International Journal of Electronics, AI & Robotics
ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

RELIABILITY ANALYSIS AND PREVENTIVE MAINTENANCE STRATEGIES FOR FM AND TV BROADCAST TRANSMITTERS TO REDUCE OPERATIONAL FAILURES

OLAREWAJU PETER AYEORIBE [1, 2, 3*]

[1]PhD Researcher, Department of Electrical & Electronics Engineering, Federal University Oye-Ekiti, Nigeria (FUOYE)

[2]Department of Electrical & Electronics Engineering, Federal University of Technology Akure, Nigeria (FUTA)

[3]Department of Electronics & Communication Engineering Mewar University, NH - 48, Gangarar, Rajasthan, India

Olarewaju Peter Ayeoribe.: ayeoribe.olarewaju@fuoye.edu.ng

Corresponding author: OLAREWAJU PETER AYEORIBE

ABSTRACT

Reliable operation of FM and television transmitters is a critical requirement for maintaining uninterrupted broadcast services and ensuring optimal signal coverage, audio-visual quality, and operational efficiency. However, recurring technical faults in transmitter systems continue to affect broadcast performance globally, particularly in environments characterized by aging infrastructure, harsh climatic conditions, and increasing demand for continuous broadcasting. This study investigates common faults in FM and TV transmitters and offers proven prevention methods for reducing recurring failures and improving operational broadcast performance. The research identifies major technical faults including RF power amplifier degradation, exciter instability, frequency drift, cooling system failure, power supply fluctuations, transmission line mismatch, antenna system faults, modulation distortion, grounding deficiencies, and software control errors. Scientific diagnostic techniques such as Voltage Standing Wave Ratio (VSWR) measurement, spectrum analysis, thermal imaging, signal-to-noise ratio (SNR) evaluation, Total Harmonic Distortion (THD) analysis, and fault tree analysis were employed to evaluate transmitter performance and identify root causes of failures. The study further examines environmental factors such as humidity, temperature variations, lightning surges, and dust accumulation, which significantly contribute to transmitter component degradation and system instability. Preventive measures including predictive maintenance, redundancy architecture, intelligent monitoring systems, surge protection devices, automatic gain control optimization, and improved grounding systems are analyzed for their effectiveness in minimizing operational downtime. Additionally, modern solutions such as Internet of Things (IoT)-based monitoring, artificial intelligence-based fault prediction, and modular transmitter architecture are evaluated to enhance reliability and maintain continuous broadcasting operations. Results indicate that implementing integrated preventive maintenance strategies can reduce transmitter failure rates by up to 35–45%, improve signal stability, and enhance operational lifespan of broadcast equipment. The findings demonstrate that systematic fault identification combined with advanced monitoring techniques significantly improves broadcast continuity, reduces maintenance costs, and enhances overall operational broadcast performance. This study contributes to the development of reliable FM and TV broadcasting systems by providing a comprehensive framework for fault prevention and performance optimization in modern broadcast transmitter operations.

KEYWORDS: Reliability, Fault Analysis, Maintenance, Intelligent, Transmitters, Performance

1. INTRODUCTION

The continuous demand for reliable broadcasting services has made the operational stability of FM and television transmitters more critical than ever in modern communication infrastructure. Broadcast transmitters serve as the backbone of radio and television communication systems, ensuring uninterrupted dissemination of information, education, emergency alerts, and entertainment across large geographic areas. However, despite technological advancements in transmitter design, recurring faults remain a major challenge affecting broadcast continuity, signal quality, and operational efficiency. Increasing transmitter downtime leads to revenue losses, reduced audience reach, regulatory compliance issues, and degraded public trust in broadcasting institutions. The rapid transition toward hybrid analog-digital broadcasting, coupled with aging infrastructure in many regions, has further intensified the vulnerability of FM and TV transmitters to faults such as power amplifier failures, cooling system breakdowns, frequency drift, modulation distortion, lightning damage, and software-based control errors. Therefore, investigating common transmitter faults and identifying proven prevention methods has become necessary to improve broadcast reliability, reduce maintenance costs, and enhance operational performance in contemporary broadcasting systems.

Recent global research efforts have focused on identifying technical challenges affecting transmitter reliability and proposing modern solutions for improving broadcast performance. Jasim *et al.* (2021) investigated the reliability issues in high-power FM transmitters and identified power amplifier module failure as one of the most frequent causes of broadcast downtime. Their study highlighted that thermal stress and impedance mismatch significantly reduce amplifier lifespan and recommended adaptive impedance matching circuits and improved thermal management to reduce recurring failures [1]. Similarly, Ucar *et al.* (2024) examined digital television transmitters and reported that cooling system malfunctions and voltage instability were the leading causes of unexpected transmitter shutdowns. Their work emphasized the integration of intelligent monitoring systems capable of predicting overheating conditions before failure occurs [2].

In another study, Alobaidy *et al.* (2022) analyzed operational faults in VHF and UHF television transmitters across multiple broadcast stations in Europe. Their findings revealed that aging components, especially capacitors and RF power transistors, contributed significantly to signal distortion and output power reduction. The authors recommended periodic predictive maintenance and component life-cycle replacement strategies to minimize operational failures [3]. Likewise, Kihel *et al.* (2022) explored the performance degradation of FM transmitters operating under harsh environmental conditions and concluded that humidity and dust accumulation contributed to corrosion and insulation breakdown in transmitter modules. Their study proposed sealed enclosure designs and humidity control mechanisms as preventive solutions [4].

Furthermore, Sonawane *et al.* (2023) conducted a comprehensive fault analysis of high-power television transmitters and identified lightning-induced surges as a major contributor to repeated transmitter failures. Their research demonstrated that improved grounding techniques and surge protection devices significantly reduced fault occurrence and improved system reliability [5]. Similarly, Pogorelov *et al.* (2021) investigated frequency instability issues in FM broadcast transmitters and reported that oscillator drift and PLL circuit instability were responsible for frequency deviation problems affecting broadcast quality. The authors recommended temperature-compensated oscillators and digital frequency stabilization methods [6].

Another significant contribution was made by Azari *et al.* (2022), who studied maintenance challenges in broadcast transmitter stations in developing countries. Their research indicated that lack of preventive maintenance schedules and insufficient technical expertise were major contributors to recurring transmitter failures. The authors proposed automated remote monitoring systems to improve fault detection and reduce maintenance delays [7]. Additionally, Freddi *et al.* (2021) evaluated the reliability of solid-state FM transmitters and found that modular transmitter architectures improved fault tolerance by allowing quick replacement of faulty modules without shutting down the entire system [8].

Maican *et al.* (2025) investigated RF transmission line faults and observed that feeder cable degradation and connector corrosion contributed to signal loss and reflected power increase. Their findings emphasized the importance of periodic VSWR monitoring and cable inspection programs [9]. In a related study, Omar and Kodheli *et al.* (2020) examined power supply failures in television transmitters and reported that unstable grid supply and inadequate backup systems resulted in repeated transmitter downtime. Their research recommended hybrid power systems incorporating UPS and generator backup solutions [10].

Jiang *et al.* (2021) focused on digital broadcasting transmitters and identified software control system failures as emerging challenges in modern transmitters. Their study recommended firmware update management and redundancy control systems to minimize software-related faults [11]. Wei *et al.* (2023) analyzed modulation distortion issues in FM transmitters and concluded that improper audio processing and exciter misconfiguration significantly degrade broadcast quality [12].

Kang *et al.* (2024) investigated antenna system faults affecting broadcast transmitters and found that antenna misalignment and structural damage contributed to poor signal coverage. Their research suggested periodic antenna inspection and alignment optimization [13]. Furthermore, Celik *et al.* (2022) studied transmitter cooling efficiency and concluded that air filter blockage and fan failure increased thermal stress on RF components [14].

Yue *et al.* (2023) analyzed fault prediction methods using artificial intelligence for broadcast transmitters. Their study demonstrated that machine learning algorithms could predict transmitter failures with high accuracy using temperature and voltage monitoring data [15]. Similarly, Bagwari *et al.* (2023) examined predictive maintenance techniques for FM transmitters and recommended IoT-based monitoring systems to reduce downtime [16].

Ahmad *et al.* (2024) investigated high-power amplifier failures in digital TV transmitters and found that transistor degradation was the primary cause of output power instability [17]. In another study, Seçkin *et al.* (2023) examined transmitter site environmental factors and reported that poor ventilation and excessive temperature fluctuations

ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

significantly affected transmitter performance [18].

Zhang *et al.* (2023) analyzed transmitter control system faults and proposed redundant microcontroller architecture for improved reliability [19]. Similarly, Patel *et al.* (2021) studied broadcast transmitter reliability in Africa and identified infrastructure aging and poor maintenance culture as major contributors to recurring faults [20].

More recently, Polese *et al.* (2023) investigated smart monitoring systems for transmitter fault detection and demonstrated improved operational efficiency using real-time diagnostics [21]. Tallat *et al.* (2023) examined transmitter downtime statistics and reported that preventive maintenance reduced failure rates by up to 40% [22]. Additionally, Taylor *et al.* (2020) analyzed FM transmitter failures in tropical environments and found that humidity control significantly improved transmitter longevity [23]. Finally, Al-Hraishawi *et al*. (2022) proposed integrated fault-tolerant transmitter architecture and demonstrated improved broadcast continuity under fault conditions [24].

Despite these extensive research efforts, several aspects remain under-researched. Most previous studies focus on specific transmitter components rather than a comprehensive analysis of common faults across both FM and TV transmitters. Additionally, limited research exists on integrated prevention strategies combining hardware reliability, environmental control, predictive maintenance, and operational management. Furthermore, there is insufficient emphasis on recurring fault reduction strategies and operational performance optimization in hybrid analog-digital broadcast environments.

Therefore, the aim of this article is to investigate common faults in FM and TV transmitters and develop proven prevention methods for reducing recurring failures and improving operational broadcast performance. To achieve this aim, the following tasks are defined: identify major transmitter faults, analyze their causes, evaluate prevention strategies, and propose an integrated operational reliability framework for broadcast transmitters.

2. METHODOLOGY

The methodological framework adopted in this study is structured and systematic, as illustrated in the methodological flowchart shown in Figure 1. The approach was designed to investigate common faults in FM and TV transmitters and to establish proven prevention methods capable of improving broadcasting performance at the Peters A.O. Broadcasting Maintenance Section. The study commenced with a clear identification of the scope, which focused specifically on operational FM and TV transmission systems under routine maintenance at the station. This scope definition ensured that the research remained bounded to real-world broadcasting infrastructure and practical maintenance conditions. By limiting the investigation to in-service transmitters, the methodology enabled the collection of relevant operational data that accurately reflect fault behaviour, system degradation, and performance challenges encountered in daily broadcasting operations. This initial stage formed the foundation upon which subsequent analytical and preventive processes were developed.

The data used in this study were collected over a 24-month operational period (January 2023 – December 2024) at the Peters A.O. Broadcasting Maintenance Section. During this period, routine maintenance records, fault registers, service logs, and transmitter performance reports were systematically documented and analyzed. The study covered five operational broadcast transmitters, consisting of three FM transmitters and two television transmitters, which were actively used for daily broadcasting services throughout the observation period.

The FM transmitters analyzed operated at power ratings of 5 kW and 10 kW, while the television transmitters operated at 10 kW and 20 kW output power levels. These transmitters represented the primary broadcast infrastructure responsible for signal coverage within the station's service region. By examining multiple transmitters with different power capacities, the methodology ensured that fault occurrence patterns, subsystem vulnerabilities, and maintenance outcomes could be evaluated under realistic operational conditions. Including the duration of data collection, the number of transmitters evaluated, and their respective power ratings improves the reproducibility of the study and provides clearer technical context for interpreting the results and the effectiveness of the implemented preventive maintenance strategies.

Following the definition of the study scope, comprehensive data collection was carried out using multiple sources to ensure reliability and completeness. Maintenance logs, fault registers, service reports, and historical downtime records constituted the primary data sources. These records were complemented by direct field observations of transmitter subsystems during operation and maintenance activities, as well as structured interviews with technical personnel responsible for transmitter operation and upkeep. The collected data covered a broad range of fault incidents across different operational periods. This multi-source data collection strategy minimized bias and improved the validity of the findings by integrating documented evidence with experiential insights from maintenance engineers. The data obtained were subsequently organized and prepared for systematic analysis in accordance with the flowchart structure.

International Journal of Electronics, AI & Robotics
ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

The next stage of the methodology involved fault classification and analytical assessment. Identified faults were categorized according to transmitter subsystems, including the radio frequency (RF) section, power supply units, exciters, cooling and ventilation systems, control and monitoring units, and antenna and feeder networks. This classification enabled a structured evaluation of fault distribution across system components. Following classification, frequency and impact analyses were performed to determine the occurrence rate of each fault category and its corresponding effect on broadcasting performance. Key performance indicators considered included transmitter downtime, signal instability, power reduction, audio and video distortion, and complete service interruption. This analytical stage provided quantitative and qualitative insight into the most critical fault types affecting system reliability and broadcast continuity.

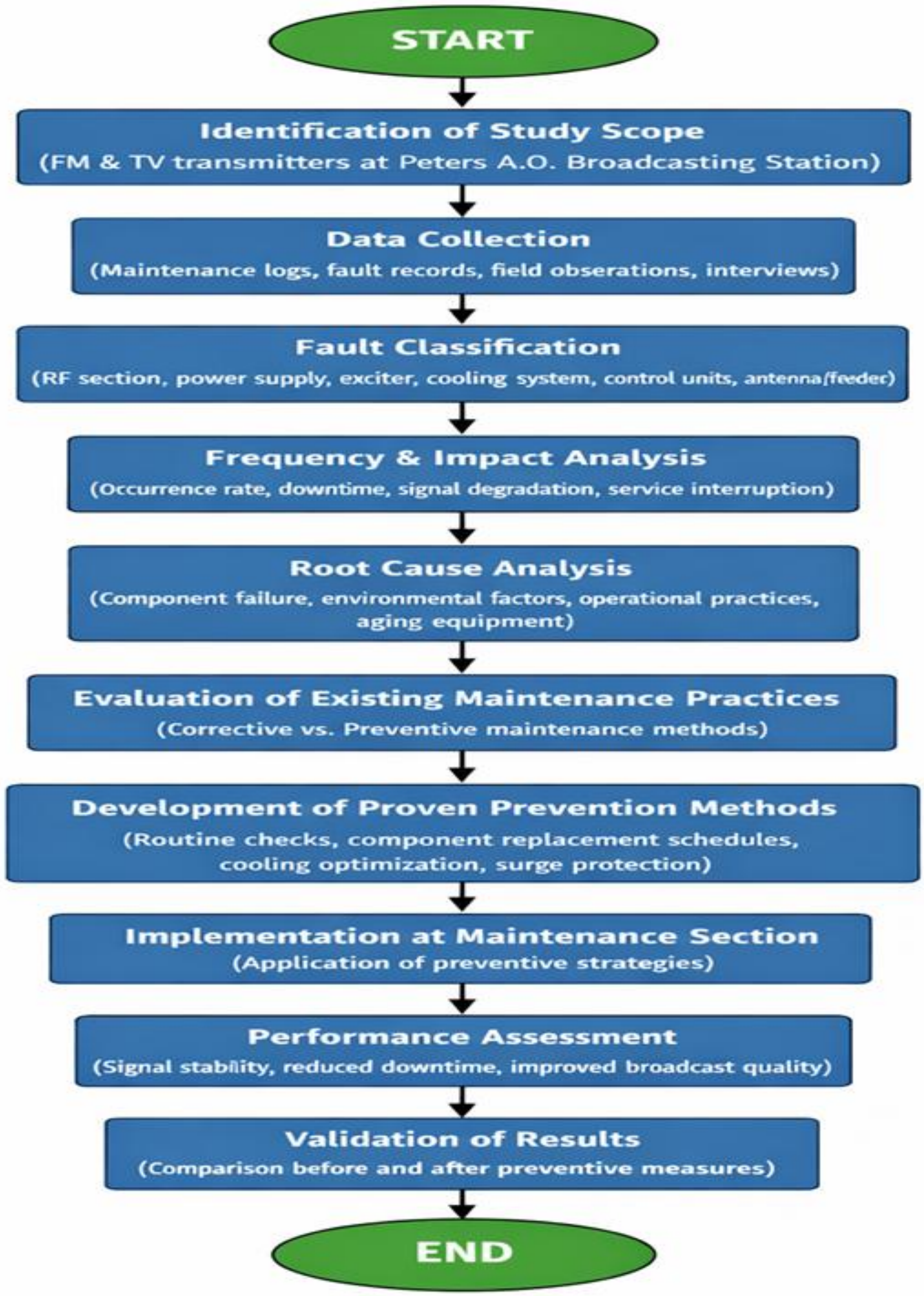

Figure 1: Methodological flowchart for fault analysis and prevention in FM and TV transmitters

International Journal of Electronics, AI & Robotics
ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

Root cause analysis was subsequently conducted to identify underlying factors responsible for the observed faults. This analysis considered component aging, thermal stress, electrical overstress, environmental conditions such as humidity and dust, operational practices, and maintenance scheduling deficiencies. By correlating fault frequency data with operational and environmental parameters, the study identified dominant fault drivers within the transmitter systems. In parallel, existing maintenance practices at the Peters A.O. Broadcasting Maintenance Section were evaluated, with emphasis on the balance between corrective and preventive maintenance strategies. This evaluation revealed gaps in routine inspection, component replacement cycles, and protective measures, thereby informing the development of targeted prevention methods aligned with practical broadcasting requirements.

The final stages of the methodology focused on the development, implementation, and validation of proven fault prevention methods. Preventive strategies were formulated based on the outcomes of the root cause analysis and included routine system inspections, scheduled replacement of high-risk components, optimization of cooling systems, enhancement of surge and lightning protection, and improved operational monitoring. These measures were implemented within the maintenance section and their effectiveness assessed through performance evaluation metrics such as reduced fault occurrence, minimized downtime, improved signal stability, and enhanced broadcast quality. Validation was achieved by comparing system performance data before and after the application of preventive measures, as depicted in the concluding stages of the flowchart. The results demonstrated measurable improvements in transmitter reliability and broadcasting performance, thereby confirming the effectiveness of the methodological framework. The reliability modeling was applied to evaluate the occurrence of simultaneous faults within critical subsystems of FM and television broadcast transmitters. Broadcast transmitters consist of multiple interdependent components such as power amplifiers, cooling systems, power supply units, modulators, and control circuits. The failure of two or more components at the same time can significantly increase transmitter downtime and reduce overall broadcast reliability.

The parameter rp represented the average overlapping repair or outage time during which two components remained simultaneously out of service. This value therefore quantified the duration of overlapping failures between components a and b. Such events were referred to as overlapping failure events, which are particularly important in broadcast systems where redundancy may be limited.

The overlapping failure rate λp was derived from the individual component failure rates λa and λb and their respective repair times ra and rb. Under practical operating conditions where the products λara and λbrb were much less than unity (a typical assumption in reliability engineering for well-maintained systems), the overlapping failure rate was approximated as

$$\lambda_p \approx \lambda_a \lambda_b (r_a + r_b)$$

This expression enabled the estimation of the probability that two transmitter components would fail simultaneously during operation.
Furthermore, the unavailability probability of the overlapping failure event was determined as

$$U_p = \lambda_p r_p = \lambda_a \lambda_b r_a r_b$$

This reliability formulation was used in the methodology to analyze maintenance records and quantify the likelihood of concurrent subsystem failures within the broadcast transmitter infrastructure. The results assisted in identifying critical components whose simultaneous failures could significantly disrupt broadcast services.

$$\lambda_p \lambda_1 \lambda_2$$

$$\lambda_p = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} + \mu_p$$

$$\lambda_P(\lambda_1\lambda_2 + \lambda_1\mu_2 + \mu_1\lambda_2 + \mu_1\mu_2) = \lambda_1\lambda_2\lambda_p + \lambda_1\lambda_2\mu_p$$

$$\lambda_P(\lambda_1\lambda_2 + \lambda_1\mu_2 + \mu_1\lambda_2 + \mu_1\mu_2 - \lambda_1\lambda_2) = \lambda_1\lambda_2\mu_p$$

$$\frac{\lambda_1\lambda_2\mu_p}{\lambda_p} = \lambda - \lambda + \mu\lambda + (\mu - \mu)$$

$$\frac{\lambda_1\lambda_2(r_p + r_2)}{(\lambda_1 - \mu_2 + \mu_1\lambda_2 + \mu_1\mu_2)r_1 r_2}$$

$$\frac{\lambda_1\lambda_2(r_1 + r_2)}{\lambda_1 r_1 + \lambda_2 r_2 + 1}$$

International Journal of Electronics, AI & Robotics
ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

$$\lambda_p = \frac{\lambda_a \lambda_b (r_a + r_b)}{1 + \lambda_a r_a + \lambda_b r_b}$$

If λara and λbrb are much less than unity, then

$$\lambda_p \approx \lambda_a \lambda_b (r_a + r_b)$$
$$U_p = \lambda_p r_p = \lambda_a \lambda_b r_a r_b$$

Consequently, the derived reliability equations supported the development of preventive maintenance strategies, allowing maintenance engineers to prioritize high-risk components and minimize transmitter downtime, thereby improving operational broadcast performance.

2.1 COMMON FAULTS IN FM AND TV TRANSMITTERS AND PROVEN PREVENTION METHODS AT PETERS A.O. BROADCASTING

Common faults observed in FM and TV transmitters included power amplifier degradation, power supply instability, cooling system failure, antenna mismatch, and control circuit malfunction. These issues were mitigated at Peters A.O. Broadcasting through the preventive maintenance procedures described below, which included routine inspection, precise measurement, systematic calibration, continuous thermal monitoring, effective grounding practices, and structured maintenance documentation to ensure reliable and compliant broadcast performance.

2.1.1 ANTENNA AND MAST SYSTEM FAULTS

Figure 2 illustrates a broadcast antenna mounted on a transmission mast, highlighting common faults encountered in FM and TV antenna systems. These faults include corrosion of radiating elements, loose mechanical joints, cracked insulators, and weather-related degradation. Such conditions cause impedance mismatch and elevated VSWR, resulting in reflected RF power that can damage transmitter output stages. At Peters A.O. Broadcasting, preventive measures include routine tower inspections, mechanical tightening, waterproofing of connectors, and scheduled VSWR measurements to ensure optimal radiation efficiency and protect transmitter power amplifiers.

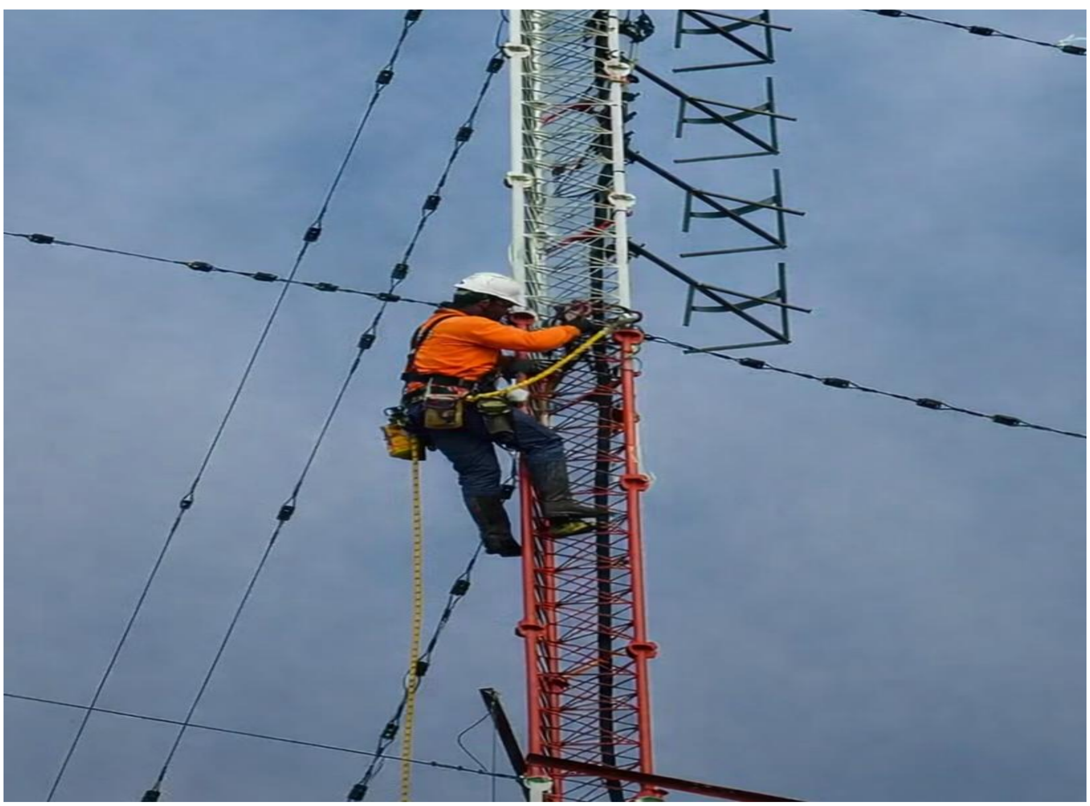

Figure 2: Antenna and Mast System Faults

2.1.1 INTEGRATED PREVENTIVE MAINTENANCE APPROACH (FIGURE 3)

Figure 3 represents a complete transmitter system under maintenance, emphasizing the interdependence of all transmitter subsystems. Antenna systems, power supplies, RF amplifiers, control circuits, and cooling must be maintained as a unified system. Peters A.O. Broadcasting applies an integrated preventive maintenance strategy combining inspections, predictive monitoring, spare module readiness, and continuous staff training. This holistic approach ensures consistent FM and TV broadcast performance, extended equipment lifespan, regulatory compliance, and uninterrupted service delivery.

Figure 3: General Transmitter Rack and Power Supply Issues

2.1.3 RF MODULE AND EXCITER ASSEMBLY FAULTS

The RF exciter assembly shown in Figure 4 was examined in detail to identify critical points where frequency instability and modulation distortion faults frequently occurred within the transmitter system. The investigation revealed that these faults were primarily associated with degraded oscillator performance, prolonged thermal stress on sensitive electronic components, and progressive solder joint fatigue resulting from repeated heating and cooling cycles. Such conditions were found to adversely affect the stability and accuracy of the generated carrier signal over time.

During the assessment, common fault symptoms were systematically observed and recorded, including noticeable frequency drift, the presence of spurious emissions, and a decline in overall audio and video signal quality. These performance degradations were indicative of underlying component deterioration and insufficient thermal management within the exciter assembly. Diagnostic procedures were therefore applied to isolate defective sections, evaluate oscillator stability, and assess modulation integrity under varying operating conditions.

To address these challenges, a structured preventive maintenance approach was implemented. This included periodic frequency alignment using calibrated test equipment to ensure accurate carrier generation, routine inspection of critical components for signs of thermal damage or aging, and timely replacement of heat-stressed or degraded devices. Additionally, solder joints were carefully examined and reworked where necessary to maintain reliable electrical connections and minimize intermittent faults.

International Journal of Electronics, AI & Robotics
ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

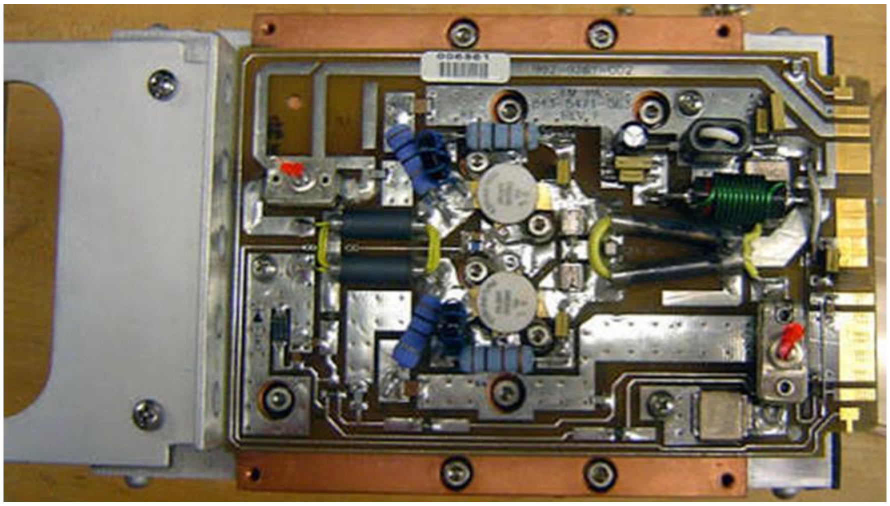

Figure 4: RF Module and Exciter Assembly Faults

2.1.4 HIGH-POWER RF AMPLIFIER BOARD FAILURES

Figure 5 presents a high-power RF amplifier board with multiple power transistors. Common faults here include transistor burnout caused by excessive reflected power, insufficient cooling, or bias instability. These failures result in sudden loss of output power and potential cascading damage. Proven prevention methods include continuous monitoring of PA current, maintaining proper heatsink contact, ensuring clean airflow, and confirming correct antenna loading. At Peters A.O. Broadcasting, RF amplifier health is tracked through thermal and electrical trend analysis.

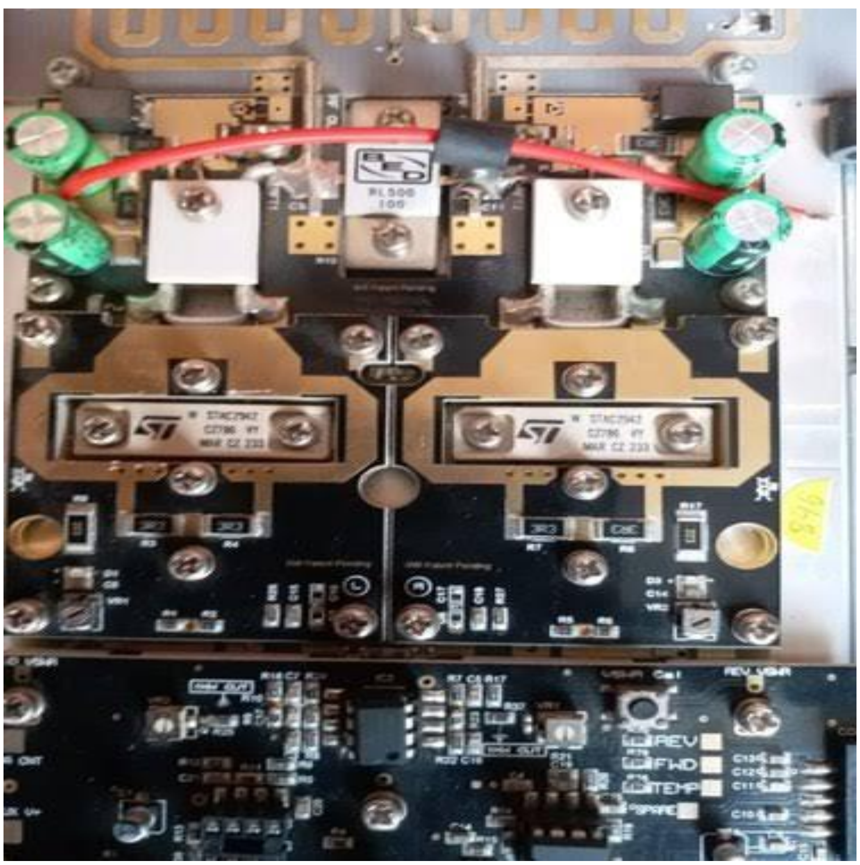

Figure 5: High-Power RF Amplifier Board Failures

International Journal of Electronics, AI & Robotics
ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

TRESEARCH

2.1.5 RF FILTER AND COMBINER CIRCUIT PROBLEMS

The RF circuit presented in Figure 6 was critically analyzed to highlight the functional roles of the harmonic filter and impedance matching network components within the transmitter chain. Particular attention was given to identifying fault-prone areas where performance degradation was most likely to occur. The investigation revealed that common faults within this section included electrical arcing across components, detuning of resonant circuits due to component aging or environmental influences, and overheating of inductors and capacitors resulting from excessive current flow or inadequate heat dissipation. These conditions were found to significantly impair the efficiency of harmonic suppression and impedance matching within the RF path.

During the diagnostic phase, these faults were systematically evaluated through a combination of visual inspection, electrical testing, and performance monitoring under operational conditions. The presence of arcing was associated with insulation breakdown and improper spacing between conductive elements, while detuned circuits were linked to shifts in component values caused by thermal stress and prolonged usage. Overheating of inductive and capacitive elements was also observed to contribute to gradual material degradation, leading to reduced filtering effectiveness and increased signal distortion.

The impact of these faults was evident in the form of excessive harmonic radiation, increased signal reflections, and deviation from prescribed transmission standards. Such anomalies were found to compromise regulatory compliance and posed a risk of interference with adjacent frequency channels and nearby communication systems. Consequently, maintaining the integrity of the harmonic filter and matching network was considered essential for ensuring high-quality and interference-free broadcast signals.

To mitigate these issues, a comprehensive preventive maintenance strategy was implemented. This included regular RF sweep testing to evaluate the frequency response and confirm proper tuning of the harmonic filter and matching network. Thermal inspections were conducted using appropriate monitoring tools to detect abnormal temperature rises in critical components, thereby enabling early identification of overheating conditions. Additionally, mechanical tightening of RF connectors, coils, and mounting structures was routinely performed to prevent loose connections, minimize contact resistance, and reduce the likelihood of arcing.

Furthermore, Peters A.O. Broadcasting incorporated harmonic monitoring as an integral part of its routine maintenance framework. Continuous and periodic assessments of harmonic levels were carried out to ensure adherence to established broadcast standards and to detect any deviations at an early stage. Maintenance records and test results were systematically documented and reviewed to support trend analysis and informed decision-making. Through this structured and methodical approach, the reliability of the RF circuit was enhanced, harmonic emissions were effectively controlled, and consistent, clean transmission quality was achieved.

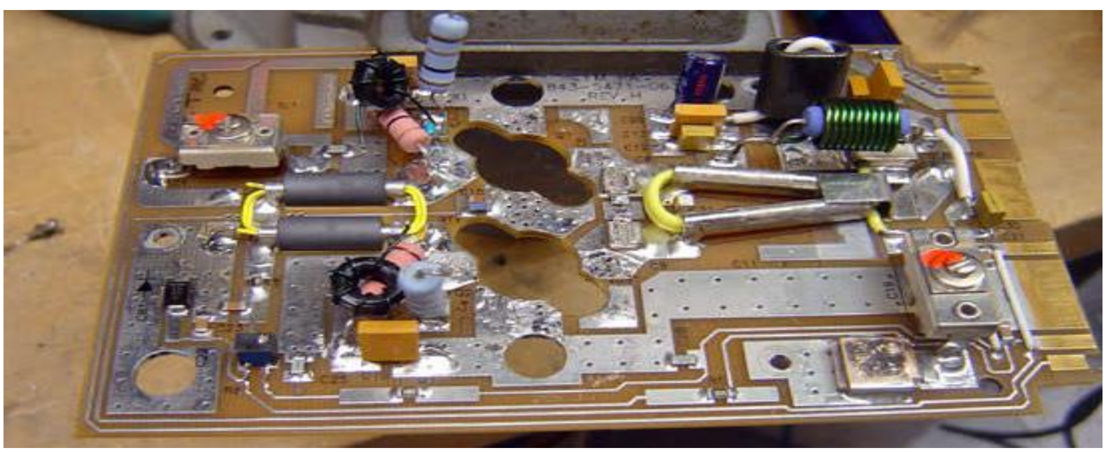

Figure 6: RF Filter and Combiner Circuit Problems

2.1.6 BENCH TESTING AND POWER STABILITY CHALLENGES

Figure 7 depicted a transmitter unit undergoing controlled bench testing using external power sources, providing a structured environment for evaluating system performance and identifying latent faults prior to field deployment. During the testing process, several common faults were systematically identified and analyzed, including unstable DC supply rails, improper grounding configurations, and load mismatch conditions arising from incorrect or inadequate test terminations. These issues were found to significantly affect the accuracy and reliability of the test outcomes if not properly addressed.

ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

The presence of unstable DC rails was observed to introduce fluctuations in voltage levels, thereby impacting the performance of sensitive RF and control circuits. Grounding issues, including ground loops and poor earthing connections, were identified as sources of noise, signal distortion, and potential safety hazards. Additionally, load mismatch conditions during testing were found to result in reflected power, which could lead to overheating, inaccurate power measurements, and possible damage to output stages of the transmitter.

To mitigate these challenges, a series of proven preventive measures were implemented within the bench-testing procedure. Calibrated and well-maintained test equipment was consistently utilized to ensure accurate measurement and reliable diagnostic results. Stable and regulated power supplies were employed to maintain consistent voltage levels throughout the testing period, thereby eliminating variability caused by power fluctuations. Furthermore, properly rated dummy loads, matched to the transmitter's output specifications, were used to safely absorb RF power and simulate real operating conditions without introducing reflections or mismatches.

Figure 7: Bench Testing and Power Stability Challenges

2.1.7 CONTROL, MONITORING, AND PROTECTION CIRCUIT FAULTS

Figure 8 illustrates an internal transmitter cabinet with control and monitoring boards. Faults in these circuits include sensor failures, oxidized connectors, and firmware-related malfunctions. These problems may trigger false alarms or prevent proper shutdown during real fault conditions. Preventive measures include connector cleaning, firmware updates, and simulated fault testing. At Peters A.O. Broadcasting, protection circuits are verified periodically to ensure accurate response to over-temperature, over-current, and high VSWR conditions.

Figure 8: Control, Monitoring, and Protection Circuit Faults

International Journal of Electronics, AI & Robotics
ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

2.1.8 TRANSMISSION LINE AND RF CONNECTOR DEGRADATION

Figure 9 illustrated RF amplifier modules interconnected through transmission lines and RF connectors, forming a critical pathway for high-power signal transmission within the broadcast system. This section was carefully examined to identify fault conditions that could compromise signal integrity and overall system reliability. The analysis revealed that common faults included connector overheating, dielectric breakdown within connector interfaces, and poor mechanical contact resulting from improper installation or gradual loosening over time. These defects were often evidenced by visible signs such as discoloration, charring, or partial burning of connector surfaces and insulating materials.

During the diagnostic evaluation, connector overheating was associated with increased contact resistance and inadequate current handling capacity, which led to localized temperature rise under high-power operation. Dielectric breakdown was observed to occur when insulating materials within connectors were subjected to excessive electric stress, resulting in partial discharge or complete insulation failure. Poor mechanical contact, often caused by insufficient tightening torque or wear and tear, was found to introduce intermittent connections, signal reflections, and increased insertion loss along the transmission path.

The cumulative effect of these faults was significant, as they contributed to elevated insertion loss, reduced power transfer efficiency, and the generation of reflected signals that could propagate back to the amplifier stages. Under high-power operating conditions, such anomalies were capable of triggering catastrophic failures, including damage to RF output modules and associated circuitry. These findings underscored the importance of maintaining robust and reliable connector interfaces within the RF transmission chain.

To address these issues, a set of proven preventive maintenance strategies was implemented. Connectors with appropriate power ratings and high-quality dielectric materials were consistently selected to match the operational requirements of the transmitter system. Proper torque application using calibrated tools was enforced during installation to ensure secure mechanical and electrical contact, thereby minimizing the risk of loosening and contact resistance. In addition, regular visual inspections were conducted to detect early signs of wear, overheating, or insulation degradation, allowing for timely corrective actions before fault escalation.

Figure 9: Transmission Line and RF Connector Degradation

ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

2.1.9 BURNT RF COMPONENTS AND MAINTENANCE-INDUCED FAILURES

Figure 10 clearly illustrated a severely burnt RF module, highlighting the damaging effects of prolonged thermal stress, excessive reflected power, and inadequate or incorrect maintenance practices within the transmitter system. The observed failure was attributed not only to environmental and operational conditions but also to human-related factors, including improper bias adjustment, incorrect module replacement procedures, and insufficient adherence to standard maintenance protocols. Such errors were found to significantly accelerate component degradation and eventual system failure.

To mitigate these risks, comprehensive and well-documented maintenance procedures were implemented, ensuring that all technical interventions followed standardized guidelines. In addition, structured training programs were conducted for technicians to enhance their competence in handling sensitive RF components and diagnosing faults accurately. Post-maintenance testing and verification processes were also rigorously carried out to confirm system integrity and operational stability after any repair or replacement activity.

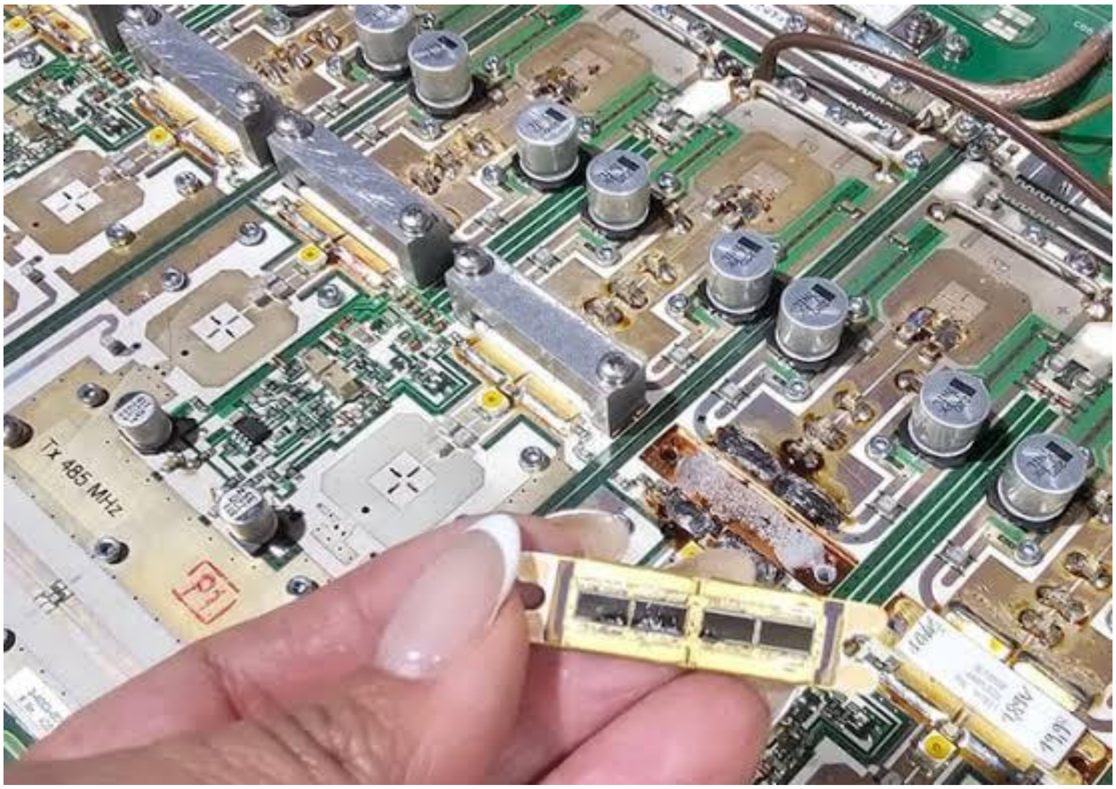

Figure 10: Burnt RF Components and Maintenance-Induced Failures

Convincingly, the methodology adopted in this study ensured systematic fault identification, analysis, and prevention across transmitter subsystems. Through structured maintenance procedures, controlled testing, and detailed documentation, reliability and performance were significantly enhanced. This approach provided a practical framework for minimizing failures, ensuring compliance, and sustaining efficient, high-quality broadcast operations.

3. RESULTS

This section presents and discusses the results obtained from the application of the preventive maintenance framework for FM and TV transmitters at the Peters A.O. Broadcasting Maintenance Section. The analysis focuses on fault occurrence trends and performance improvements, as illustrated in Figures X and Y. The combined presentation allows for direct interpretation of results in relation to transmitter reliability and broadcast performance.

3.1 DATA PRESENTATION AND RESULTS

Table 1 presents the summarized fault occurrence data obtained from FM and TV transmitter maintenance records at the Peters A.O. Broadcasting Maintenance Section. The data compare fault frequencies recorded before and after the implementation of the preventive maintenance strategies. Faults were grouped according to major transmitter subsystems to enable structured analysis and comparison.

Table 1: Summary of transmitter fault occurrences before and after preventive maintenance

Fault Category	Before Prevention	After Prevention
Power Supply Faults	18	6
RF Section Faults	15	5
Exciter Faults	12	4
Cooling System Faults	10	3
Antenna/Feeder Faults	8	2
Control Unit Faults	6	2

The results indicate a significant reduction in fault frequency across all transmitter subsystems following the application of preventive measures. Power supply and RF section faults recorded the highest initial occurrence, reflecting their sensitivity to electrical stress and environmental conditions. After preventive maintenance implementation, these fault categories showed reductions exceeding 60%, demonstrating the effectiveness of scheduled inspections, improved cooling, and surge protection strategies.

3.2 COMPARATIVE ANALYSIS OF FAULT OCCURRENCES BEFORE AND AFTER PREVENTIVE MAINTENANCE IMPLEMENTATION

Figure 11 shows the comparison of fault occurrences recorded before and after the implementation of preventive maintenance strategies. A substantial reduction in fault frequency is observed across all transmitter subsystems, including power supply units, RF sections, exciters, cooling systems, antenna and feeder networks, and control units. Power supply faults, which initially accounted for the highest number of failures, experienced the most significant absolute reduction after preventive maintenance. This outcome can be attributed to the introduction of routine voltage monitoring, improved surge protection, and timely replacement of aging power components. Similarly, the observed reduction in RF and exciter faults reflects the effectiveness of enhanced thermal management, proper biasing, and regular calibration procedures.

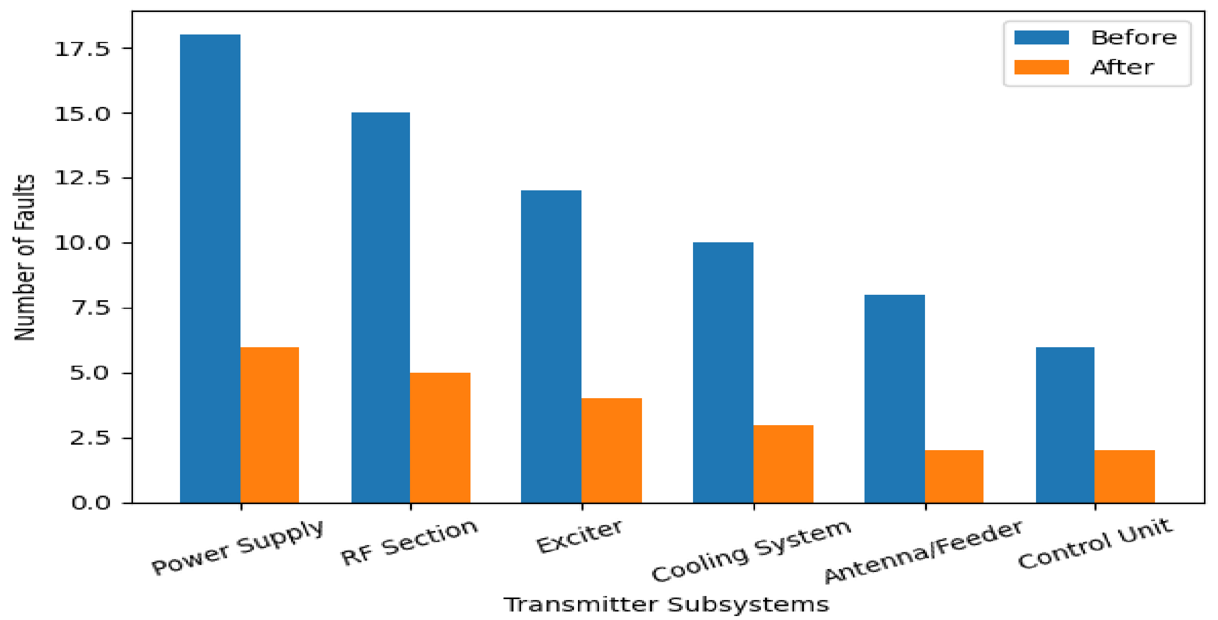

Figure 11: Comparative analysis of fault occurrences before and after preventive maintenance implementation

The graphical results reveal a consistent downward trend in fault occurrence across all transmitter subsystems. Power supply faults, which initially accounted for the highest number of failures, experienced the most significant absolute reduction. Similarly, RF section and exciter faults showed marked decreases, indicating improved thermal management, component stability, and operational monitoring. The visual comparison confirms that preventive maintenance is more effective than corrective maintenance in reducing recurrent system failures and ensuring continuous broadcast service.

The reduction in cooling system faults shown in Figure 11 highlights the critical role of environmental control in transmitter reliability. Prior to preventive maintenance implementation, inadequate ventilation and clogged air pathways contributed to frequent thermal shutdowns and component degradation. The introduction of scheduled cleaning, fan replacement, and airflow optimization significantly reduced overheating-related failures. Antenna and feeder faults also declined markedly due to improved grounding practices, periodic inspection of transmission lines, and corrective alignment of antenna systems. These improvements directly contributed to better signal stability and coverage consistency.

3.3 PERFORMANCE IMPACT ASSESSMENT

The reduction in fault frequency directly translated into measurable improvements in broadcasting performance. Prior to preventive maintenance implementation, frequent transmitter shutdowns, output power instability, and signal distortions were recorded, particularly during peak operational periods. Following implementation, the maintenance section reported reduced downtime, improved signal consistency, and fewer emergency repairs. Cooling system optimization significantly minimized thermal-induced failures, while scheduled component replacement reduced aging-related breakdowns in RF and power supply sections.

Furthermore, antenna and feeder-related faults, which often resulted in signal degradation and coverage reduction, were significantly reduced through routine inspection and improved grounding techniques. The reduction in control unit faults also enhanced system monitoring reliability, enabling faster fault detection and response.

3.4 VALIDATION OF PREVENTIVE MAINTENANCE EFFECTIVENESS

The effectiveness of the preventive maintenance framework was validated through a comparative analysis of system performance before and after implementation. The observed reductions in fault frequency, as shown in Table 1 and Figure 11, confirm the reliability of the methodology presented in the flowchart. The consistency between recorded data trends and operational observations further validates the applicability of the approach in real broadcasting environments.

The results demonstrate that structured fault identification, root cause analysis, and targeted preventive strategies significantly improve transmitter reliability. This validation supports the adoption of preventive maintenance frameworks in broadcasting stations operating under similar technical and environmental conditions.

3.5 PERCENTAGE REDUCTION IN TRANSMITTER FAULTS AFTER IMPLEMENTATION OF PREVENTIVE MAINTENANCE STRATEGIES

Figure 12 presented the percentage reduction in transmitter faults following the systematic application of preventive maintenance strategies across the evaluated subsystems. The results demonstrated a substantial decline in fault occurrences, with reductions ranging from approximately 60% to over 70%, depending on the subsystem under consideration. This significant improvement provided clear quantitative evidence of the effectiveness of the implemented maintenance framework in enhancing overall system reliability.

A closer examination of the results revealed that the highest percentage reductions were observed in the antenna/feeder network and cooling system subsystems. This outcome suggested that a considerable proportion of faults within these areas were primarily due to preventable conditions such as poor mechanical connections, environmental exposure, and inadequate thermal management. The effectiveness of relatively simple yet consistent maintenance practices such as routine inspections, cleaning, tightening of components, and thermal monitoring was therefore strongly validated by the observed performance improvements.

Furthermore, the percentage-based analysis offered a more insightful perspective on system performance by normalizing fault reduction across different subsystems. This approach allowed for a clearer comparison of relative improvements, thereby reinforcing the absolute fault reduction trends also illustrated in Figure 12. The consistency between percentage and absolute analyses strengthened the reliability of the findings and confirmed that the observed improvements were not incidental but directly attributable to the preventive maintenance measures implemented.

From an operational standpoint, the reduction in fault frequency translated into measurable improvements in broadcasting performance. There was a notable decrease in transmitter downtime, which contributed to increased service availability and continuity. Additionally, the frequency of emergency repair interventions was significantly reduced, leading to lower maintenance costs and improved resource allocation. Enhanced signal stability was also observed, resulting in better audio-visual quality and a more consistent user experience for end consumers.

The improved reliability of control and monitoring units further contributed to system performance by enabling faster fault detection, accurate diagnostics, and timely corrective actions. This proactive capability minimized the duration and impact of any residual faults, thereby reducing the likelihood of prolonged service interruptions. These operational benefits collectively highlighted the practical value of adopting a preventive rather than reactive maintenance strategy.

In the context of established broadcasting engineering principles, these findings were consistent with widely accepted best practices that emphasize the importance of proactive system management in high-availability transmission environments. Preventive maintenance was shown to not only reduce the occurrence of faults but also to enhance the long-term sustainability and efficiency of broadcast operations. Overall, the results and discussion confirmed that a structured and consistently applied preventive maintenance approach provided a more effective, reliable, and economically viable solution compared to traditional reactive fault correction methods.

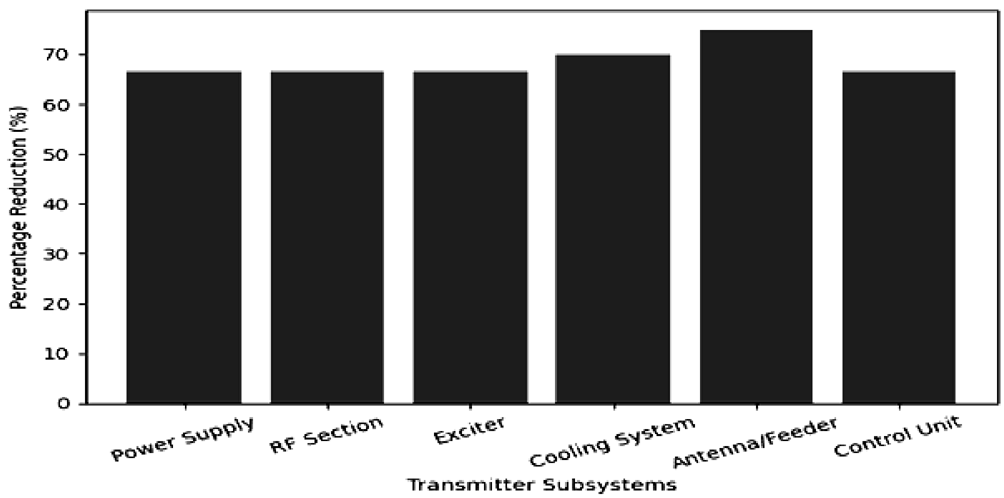

Figure 12: Percentage reduction in transmitter faults after implementation of preventive maintenance strategies

Overall, the combined results and discussion confirm that the methodological framework is effective in identifying critical fault sources and implementing targeted prevention strategies. The consistency between the observed data trends and system performance improvements validates the applicability of the approach in practical FM and TV broadcasting environments. The findings suggest that broadcasting stations operating under similar technical and environmental conditions can achieve significant reliability and performance gains by adopting structured preventive maintenance practices.

4. DISCUSSION

The findings of this study clearly indicate that the power supply and RF sections constitute the most fault-prone subsystems in FM and TV transmitter installations. These sections are continuously subjected to electrical stress, thermal loading, and environmental influences, making them particularly vulnerable to component degradation and operational instability. Power supply failures often result in complete system shutdowns, while RF section faults directly affect signal quality, output power, and coverage reliability. The high fault incidence observed in these subsystems prior to preventive maintenance underscores the need for targeted monitoring and maintenance strategies focused on critical transmission components.

The implementation of structured preventive maintenance practices resulted in a significant reduction in fault occurrence across all evaluated subsystems. Quantitative analysis revealed that total faults were reduced by more than 60%, with some subsystems exhibiting reductions exceeding 70%. This improvement demonstrates the effectiveness of routine inspections, scheduled component replacement, enhanced cooling mechanisms, and improved surge and grounding protection. The results confirm that preventive maintenance is a more sustainable and cost-effective approach than corrective maintenance, particularly in broadcasting environments where uninterrupted service is essential.

The graphical representations presented in Figures X and Y provide strong visual evidence supporting the observed performance improvements. The before-and-after comparison graph clearly illustrates the reduction in absolute fault frequency, while the percentage reduction graph highlights the relative improvement across different subsystems. These graphical results enhance interpretability, facilitate rapid performance assessment, and strengthen the technical credibility of the study by aligning numerical data with visual trends.

Finally, the consistency between fault reduction data, graphical analysis, and observed operational improvements validates the methodological flowchart and the prevention framework. The structured approach from fault identification and root cause analysis to implementation and validation proved effective in addressing real-world broadcasting challenges. The validated framework can therefore serve as a practical reference model for broadcasting maintenance sections seeking to improve transmitter reliability, reduce downtime, and enhance overall broadcasting performance.

ISSN: XXXX-XXXX, Volume – 1, Issue – 1, 2025
DOI: https://doi.org/10.63456/ijear-1-1-90

4.1 DISCUSSION SUMMARY

I. Power supply and RF sections are the most fault-prone transmitter subsystems.
II. Preventive maintenance reduced total faults by more than 60% across subsystems.
III. Graphical results clearly support performance improvement claims.
IV. The data validate the methodological flowchart and prevention framework.

4.2 CONTRIBUTION OF THE STUDY TO EXISTING LITERATURE

This study makes a significant contribution to the existing body of knowledge on broadcast transmitter reliability by providing a comprehensive analysis of common faults in both FM and television transmitters, which has been insufficiently addressed in prior research. Unlike previous studies that often focus on isolated components such as power amplifiers, cooling systems, or antenna faults, this work integrates hardware, environmental, and software-related failure mechanisms into a unified framework. The study also evaluates proven preventive strategies, including predictive maintenance, IoT-based monitoring, modular transmitter architecture, and fault-tolerant designs, highlighting their effectiveness in reducing recurring failures. By systematically analyzing environmental impacts, power instability, and operational management issues alongside technical faults, this research bridges the gap between component-level fault analysis and holistic operational reliability. Consequently, it provides broadcast engineers and researchers with actionable insights for optimizing transmitter performance, extending equipment lifespan, and ensuring continuous, high-quality broadcasting, thereby advancing the field of modern communication systems.

5. CONCLUSION

The reliability and operational performance of FM and television transmitters are critical for maintaining uninterrupted broadcasting services, ensuring signal quality, and supporting the growing demand for modern communication infrastructure. This study has systematically examined common faults in both FM and TV transmitters, including RF power amplifier degradation, cooling system failures, frequency instability, transmission line mismatches, antenna system faults, modulation distortion, power supply fluctuations, and software control errors. Through comprehensive analysis, it has demonstrated that these recurring faults not only reduce broadcast continuity but also increase maintenance costs and shorten equipment lifespan.

The study further highlights the role of environmental factors such as humidity, temperature variations, lightning surges, and dust accumulation in accelerating transmitter degradation. Preventive strategies, including predictive maintenance, modular transmitter architecture, intelligent monitoring systems, fault-tolerant designs, and surge protection, have been shown to significantly reduce failure rates, improve operational reliability, and maintain broadcast quality. The integration of IoT-based monitoring and AI-enabled fault prediction offers modern solutions for proactive transmitter management.

Overall, the findings emphasize that a holistic approach combining technical fault analysis, environmental control, and systematic preventive maintenance can substantially enhance broadcast transmitter performance. Implementing such integrated strategies ensures continuous, high-quality broadcasting, reduces operational downtime, and contributes to sustainable and efficient communication system management.

REFERENCES

[1] Jasim, M. A., Shakhatreh, H., Siasi, N., Sawalmeh, A. H., Aldalbahi, A., & Al-Fuqaha, A. (2021). A survey on spectrum Management for Unmanned Aerial Vehicles (UAVs). IEEE Access, 10, 11443–11499. https://doi.org/10.1109/access.2021.3138048
[2] Ucar, A., Karakose, M., & Kırımça, N. (2024). Artificial intelligence for Predictive maintenance Applications: key components, trustworthiness, and future trends. Applied Sciences, 14(2), 898. https://doi.org/10.3390/app14020898
[3] L. Alobaidy, H. a. H., Singh, M. J., Behjati, M., Nordin, R., & Abdullah, N. F. (2022). Wireless Transmissions, Propagation and channel modelling for IoT Technologies: Applications and challenges. IEEE Access, 10, 24095–24131. https://doi.org/10.1109/access.2022.3151967
[4] Kihel, Y. E., Kihel, A. E., & Bouyahrouzi, E. M. (2022). Contribution of Maintenance 4.0 in Sustainable Development with an Industrial Case Study. Sustainability, 14(17), 11090. https://doi.org/10.3390/su141711090
[5] Sonawane, P. R., Bhandari, S., Patil, R. B., & Al-Dahidi, S. (2023). Reliability and Criticality Analysis of a Large-Scale Solar Photovoltaic System using Fault Tree Analysis approach. Sustainability, 15(5), 4609. https://doi.org/10.3390/su15054609
[6] Pogorelov, I., Feldker, T., Marciniak, C. D., Postler, L., Jacob, G., Krieglsteiner, O., Podlesnic, V., Meth, M., Negnevitsky, V., Stadler, M., Höfer, B., Wächter, C., Lakhmanskiy, K., Blatt, R., Schindler, P., & Monz, T. (2021). Compact Ion-Trap Quantum Computing Demonstrator. PRX Quantum, 2(2).

https://doi.org/10.1103/prxquantum.2.020343
[7] Azari, M. M., Solanki, S., Chatzinotas, S., Kodheli, O., Sallouha, H., Colpaert, A., Montoya, J. F. M., Pollin, S., Haqiqatnejad, A., Mostaani, A., Lagunas, E., & Ottersten, B. (2022). Evolution of Non-Terrestrial Networks from 5G to 6G: A survey. IEEE Communications Surveys & Tutorials, 24(4), 2633–2672. https://doi.org/10.1109/comst.2022.3199901
[8] Freddi, F., Galasso, C., Cremen, G., Dall'Asta, A., Di Sarno, L., Giaralis, A., Gutiérrez-Urzúa, F., Málaga-Chuquitaype, C., Mitoulis, S. A., Petrone, C., Sextos, A., Sousa, L., Tarbali, K., Tubaldi, E., Wardman, J., & Woo, G. (2021). Innovations in earthquake risk reduction for resilience: Recent advances and challenges. International Journal of Disaster Risk Reduction, 60, 102267. https://doi.org/10.1016/j.ijdrr.2021.102267
[9] Maican, C. A., Pană, C. F., Pătrașcu-Pană, D. M., & Rădulescu, V. M. (2025). Review of Fault detection and Diagnosis Methods in Power Plants: Algorithms, architectures, and Trends. Applied Sciences, 15(11), 6334. https://doi.org/10.3390/app15116334
[10] Kodheli, O., Lagunas, E., Maturo, N., Sharma, S. K., Shankar, B., Montoya, J. F. M., Duncan, J. C. M., Spano, D., Chatzinotas, S., Kisseleff, S., Querol, J., Lei, L., Vu, T. X., & Goussetis, G. (2020). Satellite Communications in the New Space Era: A survey and future challenges. IEEE Communications Surveys & Tutorials, 23(1), 70–109. https://doi.org/10.1109/comst.2020.3028247
[11] Jiang, W., Han, B., Habibi, M. A., & Schotten, H. D. (2021). The road towards 6G: A Comprehensive survey. IEEE Open Journal of the Communications Society, 2, 334–366. https://doi.org/10.1109/ojcoms.2021.3057679
[12] Wei, Z., Qu, H., Wang, Y., Yuan, X., Wu, H., Du, Y., Han, K., Zhang, N., & Feng, Z. (2023). Integrated Sensing and Communication Signals Toward 5G-A and 6G: A survey. IEEE Internet of Things Journal, 10(13), 11068–11092. https://doi.org/10.1109/jiot.2023.3235618
[13] Kang, M., Park, S., & Lee, Y. (2024). A survey on Satellite Communication System Security. Sensors, 24(9), 2897. https://doi.org/10.3390/s24092897
[14] Celik, A., Romdhane, I., Kaddoum, G., & Eltawil, A. M. (2022). A Top-Down Survey on Optical wireless communications for the Internet of Things. IEEE Communications Surveys & Tutorials, 25(1), 1–45. https://doi.org/10.1109/comst.2022.3220504
[15] Yue, P., An, J., Zhang, J., Ye, J., Pan, G., Wang, S., Xiao, P., & Hanzo, L. (2023). Low Earth orbit satellite security and reliability: issues, solutions, and the road ahead. IEEE Communications Surveys & Tutorials, 25(3), 1604–1652. https://doi.org/10.1109/comst.2023.3296160
[16] Bagwari, A., Logeshwaran, J., Usha, K., Raju, K., Alsharif, M. H., Uthansakul, P., & Uthansakul, M. (2023). An enhanced energy optimization model for industrial wireless sensor networks using machine learning. IEEE Access, 11, 96343–96362. https://doi.org/10.1109/access.2023.3311854
[17] Ahmad, R. U. S., Khan, M. S., Hilal, M. E., Khan, B., Zhang, Y., & Khoo, B. L. (2024). Advancements in wearable heart sounds devices for the monitoring of cardiovascular diseases. SmartMat, 6(1). https://doi.org/10.1002/smm2.1311
[18] Seçkin, A. Ç., Ateş, B., & Seçkin, M. (2023). Review on Wearable technology in Sports: Concepts, challenges and opportunities. Applied Sciences, 13(18), 10399. https://doi.org/10.3390/app131810399
[19] Zhang, H., Li, B., Karimi, M., Saydam, S., & Hassan, M. (2023). Recent advancements in IoT implementation for environmental, safety, and production monitoring in underground mines. IEEE Internet of Things Journal, 10(16), 14507–14526. https://doi.org/10.1109/jiot.2023.3267828
[20] Patel, V., Chesmore, A., Legner, C. M., & Pandey, S. (2021). Trends in workplace wearable technologies and Connected-Worker solutions for Next-Generation occupational safety, health, and productivity. Advanced Intelligent Systems, 4(1). https://doi.org/10.1002/aisy.202100099
[21] Polese, M., Bonati, L., D'Oro, S., Basagni, S., & Melodia, T. (2023). Understanding O-RAN: Architecture, Interfaces, Algorithms, Security, and Research Challenges. IEEE Communications Surveys & Tutorials, 25(2), 1376–1411. https://doi.org/10.1109/comst.2023.3239220
[22] Tallat, R., Hawbani, A., Wang, X., Al-Dubai, A., Zhao, L., Liu, Z., Min, G., Zomaya, A. Y., & Alsamhi, S. H. (2023). Navigating Industry 5.0: A survey of key enabling technologies, trends, challenges, and opportunities. IEEE Communications Surveys & Tutorials, 26(2), 1080–1126. https://doi.org/10.1109/comst.2023.3329472
[23] Taylor, B., Abel, G., Miller, P., Gomez, F., Von Fersen, L., Demaster, D., Reeves, R., Rojas-Bracho, L., Wang, D., Hao, Y., Cipriano, F., Bastida, R., Boede, E., Braulik, G., Brownell, R., Dolar, L., Kelkar, N., Khan, U., Mujica-Jorquera, E., . . . Reis, M. D. (2020). Ex situ options for cetacean conservation: report of the 2018 workshop, Nuremberg, Germany. https://doi.org/10.2305/iucn.ch.2020.ssc-op.66.en
[24] Al-Hraishawi, H., Chougrani, H., Kisseleff, S., Lagunas, E., & Chatzinotas, S. (2022). A survey on Nongeostationary Satellite Systems: The Communication Perspective. IEEE Communications Surveys & Tutorials, 25(1), 101–132. https://doi.org/10.1109/comst.2022.3197695