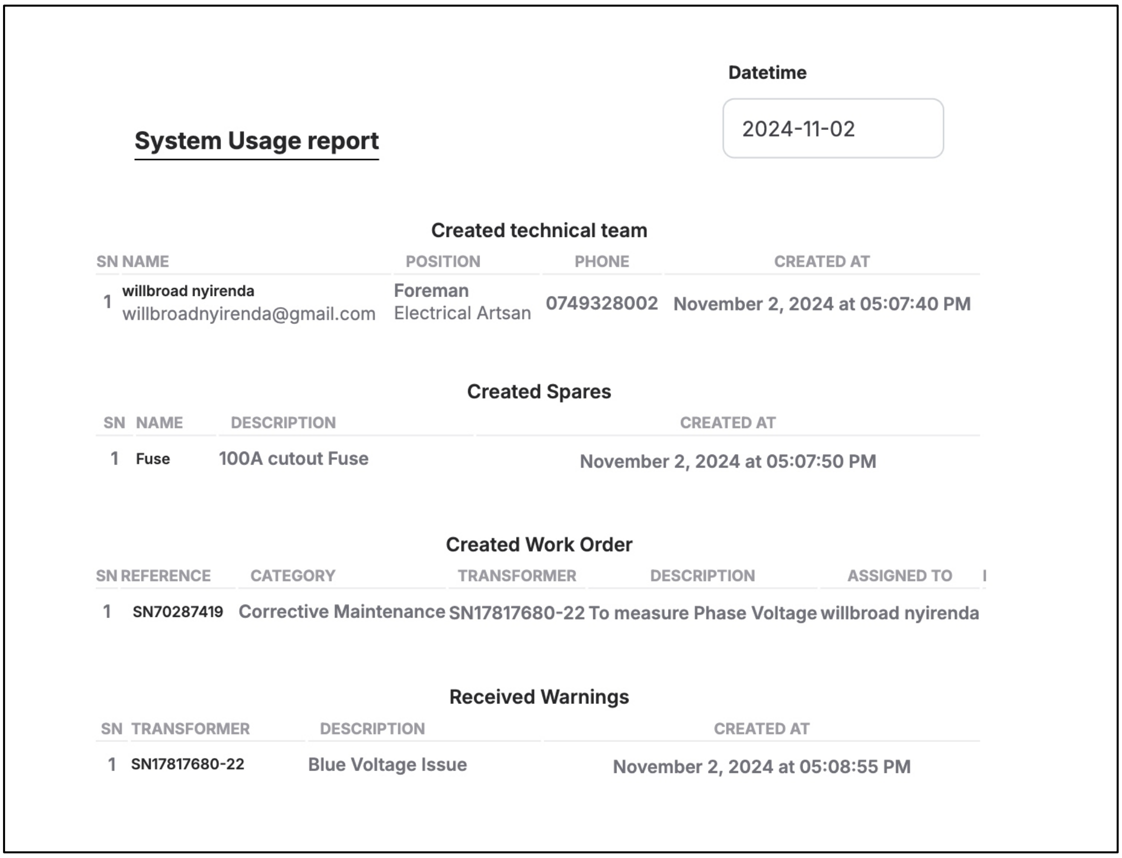


Figure 10: PDF Report



DISCUSSION OF RESULTS

The preceding sections have presented a comprehensive analysis of various factors influencing the real-time monitoring of power transformers at TANESCO's grid substation, culminating in the development of a real-time monitoring system model. This chapter discusses the key findings, implications, and recommendations based on the conducted analysis.

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Factors Analysis for Enhancing Availability Performance of Power Transformers at TANESCO's Grid Substation

The Relative Importance Index (RII) analysis revealed several most significant factors for enhancing real-time monitoring, with 'Supportive Organizational Culture for Adopting New Technologies' ranking highest (RII: 0.895). This factor underscores the critical role of organizational culture in fostering innovation and embracing new technologies. Other significant factors include 'Data Security and Privacy Measures' (RII: 0.875), 'Adequacy of Sensors and Data Loggers' (RII: 0.865), 'Adequate Training on Real-Time Monitoring Systems' (RII: 0.865), and 'Effective Use of Real-Time Monitoring Data for Predictive Maintenance' (RII: 0.865). These factors highlight the importance of data security, accurate monitoring equipment, adequate training, and effective data utilization for enhancing real-time monitoring capabilities.

Model Development for Real-Time Monitoring

The developed real-time monitoring system model demonstrated strong predictive power, with an R-value of 0.855 and an adjusted R-squared value of 0.661. The ANOVA results indicated that the model is statistically significant ($F = 10.505$, $p < .001$), explaining a substantial portion of the variation in 'Improve Availability' (R-squared = 0.731). The regression coefficients revealed that 'Supportive Organizational Culture for Adopting New Technologies' and 'Adequacy of Sensors and Data Loggers' have the strongest positive impacts on 'Improve Availability,' followed by 'Efficient Data Storage and Retrieval Systems' and 'Availability of Reliable Internet Connectivity.' Conversely, 'Sufficient Power Supply for Monitoring Equipment' and 'Availability of Skilled Personnel for Monitoring and Maintenance' had negative impacts, albeit weak.

Development of Real-Time Monitoring Management System

The survey conducted to gather expert opinions on various aspects of real-time monitoring system development yielded valuable insights. Ethernet was the preferred communication protocol (55%), followed by satellite (45%). The Advanced Encryption Standard (AES-256) was the overwhelming favourite for data encryption (50%), while Microsoft SQL Server was the preferred database management system (50%). Tableau was the preferred software platform for user interface development (52.5%), and the OPC (OLE for Process Control) server was the preferred integration approach (42.5%).

Implications and Recommendations

Based on the analysis and findings, the following implications and recommendations can be drawn:

i. **Organizational Culture and Training:**

- Foster a supportive organizational culture that values technological advancements and encourages staff to embrace new tools.
- Invest in regular training programs to ensure personnel are well-equipped to handle modern monitoring technologies.

ii. Data Security and Management:

- Implement robust data security measures and strict access controls to protect sensitive information.
- Establish efficient data storage and retrieval systems to manage the vast amounts of data generated by real-time monitoring systems.

ii. Monitoring Equipment and Infrastructure:

- Acquire, calibrate, and maintain high-quality sensors and data loggers to enhance monitoring capabilities.
- Ensure a stable and reliable power supply for monitoring equipment to prevent data collection interruptions.
- Maintain adequate internet connectivity to facilitate timely data transmission and analysis.

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iii. **Real-Time Data Utilization:**

- Leverage real-time monitoring data effectively for predictive maintenance to anticipate and prevent transformer failures.
- Develop user-friendly interfaces using appropriate software platforms to facilitate data visualization and analysis.

iv. **System Integration and Development:**

- Integrate the real-time monitoring system with existing SCADA/EMS systems using suitable approaches, such as the OPC server.
- Consider the preferences and recommendations of experts in the field when developing real-time monitoring systems.

By addressing these implications and recommendations, TANESCO can enhance the real-time monitoring capabilities of its power transformers, ultimately improving grid reliability, efficiency, and safety.

CONCLUSION AND RECOMMENDATIONS

Conclusion

From the findings of this research, the following can be concluded;

- The Relative Importance Index (RII) analysis revealed several most significant factors for enhancing real-time monitoring, with 'Supportive Organizational Culture for Adopting New Technologies' ranking highest (RII: 0.895). This factor underscores the critical role of organizational culture in fostering innovation and embracing new technologies. Other significant factors include 'Data Security and Privacy Measures' (RII: 0.875), 'Adequacy of Sensors and Data Loggers' (RII: 0.865), 'Adequate Training on Real-Time Monitoring Systems' (RII: 0.865), and 'Effective Use of Real-Time Monitoring Data for Predictive Maintenance' (RII: 0.865). These factors highlight the importance of data security, accurate monitoring equipment, adequate training, and effective data utilization for enhancing real-time monitoring capabilities.
- The developed real-time monitoring system model demonstrated strong predictive power, with an R-value of 0.855 and an adjusted R-squared value of 0.661. The ANOVA results indicated that the model is statistically significant ($F = 10.505$, $p < .001$), explaining a substantial portion of the variation in 'Improve Availability' (R-squared = 0.731). The regression coefficients revealed that 'Supportive Organizational Culture for Adopting New Technologies' and 'Adequacy of Sensors and Data Loggers' have the strongest positive impacts on 'Improve Availability,' followed by 'Efficient Data Storage and Retrieval Systems' and 'Availability of Reliable Internet Connectivity.' Conversely, 'Sufficient Power Supply for Monitoring Equipment' and 'Availability of Skilled Personnel for Monitoring and Maintenance' had negative impacts, albeit weak.
- The survey conducted to gather expert opinions on various aspects of real-time monitoring system development yielded valuable insights. Ethernet was the preferred communication protocol (55%), followed by satellite (45%). The Advanced Encryption Standard (AES-256) was the overwhelming favourite for data encryption (50%), while Microsoft SQL Server was the preferred database management system (50%). Tableau was the preferred software platform for user interface development (52.5%), and the OPC (OLE for Process Control) server was the preferred integration approach (42.5%).

General Recommendations

To enhance availability performance at TANESCO grid substations, the development of a real-time monitoring and maintenance management system should focus on integrating

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advanced sensors, data loggers, and predictive maintenance tools (Liu & Hui, 2024). By using real-time data on transformer health, the system can predict potential failures and recommend proactive maintenance actions, reducing unplanned outages. Ensuring reliable communication infrastructure and secure data handling is essential, as is training TANESCO personnel to effectively operate and maintain the system.

Additionally, the system should incorporate flexible maintenance schedules driven by data and prioritize critical transformers to maximize grid stability. Backup power sources for monitoring equipment and scalability across multiple substations are important for long-term sustainability. Periodic audits, adherence to industry standards, and collaboration with external experts further ensure that the system remains robust and future-proof, improving overall transformer availability and operational efficiency.

Further Study should explore advanced innovations that can complement the proposed real-time monitoring and maintenance management system. Specifically, studies could investigate the integration of cutting-edge technologies such as advanced sensors, data loggers, and predictive maintenance tools. Emphasis should be placed on ensuring secure communication infrastructure and reliable data handling for seamless system operation. Additionally, research should examine the scalability of such systems across multiple substations, the economic viability of flexible, data-driven maintenance schedules, and the prioritization of critical transformers for improved grid stability. Collaborations with external experts and adherence to industry standards can further support the development of a robust and adaptive maintenance management framework. This extended study would offer significant insights to drive the continuous improvement of transformer availability and performance at TANESCO grid substations.

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