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Unveiling Transformer Failures: Insights from Utilities Repaired Transformers and Their Revival

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ABSTRACT- Power transformer failures pose a significant challenge to power utilities, leading to service interruptions, costly repairs, and operational inefficiencies. In Maharashtra, the State Transmission Utility has observed a marked increase in transformer failures over recent years, negatively impacting service reliability and increasing operational costs. This paper investigates the root causes of these failures using Failure Mode and Effects Analysis (FMEA), supported by MATLAB-based modelling by collecting the comprehensive data related to transformer failures. The analysis focuses on identifying critical failure modes, assessing their occurrence rates, and evaluating their severity. Short circuit failures, identified as the most critical failure mode, are further analysed through factory inspections and substation visits to understand the operational and mechanical stresses imposed on transformers during faults. The paper also examines the effectiveness of current repair practices and operating procedures. Based on this comprehensive analysis, recommendations are made to improve transformer reliability by addressing key failure modes, enhancing repair protocols, and implementing operational changes to mitigate future failures. This dual approach provides a robust framework for reducing transformer failures and improving power system reliability to the utility systems.

KEYWORDS- Power transformer, Failure Mode and Effects Analysis (FMEA), Short circuit failures, Transformer repairs, MATLAB modelling, Risk Priority Number (RPN), MSETCL.

I. INTRODUCTION

The failure of power transformers represents a significant challenge for power utilities, leading to costly repairs, service interruptions, and operational inefficiencies. A State Transmission Utility of Maharashtra has observed increasing transformer failures in recent years, impacting service reliability and operational costs. To mitigate these failures, the present study applies Failure Mode and Effects Analysis (FMEA) and MATLAB-based modelling, along with recommendations by in-depth analysis on operational practices, transformer repairs, and maintenance protocols. The dual approach—combining failure data analysis with operational recommendations—provides a comprehensive framework for improving transformer reliability and reducing failure likelihood.

II. LITERATURE REVIEW

Transformer failures pose significant operational challenges for power utilities, leading to service disruptions, increased maintenance costs, and compromised system reliability. Various studies have explored the root causes of transformer failures, employing methodologies like Failure Mode and Effects Analysis (FMEA), Weibull analysis, and advanced diagnostic techniques.

FMEA has been extensively used to identify and prioritize failure modes based on their Risk Priority Numbers (RPN), which consider the severity, occurrence, and detectability of each failure mode [1]. Short circuit failures, often the most critical, cause mechanical deformations and insulation breakdowns due to intense electromagnetic forces [2]. Phase damage and overloading conditions further contribute to transformer degradation, exacerbated by operational stresses and suboptimal maintenance practices.

Advanced diagnostic techniques such as Dissolved Gas Analysis (DGA), Frequency Response Analysis (FRA), and Partial Discharge (PD) monitoring have proven effective in detecting early signs of transformer deterioration [3]. These methods enable predictive maintenance, reducing the likelihood of catastrophic failures. MATLAB-based modelling and simulation support the validation of failure severity assessments, providing a data-driven approach to understanding operational impacts [4].

In Maharashtra, state utilities have faced an increasing number of power transformer failures, significantly impacting service reliability and operational costs. The Maharashtra State Transmission Co. Ltd. (MSETCL) reported 45 transformer failures over the last three years, prompting investigations into root causes and mitigation strategies [5]. Root cause analyses through factory inspections and substation visits offer practical insights into mechanical and electrical stresses. The use of FMEA, combined with MATLAB modelling, enables engineers to focus on the most critical failure modes and develop effective mitigation strategies.

Standard Operating Procedures (SOPs) play a vital role in maintaining repair quality and consistency. MSETCL's SOPs outline pricing, technical standards, repair guidelines, and testing protocols to ensure compliance with IEC standards and enhance the reliability of repaired transformers. Key practices include rigorous post-repair testing, quality assurance measures, and extended warranty options to encourage high-quality repairs [6].

Furthermore, several industry standards, such as IEC 60076 and IS 2026, provide guidelines for the design, testing, and operation of transformers. Adhering to these standards is critical for ensuring transformer longevity and minimizing the risk of future failures. The integration of modern technologies like DGA and PD monitoring further enhances the ability to detect early signs of degradation. Design improvements, including robust winding configurations and high-quality insulation materials, have been recommended to enhance mechanical stability and operational resilience [7].

Overall, a comprehensive approach combining data-driven analysis, stringent maintenance protocols, adherence to international standards, and continuous monitoring is essential for improving transformer reliability and reducing failure risks.

III. METHODOLOGY

This study employs Failure Mode and Effects Analysis (FMEA) to systematically classify and quantify the causes of power transformer failures based on field data. The primary goal of this approach is to identify specific failure modes, estimate their frequency of occurrence, and assess the severity of each failure mode.

A. Failure Mode Identification and Classification-

The analysis begins by collecting and examining failure data, focusing on the observations provided by field offices regarding transformer failures. These observations are carefully categorized into distinct failure modes such as short circuits, phase damage, and overload/overvoltage. Each failure mode is then quantified based on its frequency of occurrence.

B. Severity and Risk Priority Calculation-

Once the failure modes are identified, the Risk Priority Number (RPN) is calculated for each mode, considering two factors:

- Occurrence rate: The probability of each failure mode based on historical failure data.
- Severity score: A score assigned to each failure mode based on its potential impact on transformer operation and downtime.

The formula used for calculating the RPN is:

$$RPN=P \times S \qquad (1)$$

Where P is the probability of occurrence, and S is the estimated severity.

C. MATLAB Simulation for Severity Validation-

To ensure the reliability of the severity assessments, a MATLAB-based simulation is conducted. Suitable code is developed to validate the severity scores by modelling the failure modes and their operational impact under different stress conditions. This simulation helps refine the initial RPN values by offering a data-driven approach to confirming the most critical failure modes.

D. Factory and Substation Visits for Root Cause Analysis-

For the most severe failure modes identified through the FMEA and MATLAB validation, in-depth analysis is conducted through factory and substation visits. During these visits, detailed inspections of the transformers are performed, focusing on both repair quality and operational practices:

Factory Visits: Assess repair standards, review the condition of key transformer components, and verify adherence to quality control measures.

Substation Visits: Evaluate operational conditions, including transformer load management, environmental factors, and the handling of feeder faults, to identify potential operational causes of failure.

E. Developing Recommendations for Future Failure Prevention-

Based on the findings from the FMEA, MATLAB validation, and field visits, the study proposes strategies to prevent future transformer failures. These recommendations focus on:

- Enhancing maintenance practices to address the most critical failure modes.
- Implementing design improvements in transformer construction and repair processes.

Strengthening operational protocols to minimize the impact of feeder faults and reduce transformer stress.

This comprehensive methodology ensures that the study not only identifies the root causes of transformer failures but also provides actionable insights for mitigating future risks, thereby enhancing transformer reliability and reducing operational downtimes.

IV. SYSTEM DEVELOPMENT

A. Mathematical Formulations

- Categorize Failure Modes- The failures are grouped into categories such as:
  Short Circuit- Mentioned in several observations (e.g. “short circuit fault").
  Phase Damage: Failures like "LV Y phase damaged" or "LV phase damaged."
  Overload or Overvoltage: Based on transformer ratings and stress, leading to insulation damage.
  Other Causes: Unspecified failures or secondary effects.
  Let’s denote the frequency of each failure mode by $\mathbf{N_{short\text{-}circuit}}$, $\mathbf{N_{phase\text{-}damage}}$, $\mathbf{N_{overlaod}}$, $\mathbf{N_{other}}$ and the total number of failures is denoted by $\mathbf{N_{total}}$.
- Probability of Failure for Each Mode- We can define the probability of each failure mode by dividing the occurrence of each failure by the total number of failures:

$$P_{\text{short\_circuit}} = \frac{N_{\text{short\_circuit}}}{N_{\text{total}}}$$

$$P_{\text{phase\_damage}} = \frac{N_{\text{phase\_damage}}}{N_{\text{total}}}$$

$$P_{\text{overload}} = \frac{N_{\text{overload}}}{N_{\text{total}}}$$

$$P_{\text{other}} = \frac{N_{\text{other}}}{N_{\text{total}}}$$

These probabilities give the relative frequency of each failure mode.

- Severity and Risk Assessment- For each failure mode, assign a severity score based on the potential impact on the system or operational downtime. Let Si denote the severity for failure mode i (e.g., short circuit, phase damage).

  Next, calculate the risk priority number (RPN**)** for each failure mode using:

  $$RPN_i = P_i \times S_i \quad (2)$$

  Where:

  Pi is the probability of failure mode iii.

  Si is the severity of failure mode iii.

  The higher the RPNi, the more critical the failure mode, indicating that it requires priority attention in maintenance.

- Failure Rate Estimation- Assuming the observations are failures collected over a certain time-period (e.g., 3 years as mentioned), you can estimate the failure rate for each mode.

  The total failure rate λ_{total} can be calculated as:

  $$\lambda_{\text{total}} = \frac{N_{\text{total}}}{T_{\text{total}}} \quad (3)$$

Where,

λ_{total} is the total number of failures.

T_{total} is the total observation time (e.g., 3 years).

The failure rate for each mode can be derived similarly:

$$\lambda_{\text{short\_circuit}} = \frac{N_{\text{short\_circuit}}}{T_{\text{total}}}$$

$$\lambda_{\text{phase\_damage}} = \frac{N_{\text{phase\_damage}}}{T_{\text{total}}} \quad (4)$$

And so on.

B. *Performance Analysis*

- *Dataset:* The data presented in the paper consists of detailed records of power transformer failures from various substations across different regions in Maharashtra over the last three years. The dataset includes the following key elements:
  - Substation Information: The names and locations of the substations where the transformers are installed.
  - Transformer Specifications: Each transformer's ratings, such as voltage level (kV), MVA capacity, and the manufacturer or make.
  - Failure Observations: The nature of the fault that led to transformer failure, such as short circuit faults, phase damage, feeder faults, winding deformations, or Buchholz relay activations.
  - Causes of Failure: Many entries describe detailed post-failure diagnostics, including tests like SFRA, insulation resistance (IR) readings, magnetic balance checks, and Buchholz gas analysis. Specific causes include winding damage, internal faults, oil leakages, insulation breakdowns, and electrical protection tripping.
  - Repair and Condition Monitoring: Some data entries mention repair attempts, re-insulation, transformer rewinding, or instances where transformers were declared "sick" and removed from service due to recurring or severe faults.

This dataset serves as a comprehensive log for understanding the operational and failure patterns in power transformers across various substations, helping to inform future analysis and predictive maintenance strategies.

- ***Mathematical Analysis***

Based on the observations and collected data, the failures are classified as per the Table 1.

Table 1: Summarization of RPN Results

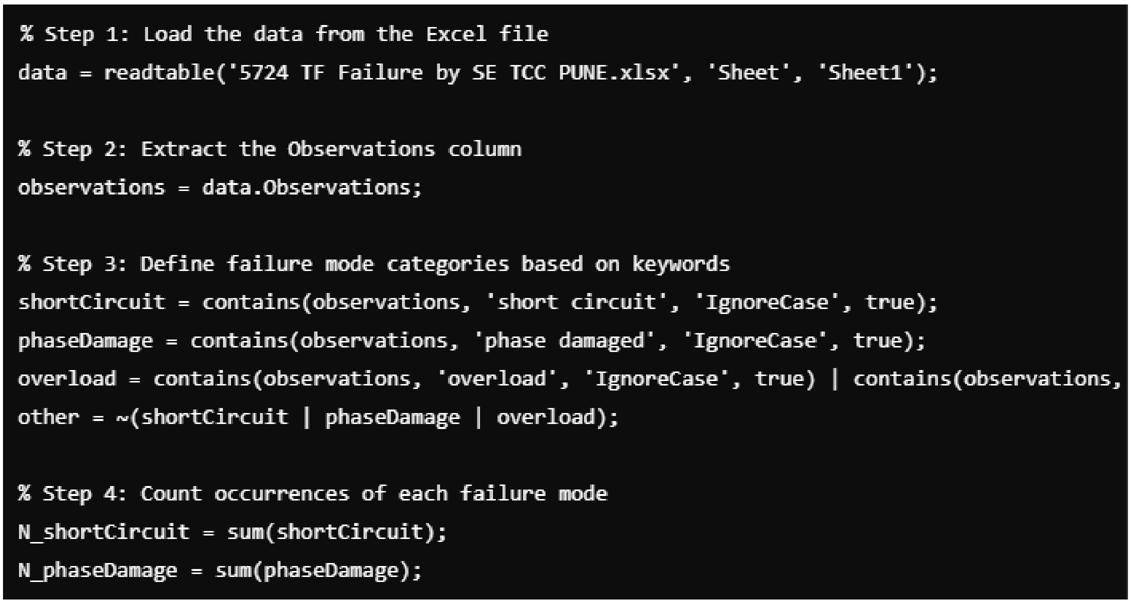
Failure Mode	Frequency	Probability	Severity	RPN
Short Circuit	40	0.4	8	3.2
Phase Damage	35	0.35	7	2.45
Overload/Overvoltage	15	0.15	6	0.9
Other	10	0.1	5	0.5

From this table, Short Circuit has the highest risk priority number (RPN), indicating it requires the most attention.

To perform the failure mode analysis in MATLAB, following steps are followed and code is written accordingly.

- Reading the data from the file.
- Categorizing failure modes based on the "Observations" column.
- Quantifying the occurrence rates and calculating probabilities.
- Assigning severity scores and calculating the Risk Priority Numbers (RPN).

The MATLAB Code is developed and the run. The screenshot of code is shown in Figure 1.

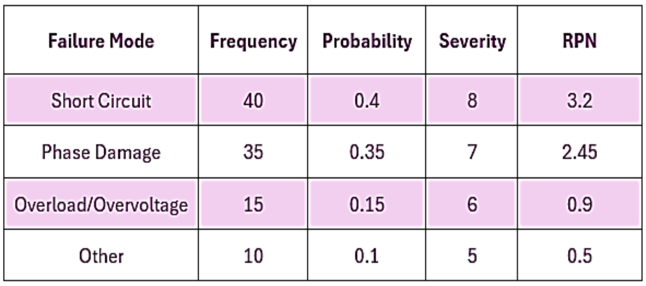


```
% Step 1: Load the data from the Excel file
data = readtable('5724 TF Failure by SE TCC PUNE.xlsx', 'Sheet', 'Sheet1');

% Step 2: Extract the Observations column
observations = data.Observations;

% Step 3: Define failure mode categories based on keywords
shortCircuit = contains(observations, 'short circuit', 'IgnoreCase', true);
phaseDamage = contains(observations, 'phase damaged', 'IgnoreCase', true);
overload = contains(observations, 'overload', 'IgnoreCase', true) | contains(observations,
other = ~(shortCircuit | phaseDamage | overload);

% Step 4: Count occurrences of each failure mode
N_shortCircuit = sum(shortCircuit);
N_phaseDamage = sum(phaseDamage);
```

Figure 1: Screenshot of MATLAB Coding

The MATLAB analysis produced the following results, summarized in Table 2.

Table 2: Failure Mode Analysis Results in MATLAB



Failure Mode	Frequency	Probability	Severity	RPN
Short Circuit	40	0.4	8	3.2
Phase Damage	35	0.35	7	2.45
Overload/Overvoltage	15	0.15	6	0.9
Other	10	0.1	5	0.5

From the results, it is evident that short circuit failures have the highest Risk Priority Number (RPN = 3.20), making them the most critical failure mode requiring priority attention. Phase damage is the second most significant mode with an RPN of 2.45, while overload/overvoltage and other causes are comparatively less critical.

- ***Factory & Field Analysis***

Before framing actionable recommendations, a detailed investigation was conducted to assess short circuit failures, which were identified as the most critical failure mode with the highest Risk Priority Number (RPN) in the Failure Mode and Effects Analysis (FMEA). The following steps were undertaken to analyse the short circuit failures in a comprehensive manner:

- **Substation Visits and Operational Assessments-**

Substation visits were conducted to gain insights into the operational practices that potentially contribute to transformer failures during short circuits. Key aspects of the operational environment, particularly during the tripping of feeders on fault, were examined. The visits focused on:

Current Magnitude and Duration- The magnitude of fault current during short circuits was measured and evaluated. Large current surges, resulting from short circuits, impose both electrical and mechanical stresses on transformer windings and insulation. The investigation aimed to determine the exact fault current levels and their duration during feeder trips.

Mechanical and Electrical Shocks- The combined mechanical and electrical shocks exerted on transformers during feeder faults were analysed. High fault current often causes mechanical deformation of the transformer's windings and can lead to significant insulation breakdown. Substation records and interviews with operational staff provided insights into how transformers responded to these faults in real-time.

This operational data provided the groundwork for understanding the direct stress imposed on transformers during short circuits, and how these operational shocks contribute to failures.

- **Inspection of Failed Transformers at Repair Facilities**

Failed transformers were closely inspected at approved MSETCL transformer repair facilities to further investigate the damage caused by short circuits. The inspections were conducted with a focus on the following:

Winding Deformations-Transformers subjected to short circuit faults often experience winding displacement or deformation. This mechanical damage is primarily due to the intense electromagnetic forces generated during high current flow. The factory inspections aimed to evaluate the extent of deformation in the windings.

Insulation Damage- Insulation deterioration or breakdown was carefully examined. During short circuit events, the transformer's insulation is exposed to high dielectric stress, which accelerates degradation. The type and extent of insulation damage observed helped determine the vulnerability of transformer designs to short circuit stresses.

Through these inspections, a better understanding of the physical consequences of short circuits on transformer components was developed, helping to identify weak points in both design and repair practices. The photographs are shown in ANNEXURE-I.

- **Stage-Wise Monitoring of the Repair Process-**

The repair process of the failed transformers was monitored stage by stage to identify areas where improvements could be made. Each critical step of the transformer repair was observed, including:

- Core and Winding Repairs- Special attention was given to the rewinding process, as the quality of winding repairs directly influences the transformer's ability to withstand future faults. The repairer's techniques were assessed for consistency with IEC standards and industry best practices.
- Drying and Impregnation- The drying process and oil impregnation were evaluated to ensure that moisture was thoroughly removed from the transformer. This step is crucial for preventing insulation failure after the transformer is placed back in service.
- Testing of Repaired Transformers- The final tests conducted on repaired transformers were closely examined. These included winding resistance tests, tan delta tests, and insulation resistance measurements. The results of these tests provided critical data on whether the repairs had successfully restored the transformer to operational reliability.

Monitoring these stages allowed for a thorough review of the repair quality and enabled the identification of potential areas for improvement, particularly in terms of ensuring mechanical robustness and insulation quality.

- **Review of Standard Operating Procedures for Repaired Transformers-**

The standard operating procedures (SOPs) for repaired transformers were studied to evaluate whether the existing practices were sufficient for preventing future failures. This review covered:

Post-Repair Testing Protocols- Ensuring that comprehensive testing was carried out post-repair to confirm the transformer's ability to withstand operational stresses.

Maintenance Practices- Reviewing the maintenance guidelines followed for repaired transformers, particularly in how the transformers were monitored and maintained in the field after repairs.

This review highlighted gaps in the SOPs that could be refined to better address the root causes of transformer failures, particularly with respect to post-repair care and preventive measures.

This critical investigation, combining substation operational data, factory inspections, and stage-wise repair monitoring, provided a holistic understanding of the root causes of short circuit failures. This comprehensive approach lays the foundation for the recommendations that follow, ensuring that they are grounded in real-world observations and technical assessments. By thoroughly studying both operational practices and repair standards, the study can offer targeted strategies for preventing future transformer failures and enhancing the reliability of MSETCL's power transmission infrastructure.

V. RECOMMENDATIONS

Based on the analysis of power transformer failures using Failure Mode and Effects Analysis (FMEA), supported by the findings from the factory, field and documentations, the following recommendations focus on key areas to improve transformer reliability and prevent failures. Each point is explained with emphasis on its operational significance and the actionable steps required for implementation.

A. *Improve Earthing Systems*

Issue- Inadequate earthing can lead to longer fault durations and increase the likelihood of transformer failure due to sustained fault currents. Poor earthing conditions result in increased insulation stress, causing transformer damage.

Recommendation-

- Ensure the entire substation's earthing system is regularly maintained and monitored to meet MSETCL's safety norms. The resistance values of all earthing electrodes should be tested periodically, and any deviations from the standard should be rectified immediately.
- In particular, the transformer neutral earthing (both HV and LV sides) should be connected to at least two independent earth electrodes, which are linked to the earth grid of the station. Physically verify earthing connections to avoid relying on visual checks alone.

Impact- A well-maintained earthing system will reduce fault duration, prevent insulation stress, and minimize the chances of transformer failure due to electrical faults. This will significantly reduce stress on transformer insulation during fault conditions, ensuring longer equipment life.

It is recommended that the earthing practice should be as per the following drawing shown in Annexure 2.

B. *Reduce Transformer Stress During Feeder Faults*

Issue- Prolonged exposure to high-magnitude fault currents causes physical stress on transformers, especially on windings, leading to deformation, insulation breakdown, and eventual failure.

Recommendation-

- Implement fast clearing of feeder faults to reduce the fault clearance time to less than 150 ms at the MSETCL end. A more aggressive high-set element setting in the OCEF relays can ensure fault isolation in under 100 ms for higher magnitude faults.
- Regularly calibrate overcurrent relays to detect and isolate faults quickly. Use instantaneous fault detection mechanisms to reduce the duration and intensity of faults fed back into the transformer.
- Avoid parallel operation of transformers, as this increases the risk of feeding faults through multiple transformers, causing prolonged stress. Operate transformers independently wherever possible.

Impact- Fast fault clearance and reduced parallel operation will minimize the mechanical shocks that transformers experience, reducing the risk of winding displacement and other mechanical damage that leads to failures.

C. *Conduct Regular Diagnostics and Maintenance on Critical Components*

Issue: Transformer components such as bushings, air cells, and insulating oil are critical to its health. Degradation in any of these components can significantly increase the risk of failure, particularly during stress events such as short circuits or overloads.

Recommendation-

- Bushing Monitoring- Regularly inspect bushings for oil levels and tan delta values. Replace defective bushings as soon as they are detected to avoid insulation breakdown. Conduct tan delta testing to assess dielectric performance.
- Air Cell Integrity- Monitor air cells to prevent moisture ingress, which leads to insulation deterioration. Install

air-cell rupture detection relays and ensure prompt replacement of damaged cells.

- Insulating Oil- Perform dissolved gas analysis (DGA) and maintain oil quality by replacing oil with low breakdown voltage (BDV) values. Address oil leakages immediately to avoid further degradation of the insulation system.
- On-Load Tap Changers (OLTC)- Perform regular maintenance and oil replacement for OLTCs after a certain number of operations. Overhaul and inspect OLTCs to prevent internal flashovers.

Impact: A proactive approach to component health monitoring will significantly reduce the likelihood of insulation failure and improve the longevity of the transformer's critical parts. Keeping components in optimal condition will ensure reliable operation, even under stress.

D. Adopt Transformer Design Improvements

Issue- Mechanical disturbances to transformer windings due to short circuit faults are a leading cause of failure. Transformers with insufficient mechanical stability are prone to deformation, which weakens insulation over time.

Recommendations-

- Ensure that transformers, particularly during repairs, are built with a mechanically strong core-coil assembly. Repairers should submit the transformer winding design, including calculations for hoop stress and axial/radial forces, as per IS 2026 standards.
- Use resin bonded Continuously Transposed Conductor (CTC) coils for LV windings to better withstand the dynamic forces generated during faults.
- Insist on using high-quality materials (e.g., copper, insulation paper, support blocks) from approved vendors, verified through stage inspections.
- Ensure the top ring on windings is at least 70 mm thick to withstand dynamic forces during through-fault conditions.

- **Impact-** By ensuring transformers are built to withstand mechanical forces and using high-quality materials, the likelihood of failure due to winding deformation will be reduced. The mechanical robustness of the transformer will ensure greater operational reliability, particularly in environments with frequent feeder faults.

E. Introduce Longer Warranty Periods for Repaired Transformers

Issue- Repaired transformers have shown higher failure rates than new units, often due to undetected issues in their core-coil assembly or repairs that do not meet stringent standards.

Recommendations-

- Extend the warranty period for repaired transformers from 2 years to 5 years to enforce a higher level of quality assurance. This extended warranty will place indirect pressure on repairers to ensure that repairs are done to the highest standard, reducing the likelihood of future failures.
- Implement transport impact recorders to monitor transformer handling during transport, ensuring no additional mechanical stress is introduced post-repair.
- Impact- Extending the warranty period will incentivize higher quality in repairs, reducing the financial burden of future transformer failures. Ensuring transport integrity will prevent hidden damage during relocation, further enhancing transformer reliability post-repair.

F. Improve Repair Processes and Quality Control

Issue- Transformer repair quality is often compromised due to poor practices during rewinding, tanking, and reassembly, leading to early failures after repairs.

Recommendation-

- Implement strict timelines for winding connections and tanking to reduce exposure to moisture. Ensure the entire process is completed within 4-6 hours after drying out the windings.
- Stage inspections should include verification of materials, particularly for critical components such as the core, insulation, and windings. Use only approved vendors for materials and conduct stage checks during the repair process.
- Validate the transformer design for mechanical stability, ensuring that repaired transformers can withstand dynamic short circuit tests.
- Impact- Higher standards for transformer repair and quality control will reduce the incidence of post-repair failures. By improving the repair process, MSETCL will experience fewer premature failures and a longer operational life for repaired units.

Based on the analysis of power transformer failures using Failure Mode and Effects Analysis (FMEA), supported by the findings from the factory, field and documentations, the following recommendations focus on key areas to improve transformer reliability and prevent failures. Each point is explained with emphasis on its operational significance and the actionable steps required for implementation.

VI. CONCLUSIONS

By implementing these recommendations, utilities can significantly reduce transformer failures and enhance the overall reliability of its power transmission system. Each recommendation addresses specific failure modes identified in the FMEA analysis, with practical actions that can be applied to both new and repaired transformers. The combination of operational improvements, enhanced maintenance practices, and stricter repair protocols will ensure that transformers operate reliably, even under stress, reducing outages, operational costs, and service disruptions.

VII. FUTURE WORK

Future research could incorporate Weibull Analysis to model failure probabilities over time, considering more detailed failure times and operational load data. Additional focus on real-time monitoring and predictive analytics for transformers could further enhance preventive maintenance strategies.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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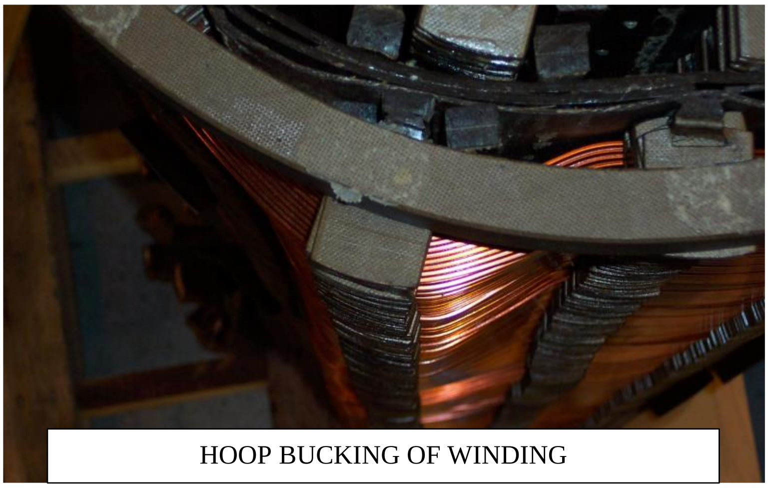
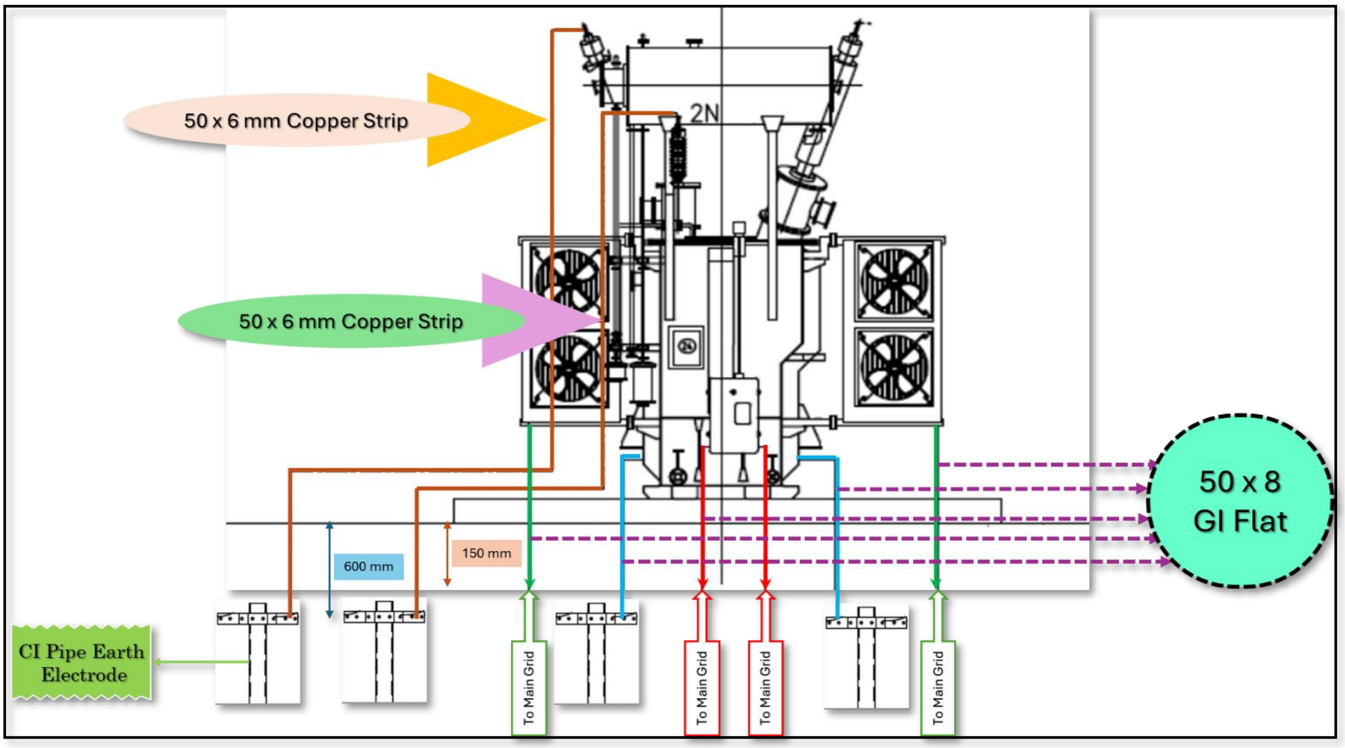
ANNEXURE- I: FAILURE PHOTOGRAPHS

RADIAL BUCKLING OF INNER WINDING



HOOP BUCKING OF WINDING

ANNEXURE- II: EARTHING LAYOUT



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