e-ISSN 2581-0405
Asian Journal of Applied Research for Community Development and Empowerment
Journal home page: http://ajarcde-safe-network.org ISSN 2581-0405

Failure Analysis of a Total Breakdown in a Firman FPG1500ECII Generator Set Using Root Cause Identification

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ARTICLE INFO

Article History:
Received: 01 July 2026
Final Revision: 07 July 2026
Accepted: 09 July 2026
Online Publication: 12 July 2026

KEYWORDS

Generator set; failure analysis; failure propagation; root cause identification; preventive maintenance.

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A B S T R A C T

Generator set failures are commonly investigated by examining individual damaged components; however, limited studies have systematically integrated failure mechanism analysis, failure propagation analysis, and Root Cause Identification (RCI) to explain the sequence of events leading to total system breakdown. This study aims to identify the failure mechanisms and root causes of a total breakdown in a Firman FPG1500ECII gasoline-powered generator set and to develop evidence-based preventive maintenance recommendations. The investigation employed a forensic engineering approach by integrating systematic visual inspection, tribological failure analysis, failure propagation analysis, Fishbone Diagram, and 5 Why Analysis. The results revealed that inadequate lubrication management was the primary initiating factor, leading to progressive piston ring wear, bearing damage, carbon deposit accumulation, valve leakage, ignition system deterioration, and ultimately complete engine failure. Failure propagation analysis demonstrated that the breakdown resulted from the interaction of multiple component failures rather than the failure of a single component. Based on the identified root causes, an evidence-based preventive maintenance schedule was developed using manufacturer recommendations and previous maintenance studies. The principal contribution of this study is the development of an integrated engineering failure analysis framework that systematically links failure mechanisms, failure propagation, and Root Cause Identification to support maintenance decision-making and improve the reliability of gasoline-powered generator sets operating under similar conditions.

Contribution to Sustainable Development Goals (SDGs):
SDG 7: Affordable and Clean Energy
SDG 8: Decent Work and Economic Growth
SDG 9: Industry, Innovation and Infrastructure
SDG 12: Responsible Consumption and Production

1. INTRODUCTION

1.1. Research Background

Generator sets (gensets) are one of the most widely used independent power sources and play a crucial role in ensuring the continuity of electricity supply across various sectors, including households, micro- and small-scale enterprises, healthcare facilities, agriculture, construction sites, and industrial applications [1], [2] Gensets provide an effective solution during power outages from the main electrical grid and in remote areas that are not yet connected to the national electricity network. With the increasing demand for a reliable electricity supply, the use of small-capacity generator sets has expanded significantly due to their relatively low investment cost, simple construction, ease of operation, and high portability. Nevertheless, the increasing intensity of genset utilization also raises the risk of performance degradation and component failure when maintenance activities are not carried out properly [3], [4], [5]

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The reliability of a generator set is highly dependent on the condition of its constituent subsystems, including the combustion system, lubrication system, ignition system, cooling system, power transmission mechanism, and electrical generation system [6], [7]. These subsystems operate in an integrated manner, such that failure in a single component can adversely affect the performance of other components. During operation, engine components are subjected to repeated mechanical loading, high combustion temperatures, metal-to-metal friction, combustion gas pressure, and contamination from carbon residues [8]. These operating conditions progressively lead to wear, deformation, deterioration of material properties, and functional degradation of engine components. If such damage is not detected and addressed promptly through an appropriate maintenance program, it may propagate into more complex system failures and ultimately result in the loss of the generator set's operational capability[9], [10].

One of the most critical failure modes in generator sets is total breakdown, a condition in which the engine cannot be started and the generator is incapable of producing electrical power [11]. Unlike performance degradation, where the engine remains operational despite reduced efficiency, total breakdown indicates a complete loss of system functionality. Under such circumstances, operations that depend on the generator set are interrupted, potentially resulting in economic losses, reduced productivity, and even safety risks in applications requiring an uninterrupted power supply. Therefore, total breakdown is not merely a technical issue but also a significant concern in the fields of reliability engineering and maintenance management [12], [13].

From a technical perspective, total breakdown in a four-stroke gasoline engine is rarely caused by the failure of a single component. Instead, it is the cumulative result of multiple failure mechanisms that develop progressively throughout the engine's service life. Piston ring wear reduces the cylinder's ability to maintain compression pressure, leading to incomplete combustion. Wear of the connecting rod bearing and main bearing increases mechanical friction, enlarges internal clearances, and reduces crankshaft rotational stability [14], [15]. Furthermore, the accumulation of carbon deposits on the combustion chamber, piston crown, valves, and spark plug electrodes impairs combustion, causes compression leakage, and increases the likelihood of engine misfire. The combined effects of these failure mechanisms result in a loss of combustion pressure, increased frictional energy losses, and disruption of the conversion of chemical energy into mechanical energy, ultimately preventing the engine from generating the rotational speed required to drive the generator [16], [17], [18].

From the perspective of maintenance engineering, total failure cannot be effectively addressed merely by replacing visibly damaged components. Such an approach often eliminates only the symptoms of failure without resolving the underlying causes, thereby increasing the likelihood that the same failure will recur once the equipment is returned to service [19], [20], [21]. Therefore, a comprehensive investigative approach is required to explain how the damage originated, how it propagated to other components, and which factors ultimately led to the loss of system functionality. This approach is commonly referred to as failure analysis, a systematic process for identifying failure mechanisms through visual inspection, component disassembly, physical condition assessment, damage pattern evaluation, and cause-and-effect analysis of the interactions among failed Failure analysis plays a vital role in improving the effectiveness of maintenance programs by providing a comprehensive understanding of failure propagation from the component level to the system level. Through this approach, engineers and researchers are able not only to identify failed components but also to determine the sequence of failure events, distinguish between primary and secondary failures, and evaluate the contribution of each failure mode to the degradation of the generator set's performance. The knowledge obtained from this analysis serves as a foundation for establishing appropriate corrective actions, developing effective preventive maintenance schedules, enhancing equipment reliability, and minimizing the risk of future downtime [23], [24].

One of the most widely adopted approaches in failure investigation is Root Cause Identification (RCI). This method aims to determine the fundamental causes of system failure rather than merely identifying observable symptoms of damage. Root Cause Identification is conducted by analyzing the relationships among component condition, operating history, maintenance practices, wear mechanisms, lubrication performance, combustion processes, and environmental factors affecting engine performance [24], [25]. By identifying the underlying causes of failure, corrective actions can be directed toward the actual sources of damage, thereby improving maintenance effectiveness compared with repeatedly replacing failed components without addressing the root cause [27], [28].

Numerous previous studies on generator sets have investigated the effects of fuel type on engine performance, fuel consumption, thermal efficiency, exhaust emissions, and performance improvements following maintenance and overhaul procedures [28], [29]. Other studies have focused on developing reliability-centered maintenance, condition-based maintenance, and predictive maintenance strategies to extend generator service life [30]. These studies have made significant contributions to the advancement of generator set maintenance systems. However, most previous research has primarily emphasized performance evaluation after successful repair, whereas investigations into the failure mechanisms responsible for total generator breakdown prior to maintenance intervention remain relatively limited [31]. Furthermore, earlier studies have generally focused on identifying failed components without comprehensively explaining the interactions among failure modes, the mechanisms of failure propagation, or the underlying root causes that ultimately result in the complete loss of generator operational functionality [32], [33].

Based on the aforementioned conditions, a significant research gap remains in the study of failure analysis for small-capacity generator sets. To date, only a limited number of studies have integrated visual inspection, component damage identification, failure mechanism analysis, and Root Cause Identification (RCI) into a comprehensive framework for explaining the causes of total breakdown in gasoline-powered generator sets. Such an integrated understanding of failure mechanisms is essential for developing more effective maintenance strategies, prioritizing component replacement, and designing fault diagnosis systems capable of detecting failures before they progress into catastrophic breakdowns.

Accordingly, this study aims to investigate the total breakdown of a Firman FPG1500ECII generator set through an integrated Failure Analysis and Root Cause Identification

approach. The investigation involves engine disassembly, visual inspection, assessment of the condition of critical components, and analysis of the interactions among failure mechanisms affecting the piston rings, connecting rod bearing, main bearing, valve system, combustion chamber, and ignition system. Unlike previous studies that primarily focused on evaluating engine performance after overhaul, this research emphasizes the identification of the root causes of failure and the failure propagation mechanisms responsible for the generator's complete operational breakdown. The findings are expected to contribute to the advancement of generator set failure diagnosis methods, enrich the body of knowledge on failure analysis of small-capacity gasoline engines, and provide a scientific basis for developing more effective maintenance strategies to enhance the reliability and service life of generator sets [34], [35].

1.2. Literature Review

1.2.1. Failure Analysis

Failure analysis is one of the most widely applied approaches in mechanical engineering for identifying the root causes of failures in mechanical components and systems. This approach aims to explain how a failure occurs, the mechanisms by which damage propagates through individual components, and the cause-and-effect relationships that ultimately lead to the loss of a system's operational functionality [36] . Unlike routine inspections, which primarily identify damaged components, failure analysis seeks to reveal the underlying physical and operational mechanisms responsible for the initiation and progression of damage into system-level failure. Consequently, failure analysis serves not only as a basis for corrective actions but also as a fundamental element in the development of reliability-based maintenance (RBM) strategies [36], [37].

In internal combustion engines (ICEs), component failure generally begins with material degradation caused by repeated mechanical loading, elevated operating temperatures, friction, material fatigue, corrosion, or inadequate lubrication. These degradation processes lead to dimensional changes, deterioration of material strength, and progressive wear of critical engine components such as pistons, piston rings, bearings, valves, crankshafts, and other power transmission mechanisms [38]. If these defects are not detected and addressed promptly, failure propagation may occur from the component level to the subsystem level, eventually resulting in total engine breakdown. Therefore, a thorough understanding of the failure mechanisms affecting individual components is essential for establishing effective maintenance strategies and improving engine reliability [39], [40].

One of the engine components most susceptible to failure in gasoline engines is the piston ring. Piston rings function to maintain cylinder compression, regulate the distribution of lubricating oil along the cylinder wall, and facilitate heat transfer from the piston to the cylinder block. Wear of the piston rings can lead to compression leakage (blow-by), increased lubricating oil consumption, reduced combustion efficiency, and a decline in engine power output. Furthermore, reduced compression pressure leads to incomplete combustion, increasing fuel consumption and exhaust gas emissions. Consequently, the condition of piston rings is widely regarded as one of the primary indicators in engine health assessment [41], [42].

In addition to piston rings, connecting rod bearings and main bearings are critical components that significantly influence engine reliability. These bearings are designed to minimize friction between the rotating shaft and the bearing housing, thereby ensuring stable crankshaft rotation. Bearing failure is commonly initiated by lubrication system deficiencies, which prevent the lubricating oil film from effectively separating the contacting metal surfaces. As a result, operating temperatures increase, leading to scoring, abrasive wear, surface deformation, and eventually catastrophic bearing failure. If bearing deterioration continues, the resistance to crankshaft rotation increases, reducing the engine's mechanical efficiency and ultimately preventing normal engine operation [43], [44].

The combustion system is another critical factor contributing to engine failure. Carbon deposit accumulation on the combustion chamber, piston crown, valves, and spark plug electrodes is a common phenomenon in gasoline engines that have been operated for extended periods or have experienced incomplete combustion. These carbon deposits alter the effective combustion chamber volume, interfere with the ignition of the air–fuel mixture, increase the likelihood of engine misfire, and accelerate valve leakage. Under certain operating conditions, excessive carbon accumulation can also create localized hot spots within the combustion chamber, thereby increasing thermal stresses and accelerating the degradation of engine component materials [45].

The identification of the underlying causes of failure is performed using the Root Cause Identification (RCI) approach in maintenance engineering. RCI is a systematic investigative process aimed at determining the most fundamental causes of a failure so that corrective actions can be implemented effectively. Rather than focusing solely on the damaged components, Root Cause Identification also evaluates the contributing factors that influence failure occurrence, including lubrication quality, operating conditions, maintenance practices, environmental conditions, and component service life. By identifying the root causes of failure, corrective measures can address not only the observable symptoms but also prevent the recurrence of similar failures in future operation [46], [47].

Numerous previous studies have demonstrated that failure analysis makes a significant contribution to improving machine reliability. Most of these studies have focused on the wear mechanisms of engine components, bearing failure analysis, the influence of lubrication systems on component service life, and the relationship between combustion conditions and material degradation [38]. Other research has primarily investigated condition-based maintenance (CBM), predictive maintenance (PdM), and reliability assessment using Failure Mode and Effects Analysis (FMEA) and Reliability-Centered Maintenance (RCM) methodologies [48]. The findings of these studies consistently indicate that identifying the root causes of failure can reduce failure frequency, improve system reliability, and extend equipment service life [49].

Nevertheless, research on failure analysis of small-capacity generator sets has predominantly focused on performance improvement following maintenance procedures, the effects of different fuel types on combustion efficiency, and fuel consumption evaluation. Studies that comprehensively integrate visual inspection, component damage identification, failure mechanism analysis, and Root Cause Identification (RCI) to investigate generator sets that have experienced total breakdown remain relatively scarce. Furthermore, most existing studies

https://doi.org/10.29165/ajarcde.v10i3.1190

merely report the condition of failed components without explaining the interactions among individual failure mechanisms that ultimately lead to the complete loss of system functionality [50].

Based on the literature review, it can be concluded that there remains a significant opportunity to advance failure analysis of generator sets through a more comprehensive approach. This study not only identifies the damage affecting each major engine component but also investigates the failure propagation mechanisms and determines the root causes responsible for the total breakdown of the generator set. This integrated approach is expected to provide a novel contribution to the development of generator set fault diagnosis methodologies and to establish a scientific basis for designing more effective preventive maintenance strategies aimed at improving equipment reliability and extending service life.

Although visual inspection, tribological analysis, and Root Cause Identification have individually been applied in mechanical failure investigations, previous studies generally focused only on identifying damaged components or evaluating generator performance after repair. Few studies have systematically integrate component-level damage identification, tribological failure mechanisms, failure propagation pathways, and Root Cause Identification into a unified analytical framework specifically for total breakdown in small gasoline-powered generator sets. Therefore, the novelty of this study lies not merely in combining several established methods, but in developing a comprehensive diagnostic framework capable of explaining how multiple interacting failure mechanisms evolve from lubricant degradation to complete system failure and subsequently translating these findings into structured preventive maintenance recommendations. This integrated framework provides a more systematic basis for reliability improvement than conventional component-based failure investigations.

1.3. Research Objective

This study aims to investigate the total breakdown of a Firman FPG1500ECII generator set using an integrated Failure Analysis and Root Cause Identification (RCI) approach. The investigation involves engine disassembly, visual inspection, assessment of the condition of critical components, and evaluation of the failure mechanisms affecting the piston rings, connecting rod bearing, main bearing, valve system, spark plug, and combustion chamber. Furthermore, the study seeks to analyze the interactions among individual failure modes (failure propagation) in order to determine the root causes responsible for the loss of the generator set's operational capability. The findings are expected to contribute to the advancement of failure diagnosis methodologies for small-capacity generator sets, provide a scientific reference for the development of effective preventive maintenance strategies, and enhance generator set reliability and service life through the systematic identification of failure causes.

2. MATERIALS AND METHODS

2.1. Research Materials

The research object in this study is a Firman FPG1500ECII generator set equipped with a four-stroke gasoline engine, having a rated power output of 1000 W and a maximum power output of 1200 W. The generator set was in a state of total breakdown, meaning that the engine could not be started and was incapable of generating electrical power, thereby rendering it unable to perform its intended operational function. This condition indicated the presence of failure in one or more engine subsystems, necessitating a comprehensive investigation to identify the root causes of the damage prior to any repair activities.

This study focuses on the failure analysis of major engine components that directly affect the generator's power-generation capability. The analyzed components include the cylinder block, piston, piston rings, connecting rod, connecting rod bearing, crankshaft, main bearing, cylinder head, intake valve, exhaust valve, combustion chamber, spark plug, carburetor, and lubrication system. The selection of these components was based on the results of the preliminary inspection, which indicated signs of wear, carbon deposit accumulation, lubricant degradation, and mechanical damage that were suspected to be the primary contributors to the generator set failure.

The primary materials analyzed in this study consist of engine components that experienced damage during service operation. Each component was examined to assess its physical condition, degree of wear, surface discoloration, deformation, cracking, scoring, carbon deposits, and other damage characteristics that could serve as indicators of the underlying failure mechanisms. The condition of each component was evaluated by comparing the observed damage with the technical specifications and service criteria recommended by the manufacturer, thereby enabling the extent of deviation and deterioration that occurred during operation to be determined.

The equipment used in this study consisted of a set of hand tools for engine disassembly and reassembly, a feeler gauge for measuring valve clearance and piston ring end gap, a vernier caliper with an accuracy of 0.02 mm for measuring component dimensions, an outside micrometer for measuring shaft diameters and the thickness of worn components, and a dial indicator for evaluating crankshaft runout when required. In addition, a compression tester was employed to measure cylinder compression pressure prior to engine disassembly, a digital multimeter was used to verify the continuity of the ignition and electrical generation systems, and a digital tachometer served as a supporting instrument for measuring engine speed following the completion of repair procedures.

The condition of each component was documented using a high-resolution digital camera to provide visual evidence throughout every stage of the investigation. All damaged components were photographed both before and after cleaning to enable detailed observation of damage characteristics, wear patterns, and the locations of defects. These visual records were subsequently used as the basis for identifying the underlying failure mechanisms and analyzing the interactions among individual failures (failure propagation).

Root Cause Identification (RCI) was performed using the results of visual inspection, dimensional measurements, damage pattern analysis, and evaluation of the cause-and-effect relationships among failed components. The collected data were then analyzed to determine the primary failure, secondary failures, and the root causes responsible for the generator set's total breakdown. Figure 1 shows the Firman FPG1500ECII generator set used as the research object prior to engine disassembly and failure investigation.

Figure 1. Unit Generator Firman FPG1500ECII

2.1.1. Operational History of the Generator Set

Prior to failure, the Firman FPG1500ECII generator set had been operated daily to supply power to a micro, small, and medium enterprise (MSME) food business. The generator typically operated from approximately 08:00 to 21:00, corresponding to an average daily operating duration of about 13 hours, to supply electricity for business activities. In addition to its primary function, the generator was also used as an emergency backup power source during unexpected outages of the public electricity grid (PLN). Owing to its intensive operating schedule, maintenance activities were generally performed only after operational problems became apparent, and no documented preventive maintenance records were available. Engine oil replacement intervals frequently exceeded the manufacturer's recommended service interval of 50 operating hours, while routine inspection of the air filter and lubrication system was not consistently performed. Furthermore, the generator was operated in a dusty commercial environment, increasing the likelihood of airborne contaminants entering the air intake and lubrication systems, thereby accelerating lubricant degradation and abrasive wear on critical engine components.

2.2. Research Methods

This study employed a failure investigation methodology using a Root Cause Identification (RCI) approach to determine the underlying causes of the complete breakdown of the Firman FPG1500ECII generator set. The investigation was conducted systematically through a series of stages, including preliminary inspection, engine disassembly, identification of component damage, analysis of failure mechanisms, analysis of failure propagation, and determination of the root causes of failure. This integrated approach was adopted to establish the cause-and-effect relationships between the failure of individual components and the complete loss of the generator set's operational functionality. The research methodology is illustrated in Figure 2.

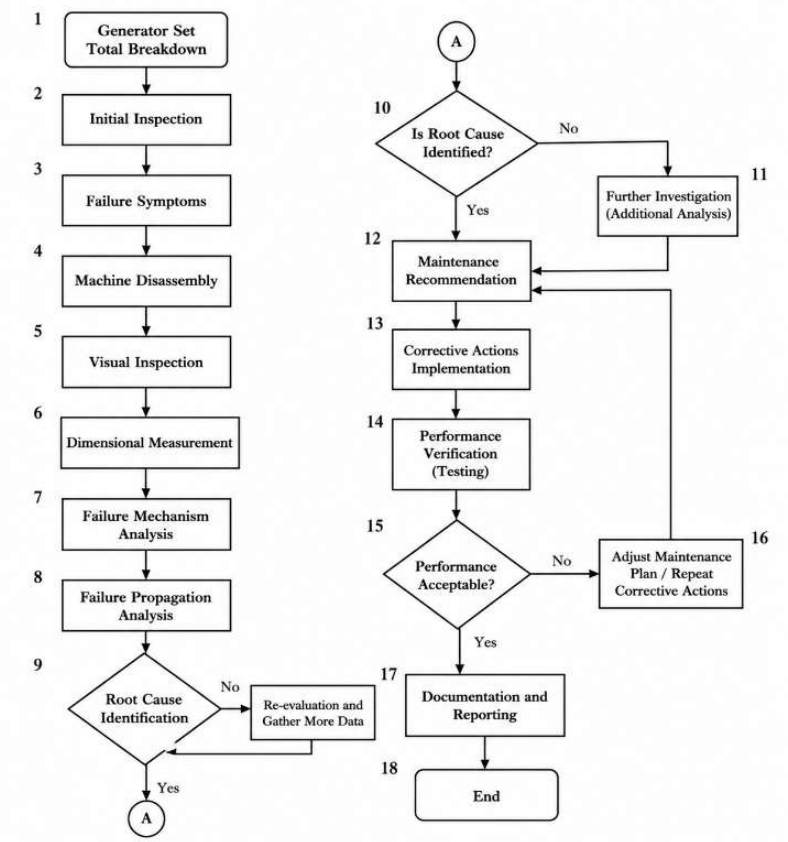

Figure 2. Flowchart of the maintenance and performance testing process for the Firman FPG1500ECII generator set

The first stage consisted of an initial inspection of the generator set that was in a total breakdown condition. The inspection was performed without engine disassembly to obtain preliminary information regarding the failure symptoms. The parameters evaluated included the physical condition of the generator set, engine starting capability, ignition system condition, fuel system, lubrication system, crankshaft rotation, and the generator's ability to produce electrical power. The results

https://doi.org/10.29165/ajarcde.v10i3.1190

of the initial inspection served as the basis for determining the disassembly procedure and identifying the components requiring further examination.

The next stage involved the complete engine disassembly in accordance with the recommended generator set maintenance procedures. The disassembly was carried out systematically, beginning with the removal of the fuel system, ignition system, cylinder head, piston assembly, connecting rod, crankshaft, main bearing, and finally the generator components. Each component was assigned a unique identification code to maintain the correct reassembly sequence and facilitate documentation throughout the investigation.

All disassembled components subsequently underwent a visual inspection to identify the types of damage present, including wear, cracking, scoring, deformation, discoloration caused by elevated temperatures, corrosion, and carbon deposit accumulation. In addition to the visual examination, dimensional measurements were performed on components exhibiting signs of wear using a vernier caliper, outside micrometer, and feeler gauge. The measured dimensions were then compared with the manufacturer's technical specifications to determine the extent of deviation and deterioration of each component.

The subsequent stage involved failure mechanism analysis, in which the damage characteristics observed in each component were evaluated to determine the degradation mechanisms that occurred during service operation. The analysis was based on wear characteristics, surface conditions of the components, lubrication performance, combustion processes, and the interactions among interconnected components. At this stage, the failure mechanisms were classified according to their dominant causes, including abrasive wear, adhesive wear, fatigue wear, lubrication failure, and incomplete combustion.

Once the failure mechanisms of the individual components had been identified, a failure propagation analysis was conducted to explain the sequence by which damage developed from one component to another. This analysis aimed to determine whether the observed damage represented a primary failure or resulted from the failure of another component as a secondary failure. The relationships among individual failures were evaluated using a cause-and-effect approach to explain how the combined failures of the combustion system, lubrication system, ignition system, and power transmission mechanism ultimately resulted in the complete loss of the generator set's operational capability.

The final stage of the study was Root Cause Identification (RCI). The root cause analysis was performed by integrating the results of the visual inspection, dimensional measurements, failure mechanism analysis, and failure propagation analysis. Each observed failure indicator was systematically evaluated to identify the immediate causes, intermediate causes, and the root causes that ultimately led to the generator set's total breakdown. The identified root causes were subsequently used as the basis for developing maintenance recommendations aimed at preventing similar failures and improving the long-term reliability of the generator set.

To improve the reliability of the Root Cause Identification (RCI) and minimize investigator bias, the identified root causes were established through methodological triangulation using four complementary sources of evidence: (1) systematic visual inspection of damaged components, (2) tribological failure mechanism analysis, (3) failure propagation analysis, and (4) comparison with manufacturer recommendations and findings reported in previous studies. The consistency of the identified failure sequence was evaluated by examining the observed physical damage characteristics and assessing whether the failure progression was consistent with established tribological principles and documented failure mechanisms in the literature. The Fishbone Diagram and 5 Why Analysis were developed only after all sources of evidence consistently indicated the same sequence of failure mechanisms and root causes. Furthermore, the proposed root causes were discussed among the research team to ensure consistency between the observed physical evidence, tribological failure mechanisms, and failure propagation analysis before the final Fishbone Diagram and 5 Why Analysis were established.

This triangulation approach increased the credibility of the Root Cause Identification by ensuring that the identified root causes were supported by both qualitative observations and quantitative dimensional measurements rather than relying solely on subjective interpretation.

This investigation was designed as an engineering failure case study focusing on identifying failure mechanisms and root causes through systematic inspection and Root Cause Identification (RCI). Because the generator set had already experienced a total breakdown prior to the investigation, quantitative operational measurements such as vibration, compression pressure, lubricant viscosity, and real-time performance data could not be collected. Therefore, the analysis relied on methodological triangulation consisting of visual inspection, dimensional verification of critical components, tribological failure interpretation, and failure propagation analysis to establish the root causes.

The research data were analyzed using a qualitative descriptive analysis approach by comparing the actual condition of each component with the manufacturer's technical specifications, established theories of mechanical component failure, and findings from previous studies on internal combustion engine failures. The analysis focused on identifying the characteristics of component damage, evaluating the underlying failure mechanisms, and interpreting the interactions among individual failure modes that ultimately resulted in the total breakdown of the generator set. The findings are presented in the form of detailed descriptions, summary tables, inspection photographs, and failure propagation diagrams, providing a systematic and comprehensive explanation of the generator set failure mechanisms.

3. RESULT AND DISCUSSION

3.1. *Initial Condition of the Generator Set*

The initial condition assessment of the generator set constitutes a critical stage in the failure investigation process, as it provides valuable information regarding the failure symptoms observed prior to engine disassembly. The preliminary inspection was conducted without dismantling the engine to identify indications of damage and determine which subsystems were likely affected. This stage was intended to provide an overall assessment of the generator set's operational condition and to serve as the basis for planning subsequent inspection procedures. The evaluated parameters included the physical condition of the generator set, engine starting capability, starting system performance, electrical output voltage, ignition system, fuel

system, lubricant condition, and engine sound during the initial operational test.

The inspection results indicated that the Firman FPG1500ECII generator set was in a state of total breakdown, as evidenced by the engine's inability to start despite the presence of sufficient fuel in the fuel tank. During the starting attempt, the starter exhibited noticeably greater rotational resistance than under normal operating conditions, suggesting increased mechanical resistance within the engine drive mechanism. Furthermore, the generator was unable to produce output voltage, rendering it incapable of performing its primary function as an electrical power source. Examination of the ignition system also revealed that the spark plug generated a relatively weak spark, while the lubricating oil appeared dark black and exhibited clear signs of degradation resulting from prolonged service. No significant external damage was observed on the generator frame or housing during the visual inspection, indicating that the initial evidence pointed to failures within the internal engine components.

Table 3. Initial Failure Symptoms of the Firman FPG1500ECII Generator Set

No.	Observation Parameter	Condition	Initial Assessment
1	Engine start	Failed	Engine could not be started despite sufficient fuel supply.
2	Generator output	No voltage	Generator failed to produce electrical output.
3	Starter rotation	Heavy	High mechanical resistance during cranking.
4	Engine noise	Abnormal	Irregular mechanical sound before engine stopped completely.
5	Fuel supply	Available	Fuel level was adequate and fuel flow was normal.
6	Spark plug ignition	Weak	Weak spark indicated poor ignition performance.
7	Lubricating oil condition	Dark and degraded	Lubricating oil showed signs of oxidation and contamination.
8	External physical condition	Normal	No visible cracks or external damage were observed.

Based on Table 3, it can be observed that the failure symptoms did not originate from a single subsystem but rather resulted from a combination of multiple damage indicators. The engine's inability to start despite an adequate fuel supply suggests that the failure was likely associated with the combustion system, compression system, or the engine rotating mechanism. The increased resistance experienced during the starting process indicates elevated mechanical friction, which may have been caused by wear of the connecting rod bearing, main bearing, or crankshaft components. Meanwhile, the absence of generator output voltage is a direct consequence of the engine's inability to achieve the rotational speed required to drive the generator rotor.

The relatively weak spark produced by the spark plug indicates that the combustion process was not operating efficiently. This condition may have resulted from carbon deposit accumulation on the spark plug electrodes, deterioration of the ignition system, or compression leakage caused by worn piston rings or valve system defects. Furthermore, the dark black appearance of the lubricating oil indicates significant lubricant degradation due to oxidation, contamination by metallic wear particles, and the accumulation of combustion residues. The deterioration of lubricant quality reduces its ability to maintain an effective lubricating film, thereby increasing direct metal-to-metal contact and accelerating the wear of engine components.

The results of the preliminary inspection indicate that the generator set experienced a systemic failure, involving the simultaneous malfunction of multiple interconnected subsystems. Consequently, the investigation could not rely solely on external examination but required further analysis through engine disassembly, detailed visual inspection of all critical components, wear measurements, and failure mechanism analysis to identify the root causes responsible for the generator set's total breakdown.

3.2. *Visual Inspection Results*

Visual inspection constitutes a fundamental stage in the failure analysis process, as it aims to identify the physical damage characteristics of each engine component suspected of contributing to the total breakdown of the generator set. The inspection was performed after complete engine disassembly to evaluate the actual condition of each component without employing destructive testing methods. During the inspection, every component was systematically examined for evidence of wear, scoring, cracking, deformation, surface discoloration resulting from elevated temperatures, leakage, and carbon deposit accumulation. In addition, all components were documented using a high-resolution digital camera to enable detailed evaluation of the damage characteristics and comparison with failure mechanisms reported in previous studies. The results of the visual inspection provided the foundation for determining the failure mechanisms, analyzing failure propagation, and conducting Root Cause Identification (RCI) to determine the underlying causes responsible for the loss of the generator set's operational functionality.

 https://doi.org/10.29165/ajarcde.v10i3.1190

Table 4. Visual Inspection Results of the Firman FPG1500ECII Generator Set Components

No.	Component	Visual Condition	Inspection Findings	Failure Mechanism	Effect on Generator Operation
1	Piston Ring		The piston rings exhibited significant wear, loss of elasticity, and carbon deposits accumulated within the ring grooves.	Abrasive wear and compression leakage (blow-by)	Reduced cylinder compression pressure, resulting in incomplete combustion.
2	Connecting Rod Bearing		The bearing surface exhibited scoring, surface discoloration, and non-uniform wear.	Lubrication failure and adhesive wear	Increased mechanical friction, causing higher resistance during crankshaft rotation.
3	Main Bearing		The bearing exhibited excessive wear accompanied by scoring and partial surface spalling.	Fatigue wear and oil starvation	Increased bearing clearance, leading to reduced crankshaft rotational stability.
4	Spark Plug		The spark plug electrodes were covered with carbon deposits and showed signs of wear.	Carbon fouling	Weakened spark discharge, resulting in unstable and inefficient combustion.
5	Intake Valve		The intake valve was covered with carbon deposits, and wear was observed on the valve seat.	Carbon deposition and valve leakage	Reduced volumetric efficiency due to restricted intake airflow and air–fuel mixture leakage.
6	Exhaust Valve		The exhaust valve exhibited surface discoloration caused by elevated temperatures and substantial carbon accumulation.	Thermal degradation and carbon accumulation	Restricted exhaust gas flow, reducing overall combustion efficiency.
7	Cylinder Head		The combustion chamber surface of the cylinder head was heavily covered with carbon deposits.	Incomplete combustion	Reduced combustion efficiency and an increased risk of engine knocking.
8	Piston Crown		The piston crown was coated with a thick layer of carbon deposits.	High-temperature carbon deposition	Impaired heat transfer from the piston, resulting in elevated combustion chamber temperatures.

Based on Table 4, it can be observed that all major engine components exhibited interconnected damage characteristics that collectively contributed to the generator set failure. The piston rings experienced significant wear, resulting in a reduced ability to maintain cylinder compression pressure. This condition was evidenced by the enlarged ring end gap and the accumulation of carbon deposits within the ring grooves, indicating the occurrence of blow-by. The resulting reduction in compression pressure led to incomplete combustion, thereby causing a substantial decrease in engine power output.

The most severe damage was identified in the connecting rod bearing and main bearing. The surfaces of both bearings exhibited longitudinal scoring, discoloration caused by elevated operating temperatures, and non-uniform wear. These damage characteristics are indicative of lubrication failure, where the lubricating oil film was no longer capable of separating the contacting metal surfaces. Consequently, mechanical friction increased, crankshaft rotation became more resistant, and the engine's mechanical efficiency deteriorated until the engine was no longer capable of rotating under normal operating conditions.

The visual inspection also revealed significant carbon deposit accumulation on the spark plug, intake valve, exhaust valve, cylinder head, and piston crown. Carbon fouling of the spark plug electrodes weakened the spark discharge, thereby impairing the ignition of the air–fuel mixture. Meanwhile, carbon deposits on the valve surfaces contributed to valve leakage, further reducing compression efficiency and combustion performance. The heavy carbon deposits observed in the combustion chamber and on the piston crown indicate that the engine had been operating under conditions of incomplete combustion over an extended service period. These observations also suggest progressive deterioration of the combustion system, resulting in localized temperature increases and accelerated degradation of engine components.

Overall, the visual inspection findings demonstrate that the generator set failure was not caused by the malfunction of a single component but rather by the combined effects of failures in the

lubrication system, combustion system, and power transmission mechanism. Bearing wear increased mechanical friction, piston ring wear and valve leakage reduced cylinder compression, while carbon deposit accumulation adversely affected both combustion efficiency and ignition performance. The interaction of these failure mechanisms progressively degraded engine performance until it was no longer capable of generating sufficient power to drive the generator rotor, ultimately resulting in the total breakdown of the generator set.

3.3. *Failure Mechanism Analysis*

Failure mechanism analysis was conducted to explain the physical processes responsible for the degradation and eventual loss of function of each generator set component during service operation. Unlike the results of the visual inspection, which only reveal the observable surface damage, this analysis focuses on the underlying tribological mechanisms governing component failure, including the interactions among friction, lubrication, and wear. Through this approach, the effects of lubricant degradation, direct metal-to-metal contact, and carbon deposit formation on the progressive deterioration of the piston rings, bearings, spark plug, and valve system can be systematically explained. Each failure mechanism was analyzed sequentially to establish the relationship between the initial causes of component degradation and their subsequent effects on the combustion process, compression loss, increased mechanical friction, and ultimately the generator set's total breakdown. The findings of this analysis provide the foundation for understanding failure propagation at the system level, which is discussed in the subsequent section, Failure Propagation Analysis.

a) Piston Ring

Figure 3. Failure mechanism Ring Piston

Figure 3 illustrates that the failure mechanism of the piston rings is initiated by lubrication degradation, which causes the lubricating oil film to lose its ability to separate the contacting surfaces of the piston rings and the cylinder wall. According to tribological theory, the lubricant forms a hydrodynamic lubrication film that minimizes direct contact between metallic surfaces. However, when the lubricant undergoes oxidation, particle contamination, viscosity degradation, or delayed replacement, the thickness of the lubricating film decreases, causing the lubrication regime to transition from hydrodynamic lubrication to boundary lubrication. Under boundary lubrication conditions, metal-to-metal contact occurs, increasing the coefficient of friction and accelerating material removal through both adhesive wear and abrasive wear mechanisms. As a result, the piston rings gradually lose their dimensional integrity and elasticity, reducing their ability to maintain adequate contact pressure against the cylinder wall.

As piston ring wear progresses, the sealing capability of the combustion chamber deteriorates, resulting in compression loss. The increasing clearance between the piston rings and the cylinder wall allows combustion gases to escape past the rings into the crankcase (blow-by), preventing the cylinder from maintaining the compression pressure required for efficient combustion. The reduction in compression pressure lowers both the pressure and temperature at the end of the compression stroke, causing the air–fuel mixture to burn inefficiently. This condition leads to incomplete combustion, which is characterized by reduced engine power output, increased fuel consumption, higher emissions of hydrocarbons and carbon monoxide, and the accumulation of carbon deposits within the combustion chamber and ignition system components. Therefore, from a tribological perspective, the piston ring failure mechanism progresses sequentially from lubrication degradation, to accelerated wear caused by direct metal-to-metal contact, followed by compression loss, and ultimately incomplete combustion, which significantly degrades engine performance and contributes to the overall failure of the generator set.

b) Bearing

Figure 4. Failure Mechanism of Bearing

Figure 4 illustrates that the failure mechanism of the bearing is initiated by oil starvation, a condition in which the lubrication system is unable to provide a sufficient oil film to separate the

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bearing surface from the crankshaft journal. According to tribological theory, the lubricant forms a hydrodynamic lubrication film that minimizes friction and prevents direct contact between metallic surfaces. However, when the lubricant quality or quantity deteriorates due to lubricant degradation, contamination, or delayed oil replacement, the lubricating film becomes insufficient, causing the lubrication regime to transition from hydrodynamic lubrication to boundary lubrication. Under these conditions, the asperities of the bearing and journal surfaces come into direct contact (metal-to-metal contact), resulting in increased frictional forces, localized temperature rise, and elevated contact stresses on the bearing surface.

Continuous metal-to-metal contact subsequently promotes the formation of scoring, characterized by longitudinal scratches on the bearing surface produced by the combined effects of adhesive wear and abrasive wear. Adhesive wear occurs due to the formation of microscopic junctions (micro-welding) at the contact points, which subsequently fracture during relative motion between the mating surfaces. In contrast, abrasive wear is caused by metallic wear particles acting as abrasive media between the contacting surfaces. These damage mechanisms progressively roughen the bearing surface, increase the bearing clearance, and reduce the bearing's ability to support stable crankshaft rotation. As scoring becomes more severe, the coefficient of friction increases significantly, resulting in high friction, which is characterized by increased rotational resistance, higher operating temperatures, and accelerated component wear. The accumulation of this damage substantially increases the torque required to rotate the crankshaft until the condition of engine cannot rotate is reached, where excessive mechanical resistance prevents crankshaft rotation and ultimately causes the generator set to experience total breakdown. Therefore, this analysis demonstrates that bearing failure is a direct consequence of lubrication system failure, progressing sequentially through the tribological mechanisms of oil starvation, metal-to-metal contact, scoring, and high friction, ultimately leading to the complete loss of engine rotational capability.

c) Spark Plug

Figure 5. Failure Mechanism of Spark Plug

Figure 5 illustrates that the failure mechanism of the spark plug is initiated by the formation of carbon deposits on the spark plug electrodes. These deposits result from incomplete combustion, poor fuel quality, lubricating oil entering the combustion chamber, or the accumulation of combustion residues during prolonged engine operation. Carbon deposits adhering to the electrode surfaces increase the electrical resistance and reduce the spark plug's ability to generate a spark with sufficient energy. According to the operating principles of the gasoline engine ignition system, the spark must possess adequate voltage and energy to ignite the air–fuel mixture at the end of the compression stroke. Consequently, carbon fouling weakens the spark discharge (weak spark), thereby reducing ignition effectiveness.

The weakened spark subsequently leads to misfire, a condition in which the air–fuel mixture either burns incompletely or fails to ignite altogether during one or more combustion cycles. Misfire prevents the combustion pressure from reaching the level required to generate sufficient force on the piston, resulting in a significant reduction in engine power output. Under more severe conditions, particularly when carbon deposits cover most of the spark plug electrodes, repeated combustion failures occur, preventing the engine from producing the initial rotational energy required during the starting process. As a result, the engine cannot start, since the combustion energy generated is insufficient to sustain crankshaft rotation. This analysis demonstrates that the spark plug failure mechanism develops progressively, beginning with carbon deposit formation, followed by a weak spark, the occurrence of misfire, and ultimately engine starting failure, thereby contributing to the total breakdown of the generator set.

d) Valve

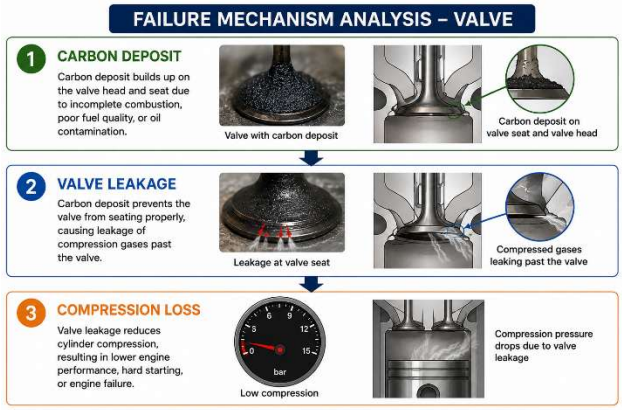

Figure 6. Failure Mechanism of Valve

Figure 6 illustrates that the failure mechanism of the valve system is initiated by the accumulation of carbon deposits on the valve head and valve seat as a result of prolonged incomplete combustion during engine operation. These carbon deposits originate from unburned hydrocarbons, lubricating oil contamination, and poor fuel quality. The progressive accumulation of deposits prevents proper contact between the valve face and the valve seat, thereby inhibiting complete valve closure. This condition leads to valve leakage, in which the air–fuel mixture or combustion gases escape through the clearance between the valve and the valve seat during the compression and expansion strokes. Such leakage indicates that the valve can no

longer effectively seal the combustion chamber, resulting in a deterioration of combustion efficiency.

Persistent valve leakage subsequently causes compression loss, as a portion of the cylinder pressure escapes through the leaking valve before combustion occurs. The reduction in compression pressure lowers the temperature achieved at the end of the compression stroke, preventing the engine from reaching the optimal conditions required for efficient combustion. Consequently, the combustion process produces less energy, leading to reduced engine power output, increased fuel consumption, and greater difficulty during engine starting. Over extended periods of operation, this condition also accelerates the formation of additional carbon deposits within the combustion chamber, further degrading the overall performance of the combustion system. The analysis demonstrates that the valve failure mechanism progresses sequentially from carbon deposit accumulation, to valve leakage, and subsequently to compression loss, ultimately contributing to engine performance degradation and becoming one of the primary factors responsible for the total breakdown of the generator set.

3.4. *Failure Propagation Analysis*

Failure propagation analysis was conducted to explain how damage that initially occurred in a single component progressively propagated through the system and ultimately resulted in the total breakdown of the generator set. Unlike failure mechanism analysis, which focuses on the physical mechanisms responsible for the degradation of individual components, failure propagation analysis emphasizes the cause-and-effect relationships among interconnected components within the system. This approach enables the identification of how lubrication system degradation initiates bearing wear, how piston ring wear and valve leakage lead to compression loss, and how carbon deposit accumulation on the spark plug disrupts the ignition system and combustion process. The interaction among these failure mechanisms progressively reduces both the mechanical and thermal efficiency of the engine until it is no longer capable of generating sufficient power to drive the generator. Accordingly, the development of the failure propagation model not only illustrates the sequence of damage evolution but also represents the principal novelty of this study. The proposed model integrates the interactions among individual component failures into a comprehensive system-level failure model, providing a holistic understanding of the mechanisms leading to generator set failure. Furthermore, this model serves as the foundation for identifying critical components and determining the root causes responsible for the generator set's total breakdown.

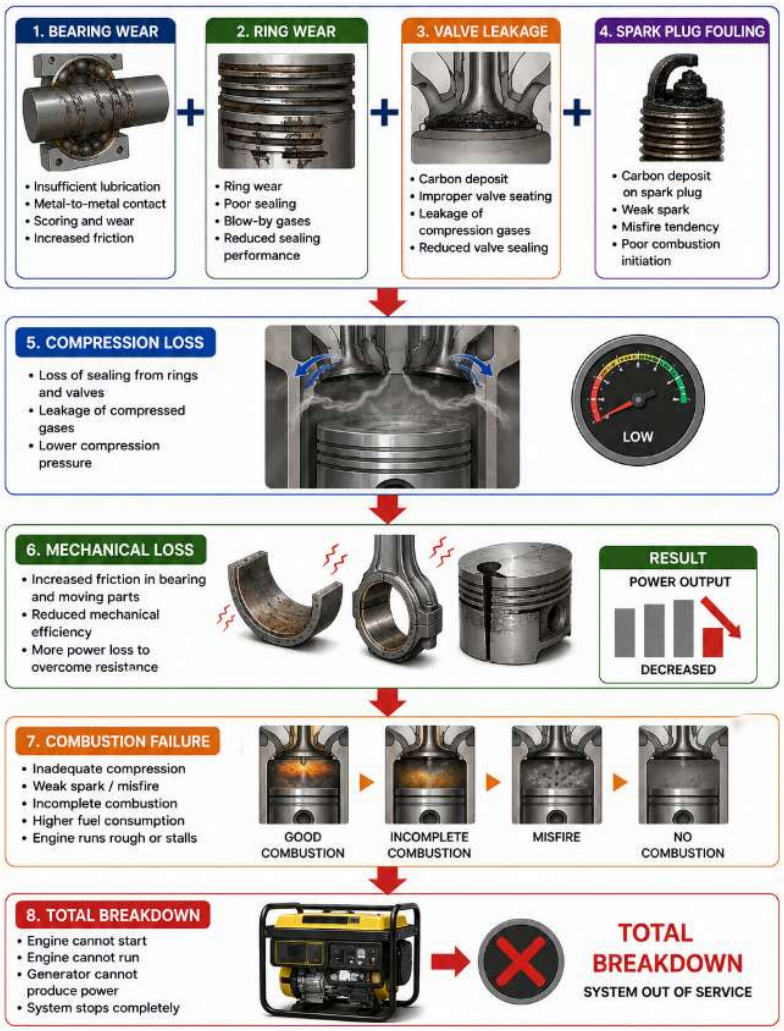

Figure 7. Failure Propagation Analysis

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Figure 7 illustrates that the total breakdown of the generator set was not caused by the failure of a single component but rather resulted from the propagation of failures involving multiple critical components that interacted throughout the engine system. The failure propagation process was initiated by bearing wear, piston ring wear, valve leakage, and spark plug fouling, each of which originated from distinct degradation mechanisms but collectively produced mutually reinforcing effects. Bearing wear increased mechanical friction, thereby reducing the efficiency of crankshaft rotation. Simultaneously, piston ring wear and valve leakage diminished the combustion chamber's ability to maintain adequate compression pressure, while carbon deposits on the spark plug degraded ignition performance and impaired the combustion process. The combined effects of these four failure modes constituted the initial stage of system-level failure propagation.

The interaction among these component failures subsequently resulted in compression loss, caused by gas leakage through the worn piston rings and leaking valves. The reduction in compression pressure lowered the temperature at the end of the compression stroke, preventing efficient combustion of the air–fuel mixture. At the same time, worn bearings generated mechanical losses in the form of increased frictional resistance, elevated operating temperatures, and greater torque requirements for crankshaft rotation. Consequently, a substantial portion of the energy produced during combustion was dissipated in overcoming mechanical resistance, leading to a continuous decline in the engine's mechanical efficiency. The combined effects of reduced compression and deteriorated ignition performance ultimately progressed to combustion failure, characterized by incomplete combustion, misfire, and eventually no combustion during several engine cycles.

The cumulative effects of compression loss, mechanical losses, and combustion failure ultimately prevented the engine from producing sufficient torque to sustain crankshaft rotation and drive the generator rotor. As a result, the generator was no longer capable of generating electrical power, leading to a total breakdown of the system. The failure propagation analysis demonstrates that generator set failure is inherently a multi-component failure process that evolves progressively from localized component degradation to complete system failure. The proposed failure propagation model represents the principal novelty of this study by integrating the cause-and-effect relationships among critical component failures into a comprehensive system-level failure framework. This model provides a more robust basis for Root Cause Identification (RCI) and supports the development of more effective preventive and predictive maintenance strategies for gasoline-powered generator sets.

3.5. *Root Cause Identification*

Root Cause Identification (RCI) represents the final stage of the failure analysis process and aims to determine the underlying causes that initiated the sequence of damage leading to the total breakdown of the generator set. Unlike failure mechanism analysis, which explains the physical degradation processes occurring in individual components, and failure propagation analysis, which describes the interactions among component failures within the system, Root Cause Identification focuses on the fundamental factors responsible for triggering these failure mechanisms. In this study, root cause identification was conducted using the Fishbone Diagram (Ishikawa Diagram) and 5 Why Analysis methodologies. The Fishbone Diagram was employed to categorize potential causes according to the machine, method, material, environment, and operator factors, thereby enabling a systematic evaluation of both technical and non-technical contributors to failure. Subsequently, the 5 Why Analysis was applied to investigate the cause-and-effect relationships in a stepwise manner until the most fundamental causes of failure were identified. The integration of these two analytical approaches provides a more comprehensive and objective framework for root cause investigation. Consequently, the analysis not only explains why the generator set experienced failure but also establishes a robust foundation for developing effective preventive maintenance and predictive maintenance strategies to minimize the likelihood of similar failures occurring in future operation.

Figure 8 illustrates that the total failure of the generator set was not caused by a single factor but rather resulted from the interaction of multiple contributing factors classified into five major categories: Machine, Method, Material, Environment, and Operator. Within the Machine category, the primary contributing factor was bearing wear, which increased mechanical friction and reduced the efficiency of power transmission through the crankshaft system. From the Method perspective, poor maintenance practices—including irregular maintenance schedules, inadequate inspection procedures, and the absence of maintenance records—prevented early detection of component deterioration, thereby accelerating failure progression. In the Material category, the use of degraded lubricating oil, characterized by oxidation, viscosity reduction, and additive depletion, diminished the lubricant's ability to maintain a protective oil film, resulting in accelerated wear of contacting components. Meanwhile, the Environment category was represented by dust contamination, which entered the engine due to ineffective filtration or poor workplace cleanliness, thereby promoting abrasive wear and further degrading lubrication performance. Finally, within the Operator category, prolonged operating hours, continuous high engine loading, and inadequate monitoring of operating time exposed critical components to sustained mechanical and thermal stresses, accelerating their degradation.

The interaction of these five categories formed a chain of interrelated causes that ultimately resulted in complete system failure. Inadequate maintenance practices allowed degraded lubricating oil to remain in service, leading to a continuous decline in lubrication effectiveness. Simultaneously, dust contamination accelerated lubricant degradation and increased the bearing wear rate. Progressive bearing wear intensified mechanical friction and elevated operating temperatures, resulting in greater mechanical losses and reduced engine efficiency. These conditions were further exacerbated by prolonged operating periods, which promoted the accumulation of fatigue damage in critical engine components. The combined effects of these factors progressively propagated throughout the system until the generator set failed completely. Therefore, the Fishbone Diagram analysis demonstrates that the root causes of failure are multifactorial. Consequently, preventing similar

failures requires more than simply replacing damaged components; it also necessitates implementing a consistent preventive maintenance program, effective lubrication management, improved workplace cleanliness, and proper control of operating hours to ensure the long-term reliability of the generator set.

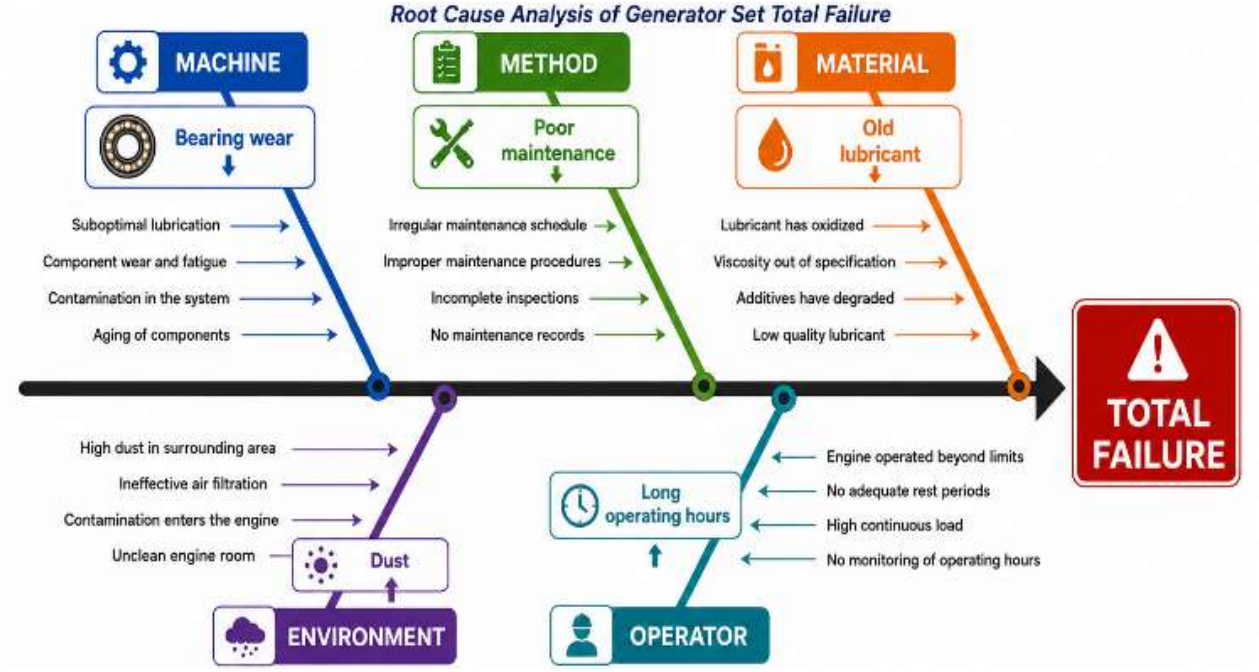

Figure 8. Root Cause Identification – Fishbone Diagram

3.6. *Maintenance Recommendation*

The results of the failure analysis indicate that the total breakdown of the Firman FPG1500ECII generator set was not caused by the failure of a single component but rather by the cumulative degradation of the lubrication system, combustion system, compression system, and ignition system. Therefore, the recommended maintenance actions should not be limited to replacing damaged components but should also focus on eliminating the root causes responsible for initiating the failure process. The proposed maintenance strategy should integrate both corrective maintenance to restore component functionality and preventive maintenance to minimize the recurrence of similar failures in future operation.

Based on the visual inspection and failure mechanism analysis, the piston rings are recommended for replacement because excessive wear resulted in compression leakage. Replacing the piston rings is essential to restore the cylinder compression pressure to the manufacturer's specified values, thereby ensuring efficient combustion. Furthermore, the connecting rod bearings and main bearings, which exhibited severe wear, scoring, and thermal discoloration associated with lubrication failure, should also be replaced with new components. Replacing these bearings is expected to reduce mechanical friction, restore stable crankshaft rotation, and improve the engine's overall mechanical efficiency.

The extensive carbon deposits observed in the combustion chamber, piston crown, valves, and spark plug electrodes indicate that the engine had been operating under prolonged incomplete combustion conditions. Consequently, all carbon deposits should be removed through a decarbonization procedure before the engine is reassembled. In addition to improving combustion efficiency, carbon removal reduces the risk of pre-ignition, misfire, and valve leakage, all of which contribute to accelerated degradation of engine components.

The analysis further revealed that lubricant degradation was a primary factor in bearing failure. Accordingly, replacing the lubricating oil and thoroughly cleaning the lubrication system are critical maintenance procedures before returning the generator set to service. In addition to using lubricating oil that complies with the manufacturer's specifications, the oil replacement interval should be strictly followed to maintain a stable lubricating film, thereby preventing direct metal-to-metal contact during operation.

Within the valve system, the inspection revealed evidence of valve leakage caused by carbon deposit accumulation and wear on the valve seat surfaces. To restore the valve sealing capability and maintain adequate cylinder compression, valve lapping should be performed, or the valves should be replaced if the wear exceeds the allowable service limit. These maintenance actions are intended to ensure complete valve sealing, thereby maintaining proper compression pressure throughout the combustion process and improving overall engine performance.

Although the proposed preventive maintenance schedule has not yet been implemented for long-term field validation, the recommended maintenance intervals were developed based on three complementary considerations: (1) the observed failure mechanisms identified during the forensic investigation, (2) maintenance recommendations provided by the generator manufacturer, and (3) preventive maintenance practices reported in previous engineering maintenance studies. Therefore, the proposed schedule represents an evidence-based maintenance

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framework intended to reduce lubrication-related failures, minimize excessive component wear, and improve the operational reliability of gasoline-powered generator sets.

Table 5. Maintenance Recommendations Based on Failure Analysis

No.	Component / Problem	Failure Identified	Recommended Maintenance Action	Expected Improvement
1	Piston Ring	Excessive wear and compression leakage	Replace with new piston rings	Restore cylinder compression and improve combustion efficiency
2	Connecting Rod Bearing	Severe wear and scoring	Replace bearing	Reduce mechanical friction and stabilize crankshaft rotation
3	Main Bearing	Excessive clearance and surface wear	Replace bearing	Improve shaft alignment and mechanical efficiency
4	Spark Plug	Carbon fouling and weak ignition	Clean or replace spark plug	Restore ignition performance and reduce misfire
5	Intake & Exhaust Valve	Carbon deposits and valve leakage	Perform valve lapping or replace valve	Restore sealing performance and compression pressure
6	Combustion Chamber	Thick carbon deposits	Perform decarbonization	Improve combustion quality and reduce knocking tendency
7	Lubrication System	Degraded lubricating oil	Replace engine oil and clean lubrication system	Reduce wear and extend component service life
8	Preventive Maintenance	Lack of periodic maintenance	Implement scheduled preventive maintenance	Prevent recurrence of total breakdown

Based on Table 5, all maintenance recommendations were developed by correlating the observed component damage with the failure mechanisms identified in the preceding analyses. Components that experienced irreversible wear, such as the piston rings and bearings, are recommended for replacement because they can no longer perform their intended mechanical functions. In contrast, components primarily affected by carbon deposit accumulation, including the combustion chamber, valves, and spark plug, may be restored through appropriate cleaning procedures, provided that no structural damage has occurred. In addition to these corrective actions, implementing a comprehensive preventive maintenance program is strongly recommended to reduce the likelihood of similar failures in future operations. Such a program should include scheduled lubricant replacement in accordance with the manufacturer's recommended service intervals, periodic inspection of the ignition system, compression pressure testing, routine assessment of bearing condition, and regular cleaning of the combustion chamber.

Overall, the maintenance recommendations proposed in this study are intended not only to restore the operational functionality of the generator set but also to establish a root cause-based maintenance strategy. This approach enables maintenance activities to be performed more effectively by focusing on eliminating the fundamental causes of failure rather than merely correcting the observable symptoms. By implementing these recommendations, the reliability of the generator set is expected to improve, the service life of critical engine components can be extended, and the risk of future total breakdown can be significantly reduced.

Based on the results of the Failure Analysis and Root Cause Identification (RCI), it can be concluded that the majority of the generator set failures were initiated by lubrication system degradation, carbon deposit accumulation, and delayed implementation of scheduled maintenance. Accordingly, the preventive maintenance schedule presented in Table 6 was developed by emphasizing routine inspections of the components that contributed most significantly to the total breakdown, namely the lubrication system, combustion system, ignition system, and mechanical components.

Periodic engine oil replacement should be considered the highest maintenance priority because the investigation identified lubricant degradation as the primary root cause of wear in the connecting rod and main bearings. Oxidized lubricant loses its ability to maintain a stable lubricating film, resulting in increased metal-to-metal contact and accelerated wear of mating surfaces. Therefore, adhering to a consistent oil replacement interval is the most effective strategy for extending the service life of moving engine components.

In addition to lubrication system maintenance, proper combustion system maintenance is essential to ensure engine reliability. Periodic inspection of the spark plug, cleaning of the combustion chamber, and removal of carbon deposits should be performed regularly to prevent misfire, compression loss, and incomplete combustion. Furthermore, periodic valve clearance adjustment is recommended to ensure efficient intake of the air–fuel mixture and effective exhaust gas evacuation, thereby maintaining optimum combustion performance.

Components subjected to high mechanical loads, such as the piston rings, connecting rod bearings, and main bearings, should undergo periodic dimensional inspections, particularly during major overhaul. Measuring component clearances and evaluating bearing surface conditions enable early detection of wear before it progresses to catastrophic failure. This approach is consistent with the principles of condition-based maintenance (CBM), in which maintenance activities are performed according to the actual condition of the components rather than solely on the basis of operating time.

Table 6. Recommended Preventive Maintenance Schedule for the Firman FPG1500ECII Generator Set

Maintenance Item	Inspection Activity	Maintenance Action	Maintenance Interval	Purpose
Engine oil	Check oil level, color, and viscosity	Replace engine oil using manufacturer-recommended lubricant	Every 50 operating hours or 3 months	Maintain lubrication performance and reduce bearing wear
Air filter	Inspect for dust and clogging	Clean or replace air filter	Every 50 operating hours	Ensure adequate air supply for combustion
Spark plug	Inspect electrode wear and carbon deposits	Clean or replace spark plug	Every 100 operating hours	Maintain ignition performance and prevent misfire
Fuel system	Inspect fuel tank, fuel hose, and carburetor	Clean fuel system and drain contaminated fuel	Every 100 operating hours	Ensure stable fuel delivery
Valve clearance	Measure valve clearance	Adjust valve clearance according to manufacturer specification	Every 200 operating hours	Maintain proper valve timing and compression
Combustion chamber	Inspect carbon deposits	Perform decarbonization	Every 200 operating hours	Improve combustion efficiency
Piston ring	Measure compression pressure	Replace piston rings if compression is below specification	Every 500 operating hours or when required	Prevent compression leakage
Connecting rod bearing	Inspect bearing clearance and wear	Replace bearing if excessive wear is detected	During major overhaul (approximately every 500 operating hours)	Reduce mechanical friction
Main bearing	Measure bearing clearance	Replace worn bearing	During major overhaul	Maintain crankshaft stability
Cooling fins	Inspect for dust and debris	Clean cooling fins	Every 100 operating hours	Prevent engine overheating
Generator output	Measure output voltage and frequency	Inspect alternator and AVR if abnormal values are detected	Every month	Maintain electrical performance
Overall engine condition	General inspection	Perform complete engine overhaul if multiple failures are identified	Every 500–1000 operating hours	Restore engine reliability

Overall, implementing the recommended preventive maintenance schedule is expected to reduce the rate of component degradation, improve the operational reliability of the generator set, extend engine service life, and minimize the likelihood of future total breakdowns caused by the combined effects of lubrication, combustion, and mechanical system failures. These recommendations demonstrate that the present study not only identifies the root causes of generator set failure but also proposes a practical maintenance strategy that can be directly implemented to enhance the reliability and availability of gasoline-powered generator sets.

The proposed preventive maintenance schedule was established by integrating the identified root causes with the manufacturer's recommended maintenance intervals and evidence reported in previous maintenance engineering studies. The recommended inspection and replacement intervals were specifically designed to address the dominant failure mechanisms identified during the investigation, particularly lubricant degradation, piston ring wear, bearing damage, carbon deposit accumulation, and ignition system deterioration. Although long-term field implementation has not yet been conducted, the proposed schedule provides an evidence-based preventive maintenance framework that is expected to reduce the likelihood of recurring failures, improve equipment reliability, and minimize unplanned downtime. Similar maintenance strategies have been reported to enhance equipment reliability by preventing progressive component deterioration before catastrophic failure occurs.

4. CONCLUSION

This study identified the failure mechanisms and root causes responsible for the total breakdown of a Firman FPG1500ECII gasoline-powered generator set by integrating systematic visual inspection, tribological failure analysis, failure propagation analysis, and Root Cause Identification (Fishbone Diagram and 5 Why Analysis). The results indicate that inadequate lubrication management initiated progressive component degradation, leading to piston ring wear, bearing damage, carbon deposit accumulation, ignition system deterioration, and ultimately complete engine failure. The main contribution of this study is the development of an integrated engineering failure analysis framework that combines multiple diagnostic approaches to systematically identify failure mechanisms and translate them into evidence-based preventive maintenance recommendations. Although the proposed maintenance schedule has not yet been validated through long-term field implementation, it provides a practical framework based on the identified failure mechanisms, manufacturer recommendations, and previous maintenance studies to improve generator reliability and reduce the likelihood of recurring failures. This study is limited by the absence of quantitative condition-monitoring data because the investigation was conducted after the generator had experienced total

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breakdown. Future research should validate the proposed maintenance schedule through long-term field implementation and incorporate quantitative diagnostic techniques, such as vibration analysis, lubricant condition monitoring, compression testing, and reliability assessment, to further strengthen Root Cause Identification and predictive maintenance strategies.

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