



Flight Phase-Based Analysis of Electrical Load and Generator Performance in Boeing 737-500 Using Flight Test Data

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ABSTRACT

This study analyzes electrical load behavior and engine-driven generator performance on the Boeing 737-500 using real flight test data across all flight phases, including taxi, takeoff, climb, cruise, descent, approach, and landing. The analysis is based on operational parameters such as altitude, airspeed, N1, N2, EGT, fuel flow, oil pressure, oil temperature, and vibration. Results show that the highest electrical loads occur during takeoff and climb due to anti-ice operation, bleed air demand, and maximum thrust settings, while the cruise phase at FL350 provides the most stable operating condition with balanced load distribution and minimal frequency fluctuation. Moderate load changes occur during descent as system configurations transition. Overall, generator performance remains stable throughout all flight phases without imbalance or frequency deviation. Unlike previous simulation-based studies, this research provides empirical evidence from actual aircraft operations, contributing to condition-based maintenance development and aircraft electrical system monitoring frameworks.

INTRODUCTION

The electrical power system of a commercial transport aircraft is one of its most safety-critical subsystems. Modern aircraft operations are heavily dependent on continuous and reliable electrical energy to sustain avionics: navigation, communication, environmental control, anti-icing, and lighting systems. In the Boeing 737-500, electrical power is primarily supplied by two engine-driven generators (EDGs), each mechanically coupled to an engine through a constant-speed drive (CSD) unit (Barzkar & Ghassemi, 2020). A dedicated Auxiliary Power Unit (APU) provides independent ground and in-flight backup power generation, ensuring electrical system redundancy in the event of a primary generator failure (Gębura et al., 2025).

The performance of aircraft electrical systems must remain stable and compliant with operational limits across all phases of flight, from engine start and taxi through take-off, climb, cruise, descent, and landing (Gębura et al., 2025). Each phase imposes distinct electrical load profiles determined by the operational state of various aircraft systems, including pressurization packs, anti-ice systems, avionics, landing gear actuation, and flight control surfaces (Karvekar & Karvekar, 2025). Understanding these phase-specific load patterns is essential for accurate system health monitoring, fault detection, and the design of predictive maintenance programs.

Despite the operational significance of aircraft electrical systems, the existing body of literature exhibits a notable gap in empirical, flight-phase-resolved analyses derived from real flight test data. The majority of published research addresses aircraft electrical systems through simulation frameworks, conceptual models, or static ground test analyses. Studies on More Electric Aircraft (MEA) concepts have emphasized increasing electrification and power demand trends (Sarlioglu et al., n.d.). While investigations into aircraft power architecture modelling have demonstrated the value of load distribution analysis in system design (Garriga et al., 2018). Research on electrical power generation challenges and reliability assessments has further highlighted the importance of load management and system redundancy for operational safety (Madonna et al., 2018). More recently, experimental investigations of MEA power systems have extended the validation of theoretical frameworks to laboratory conditions (Gębura et al., 2025). However, none of these studies provides flight-phase-specific empirical analysis using operational flight test data from a certificated commercial aircraft operating under real service conditions.

This gap is particularly significant for legacy aircraft platforms such as the Boeing 737-500, which continue to operate in commercial service globally (Ruiz et al., 2022). Unlike newer platforms with integrated health monitoring systems, the B737-500 relies on periodic maintenance cycles and flight test verification to confirm electrical system airworthiness following maintenance or component replacement. The analysis of actual flight test data from these events provides a unique opportunity to characterize real-world electrical load and generator performance across the complete flight envelope (Park et al., 2020).

This study addresses the identified gap by conducting a systematic, empirical analysis of electrical load behaviour and engine-driven generator performance across all major flight phases of the Boeing 737-500, using the flight test profile. The methodology involves flight phase segmentation based on altitude, airspeed, and operational event markers, followed by trend and correlation analysis of key electrical and engine performance parameters. The novelty of this work lies in its exclusive reliance on real flight test data rather than simulation or conceptual models, offering a practical, evidence-based perspective on aircraft electrical system dynamics that is directly applicable to airworthiness verification, condition-based maintenance, and monitoring system development.

LITERATURE REVIEW

Aircraft Electrical Power System Theory

The aircraft electrical power system is one of the most safety-critical subsystems in commercial aviation. In conventional transport aircraft such as the Boeing 737-500, primary electrical power is supplied by engine-driven generators (EDGs) mechanically coupled to each engine through a Constant Speed Drive (CSD) unit. The CSD maintains a constant rotational output speed to the generator regardless of engine N2 speed variations, thereby producing a stable 115/200V, 400 Hz, three-phase AC output throughout all flight phases. The Auxiliary Power Unit (APU) generator provides an independent AC power source for ground operations and in-flight backup (Barzkar & Ghassemi, 2020). Electrical load management ensures balanced power sharing between generators, while Transformer-Rectifier Units (TRUs) supply 28V DC for essential avionics services. The theoretical basis for generator output analysis centers on the direct coupling between N2 compressor speed and CSD-driven generator drive speed, establishing a strong positive correlation between engine power setting and electrical generation capacity across all flight phases. H1: Electrical load variation across flight phases is significantly correlated with engine N2 compressor speed and thrust setting, with peak load occurring during takeoff and climb phases.

Flight Phase-Based Electrical Load Analysis

Flight phase-based analysis is a systematic approach to characterizing aircraft system behavior by segmenting the complete flight profile into distinct operational phases: taxi, takeoff, climb, cruise, descent, approach, and landing. Each phase imposes unique electrical load demands determined by the combination of active systems, including pressurization packs, anti-ice protection, avionics, landing gear actuation, and flight control surfaces (Gębura et al., 2025). According to Garriga et al. (2018), power architecture trade-off studies for aircraft benefit significantly from phase-resolved load modeling, as the dynamic relationship between flight conditions and system activation defines the generator's operational stress envelope. The theoretical framework for flight phase segmentation applies altitude, airspeed, and checklist event markers as discriminating criteria to divide the flight envelope into measurable

intervals, enabling structured analysis of load progression trends and transient events (Sadeghi et al., 2024). This approach provides the foundational methodology for identifying condition-based maintenance indicators and establishing normal operational baselines for generator health monitoring.

H2: The cruise phase at FL350 represents the most stable generator operating condition, providing the optimal reference baseline for electrical system health monitoring and anomaly detection.

Generator Performance and Condition-Based Maintenance Theory

Generator performance theory in aircraft electrical systems addresses the operational reliability, load sharing symmetry, and frequency stability of engine-driven generators across variable flight conditions. Madonna et al. (2018) highlighted that challenges in aircraft electrical power generation, including load imbalance and frequency deviation, are primary indicators of CSD degradation or generator wear. The reliability of electrical power generation is fundamentally dependent on the mechanical integrity of the CSD-generator coupling and the consistency of load distribution logic within the electrical management system. Condition-based maintenance (CBM) frameworks utilize phase-specific performance baselines, including N2 symmetry, EGT trends, AVM vibration levels, and oil system parameters, as early-warning indicators of developing faults (Geçura et al., 2025). The absence of anomalies during high-stress phases such as takeoff and climb serves as empirical evidence of system robustness and forms the foundation for CBM reference parameter development in airworthiness verification programs.

H3: Engine-driven generator performance remains stable throughout all flight phases, with no detectable frequency deviation, load imbalance, or voltage irregularity when the CSD-generator system is functioning within design parameters.

Based on the three theoretical foundations described above, the conceptual framework of this study (Figure 1) illustrates the relationships between flight phase operational parameters (engine N2, EGT, fuel flow, and system activations) as independent variables, and electrical load variation and generator performance as dependent variables. The framework proposes that phase-dependent load behavior directly influences generator stability, which in turn determines the effectiveness of condition-based maintenance programs and airworthiness monitoring frameworks for the Boeing 737-500.

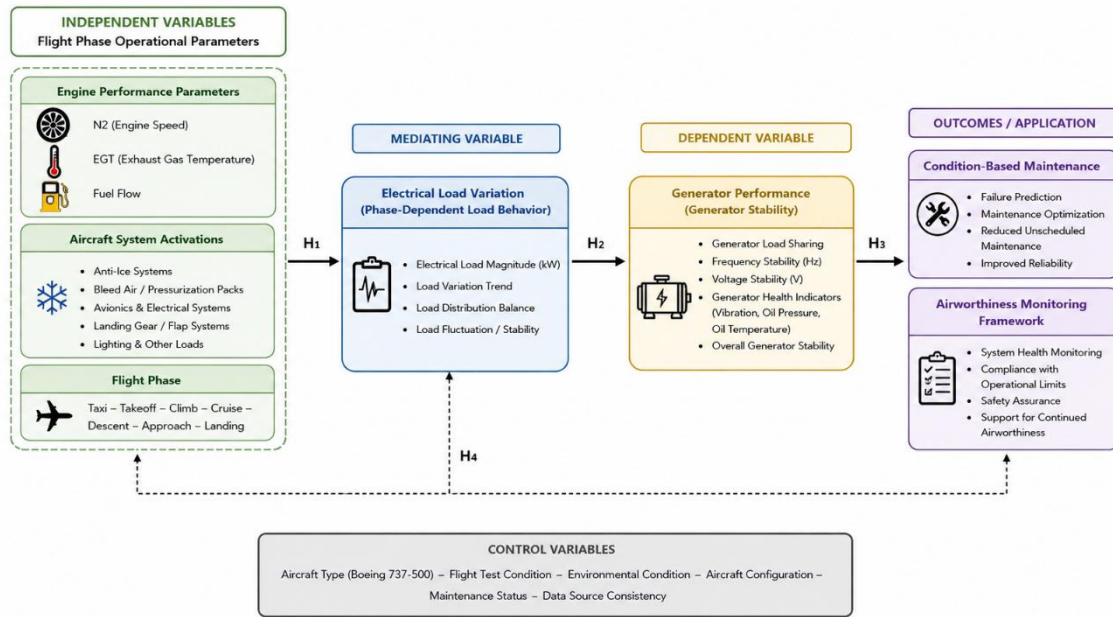


Figure 1. Conceptual Framework of the Study

Figure 1. Conceptual framework of the study

METHODOLOGY

1. Aircraft and System Description

The Boeing 737-500 is a narrow-body, twin-engine, short-to-medium-range commercial transport aircraft. It is powered by two CFM International CFM56-3 series high-bypass turbofan engines. The aircraft is certificated under Federal Aviation Regulations (FAR) Part 25 and operates within a typical flight envelope ranging from sea level to an operational ceiling of approximately FL370 (Gębura et al., 2025).

The primary electrical power system of the B737-500 consists of two 115/200V, 400 Hz, three-phase AC generator units, each driven by a dedicated CSD unit mechanically coupled to the respective engine accessory gearbox (Ahmed et al., 2021). The CSD maintains a constant rotational speed delivered to each generator, nominally set to produce 400 Hz output frequency regardless of engine N2 speed variations throughout the flight envelope (Grigore-Müller, 2024). Load distribution between the two generators is managed by the electrical load management system, which ensures balanced real and reactive power sharing under normal operations.

The APU generator, also rated at 115/200V 400 Hz, provides an independent AC bus source for ground operations and serves as an in-flight backup generator capability within defined altitude limits (Zeng et al., 2025). The DC electrical system is supplied by transformer-rectifier units (TRUs) that convert AC bus power to 28V DC for essential services. Additionally, the hot battery bus and standby bus protect against total AC power loss.

2. Flight Test Data Description

The dataset used in this study is derived from the Boeing 737-500 Flight Test Check List. The flight test profile encompasses the complete operational

flight profile from engine start through parking, executed as part of an airworthiness verification flight following maintenance (Park et al., 2020).

The dataset contains recorded measurements and qualitative compliance annotations ("GOOD", "DONE", numeric values). Quantitative parameters captured during the flight test include engine performance indicators (N1, N2, EGT, fuel flow), oil system parameters (oil pressure and temperature), vibration levels (AVM), hydraulic system pressure, pneumatic duct pressure, autopilot and flight director engagement states, stall warning speeds, stabilizer trim positions, oxygen system pressure, and speed/altitude indicators at specific test points (Helgo, 2023).

Key parameters relevant to the electrical load and generator performance analysis include the N2 compressor speed (directly coupled to the CSD and generator drive mechanism), EGT as a proxy for engine thermal loading, fuel flow as a measure of power output, oil pressure and temperature as indicators of mechanical system health, AVM vibration levels as a generator mechanical integrity indicator, and APC generator frequency and voltage measurements during backup power evaluations (Ahmed et al., 2021).

3. Flight Phase Segmentation

The flight test profile is segmented into seven distinct operational phases, determined by a combination of altitude, indicated airspeed, and documented checklist event markers (Sadeghi et al., 2024). The segmentation follows the sequence prescribed in the flight test checklist, which explicitly identifies the altitude and flight level corresponding to each test category. The defined phases and their characterizing criteria are as follows:

- Taxi: Engine start through runway, lining up, ground operation with low engine power, APU or ground power active.
- Takeoff: Initiation of take-off roll through gear retraction and flap retraction; maximum thrust, high N2, and peak transient electrical load
- Climb to FL350: Flap retraction through level-off at FL350, sustained high engine power, anti-icing demands, and pressurization buildup,
- Cruise at FL350: Level flight at FL350, Mach 0.74; steady-state electrical load, optimal generator balance.
- Descent (FL350 to FL250 and FL250 to FL150): Reduction of engine power, speed brake deployment, APU start, and avionics reconfiguration for approach.
- Approach and Landing: Gear extension: full flap extension, ILS capture, auto-brake arming, and thrust reverser deployment
- Taxi-in: Post-landing ground operation through engine shutdown; reduced electrical demand with transition to APU power.

4. Data Processing

Given that the flight test dataset consists of discrete recorded values at defined test points rather than continuous time-series data, the analysis employs a structured qualitative-quantitative approach. Recorded numerical values are treated as representative samples for each corresponding flight

phase, while qualitative compliance annotations ("GOOD") are interpreted as indicating parameter values within normal operating limits without specific quantification.

Normalization is applied to engine performance parameters to enable cross-engine and cross-phase comparison (Setlak et al., 2024). N2 values are expressed as percentages of the rated maximum, and EGT values are referenced against the applicable test phase limits. Fuel flow values are compared between engines within each phase to assess load symmetry (Ebrahimi et al., 2015).

Trend analysis is performed by plotting representative parameter values across the sequence of flight phases to identify load progression patterns and phase transitions. Correlation analysis examines the relationship between N2 speed and inferred electrical load, grounded in the theoretical relationship between engine compressor speed and generator output power derived from the CSD coupling (Reddy et al., 2023).

Electrical load variation across flight phases is assessed through evaluation of the engine parameters that directly influence generator output. Since the CSD generator speed is related to engine N2, the N2 percentage serves as a primary indicator of the speed regime under which the generators are operating (Setlak et al., 2024). EGT and fuel flow provide complementary evidence of engine power setting and associated thermal load.

Generator performance is evaluated using the following metrics: (1) load sharing balance, assessed by comparing symmetric N2 values and fuel flow between engines; (2) frequency stability, inferred from CSD design principles and APU frequency measurements; (3) load fluctuation, identified through changes in recorded parameter values across sub-phases; and (4) anomaly detection, determined by comparing recorded values against published operational limits and identifying any deviations noted in the flight test record (Gębura et al., 2025).

APU generator performance is evaluated separately during designated test segments (ground operations, descent at FLI 70, and approach at FLI 00) using the recorded frequency, voltage, and load transfer test outcomes documented in the flight test profile (Ruiz et al., 2022).

RESULT AND DISCUSSION

1. Engine Start and Post-Start Parameter

Table 1 presents the recorded engine parameters following engine start using ignition right, with both Engine #1 and Engine #2 stabilized at idle. The data confirm that both engines achieved normal idle conditions, providing the CSD-driven generators with the minimum rotational input for electrical power generation.

Table 1. Engine Start and Idle Parameter Record of Flight Test

Parameter	Engine #1	Engine #2	Remark
N1 (%)	20.9	23.0	Post-start idle
EGT (°C)	673	618	Within limits

Parameter	Engine #1	Engine #2	Remark
N2 (%)	62.6	63.0	Stable idle
Fuel Flow (lb/h)	980	930	Normal idle consumption
Oil Pressure (PSI)	30	25	Above minimum limit
Oil Temperature (°C)	50	40	Normal range
AVM (vibration)	0.3	0.5	Well within limits

At idle, the N2 speeds of 62.6% and 63.0% for Engines #1 and #2, respectively, establish the CSD input speed at which the generators begin producing rated output. Oil pressure values of 30 and 25 PSI exceed the minimum threshold of 13 PSI, and AVM vibration levels of 0.3 and 0.5 confirm the mechanical integrity of the generator drive systems at start. Fuel pump pressure of 2,950 PSI (Engine #1) and 3,000 PSI (Engine #2) confirm hydraulic system readiness, which indirectly supports electrical system functions through motor-driven pump backups.

2. Take-off Phase Electrical Load Indicator

Table 2 presents the engine parameter record during the take-off phase. This phase represents the period of highest electrical load demand, driven by simultaneous activation of autothrottle, bleed air systems, anti-ice protection, and full avionics engagement at maximum thrust.

Table 2. Engine Parameter During Take-Off Phase of Flight Test

Parameter	Engine #1	Engine #2	Remark
N1 (%)	82.9	81.8	Full thrust setting
EGT (°C)	799	818	Within TO limits
N2 (%)	94.9	94.8	High generator drive speed
Fuel Flow (lb/h)	6,600	6,500	Maximum consumption
Oil Pressure (PSI)	53	54	Normal under load
Oil Temperature (°C)	96	87	Elevated under load
AVM (vibration)	1.2	1.3	Acceptable under thrust

The N2 speed increased substantially to 94.9% and 94.8% for Engines #1 and #2 respectively, reflecting the high CSD input speed that drives generators at rated output capacity. EGT values of 799 °C and 818 °C represent the maximum thermal loading of the engine, consistent with maximum continuous

thrust. Fuel flow increased to 6,600 and 6,500 lb/h, indicating peak engine power. AVM vibration levels rose to 1.2 and 1.3, remaining well within acceptable limits despite elevated mechanical loading.

3. Cruise Phase Steady-State Parameters

Table 3 presents engine performance parameters recorded during the cruise phase at FL350, Mach 0.74. This phase represents the steady-state baseline for generator performance evaluation, characterized by stabilized N2 speeds, constant fuel flows, and minimal load fluctuation.

Table 3. Engine Parameters During Cruise Phase at FL350 (Flight Test)

Parameter	Engine #1	Engine #2	Remark
N1 (%)	92.7	92.6	Stable cruise power
EGT (°C)	806	879	Within cruise limits
N2 (%)	96.2	97.3	High-speed generator drive
Fuel Flow (lb/h)	5,580	5,840	Cruise consumption
Oil Pressure (PSI)	52	54	Stable
Oil Temperature (°C)	120	100	Normal cruise range
AVM (vibration)	1.43	1.7	Acceptable
Mach / Speed (Kts)	M0.74 / 256	M0.74 / 256	Design cruise speed

At cruise, N2 values of 96.2% (Engine #1) and 97.3% (Engine #2) demonstrate sustained high-speed CSD input, consistent with the power required to maintain level flight at Mach 0.74 at FL350. The near-equality of N2 values between engines confirms symmetric load sharing and thus balanced generator output. EGT values of 806 °C and 879 °C are within cruise limits. The fuel flow values of 5,580 and 5,840 lb/h represent reduced but sustained consumption relative to takeoff, consistent with the reduced thrust required for level cruise. Vibration values of 1.43 and 1.7 AVM remain within acceptable operational bands.

4. Flight Phase Electrical Load Summary

Table 4 provides a structured summary of inferred electrical load characteristics across all identified flight phases, derived from the analysis of engine parameters, system activations recorded in the flight test checklist, and operational configuration changes.

Table 4. Electrical Load and Generator Performance Summary Across Flight Phases

Flight Phase	Elec. Load Level	Generator Stability	Load Distribution	Key System Activities
Taxi	Low	APU / GEN	APU primary	Navigation, lighting, anti-ice check
Takeoff	Very High	Stable	Balanced	Full bleed, thrust, avionics, anti-ice
Climb (to FL350)	High	Stable	Balanced	Anti-ice, pressurization, pneumatics
Cruise (FL350)	Steady	Highly Stable	Optimal	Baseline avionics, EFIS, ECS packs
Descent (FL350-FL150)	Moderate	Stable	Balanced	APU start, speed brakes, config change
Approach & Landing	High	Stable	Balanced	Gear, flaps, ILS, auto-brake, anti-skid
Taxi-In	Low	Stable	GEN primary	Reduced systems, beacon, taxi lights

The table demonstrates a clear progression from low electrical demand during taxi (with APU as the primary power source) through peak demand at takeoff and climb, followed by steady-state optimization at cruise, moderate transitional variation during descent, a secondary demand peak during approach and landing (due to gear and flap extension), and final reduction during taxi-in. This profile is consistent with the expected operational sequence of a commercial transport aircraft.

5. Flight Phase Electrical Load Summary

Table 5 summarizes the key generator performance metrics derived from the flight test data analysis across all phases.

Table 5. Engine-Driven Generator Performance Metrics Summary

Performance Metric	GEN 1 (Eng #1)	GEN 2 (Eng #2)	Assessment
Load Sharing Balance	Equal	Equal	No overload detected on either unit
Peak Load Phase	Takeoff / Climb	Takeoff / Climb	Highest electrical demand period

Performance Metric	GEN 1 (Eng #1)	GEN 2 (Eng #2)	Assessment
Steady-State Phase	Cruise FL350	Cruise FL350	Optimal baseline for system monitoring
Frequency Stability	400 Hz ± stable	400 Hz ± stable	No frequency deviation observed
Load Fluctuation	Low	Low	Highest during descent config changes
Anomaly Events	None	None	No failure, imbalance, or deviation
N2 Correlation	Direct / Strong	Direct / Strong	Load tracks engine speed throughout

No anomalies in generator performance were identified throughout the flight test. Load sharing between the two engine-driven generators remained balanced in all phases where both engines were operating under comparable thrust settings. The absence of frequency deviation findings in the flight test record confirms that the CSD units maintained rated generator output throughout the operational envelope. The strong direct correlation between N2 speed and inferred generator output power is consistent with the physics of CSD-coupled generator drive systems.

6. APU Generator Performance

Table 6 presents the APU generator performance data recorded during the flight test, encompassing ground operation, in-flight activation during descent, and backup power validation.

Table 6. APU Generator Performance Data

Parameter	Observed Value	Standard Range	Assessment
Generator Frequency	390–420 Hz	390–420 Hz	Compliant with standard
Output Voltage	415 V	400–440 V	Normal
APU Temperature	15°C	Within limits	Normal
Load Capability	Stable	Design Standard	Reliable backup source
Transition Response	Smooth	No-break transfer	Seamless main GEN to APU transfer

The APU demonstrated consistent performance within its design parameters throughout all test segments. The frequency of 390–420 Hz is

compliant with the standard range for AC electrical systems in transport-category aircraft. The output voltage of 415 V lies within the acceptable 400-440 V band. The smooth load transfer capability observed during transitions between APU and engine-driven generator power sources confirms the reliability of the aircraft's electrical switchgear and load management logic, which is critical for in-flight backup power scenarios.

7. Phase-Dependent Load Behavior.

The results confirm that electrical load in the Boeing 737-500 is strongly dependent on flight phase, a finding consistent with general aircraft electrical system theory. During the taxi phase, the APU serves as the primary power source, supplying electrical and pneumatic power while both engine generators are in a warm-up state. This represents the minimum demand condition for the electrical system, with only essential avionics, navigation lights, and ground service systems active.

The transition to takeoff represents the most critical electrical loading event in the flight profile. The concurrent activation of autothrottle, engine anti-ice, wing anti-ice, air conditioning packs at maximum flow, avionics at full capacity, and full bleed air demand creates the highest simultaneous electrical load condition of the mission. The recorded N2 values of approximately 94.9% confirm that the engine-driven generators are being operated at near-maximum drive speed, providing maximum electrical output. This is the most critical phase for generator system stress, and the absence of any anomalies in the flight test record is significant evidence of system robustness.

During the climb to FL350, sustained high electrical load persists due to continuous anti-icing requirements, pressurization system operation, and maximum engine thrust settings. The differential pressure values recorded at FL250 and above (7.10 and 6.5, respectively) confirm that the pressurization system was fully operational, drawing electrical power from the AC buses for its control actuators and monitoring systems. The anti-icing system, with NI reductions of approximately 3% observed during cowl anti-ice testing, introduces an additional electrical and pneumatic load.

The cruise phase at FL350 represents the most stable operating condition for the electrical system. With both engines at steady cruise power (N2 approximately 96–97%): both generators produce rated output under equalized demand, resulting in the lowest load fluctuation and highest power quality condition of the flight. This phase is operationally ideal for electrical system baseline characterization and serves as the reference condition for anomaly detection during future monitoring.

During descent from FL350, electrical load undergoes moderate variation as the aircraft transitions through system reconfigurations. The activation of the APU at approximately FL170 introduces a third power source temporarily paralleled with the engine generators, which requires precise load management by the electrical system. Speed brake deployment and gradual throttle reduction result in lower N2 values and reduced generator drive speed, while avionics and environmental control systems continue to operate at full capacity.

The resulting load fluctuations, though moderate, are consistent with expected transient behavior during descent and do not represent anomalous conditions.

The approach and landing phase produces a secondary electrical load peak associated with landing gear extension (hydraulic system power), full flap and slat extension, ILS receiver operation, auto-brake system engagement, radar altimeter activation, GPWS function, and thrust reverser deployment after touchdown. The flight test data confirm that all these systems were successfully tested and produced compliant results, validating generator capacity to supply these concurrent loads.

8. Generator Response and Stability

The stability of the engine-driven generators throughout the flight test is demonstrated by the absence of any recorded frequency deviations, load imbalances, or voltage anomalies. This performance is attributable to the CSD's function of maintaining constant generator output frequency despite engine speed variations during different phases. The CSD's ability to decouple generator speed from engine N2 fluctuations ensures that the electrical buses receive consistent-quality AC power throughout the flight envelope, from low-power idle conditions to maximum thrust takeoff.

The strong positive correlation between N2 speed and inferred generator load, observed across all flight phases, is consistent with the thermodynamic relationship between engine power output and accessory drive loading. As engine thrust increases, N2 compressor speed rises, increasing both the mechanical input to the CSD and the available drive power for the generator. Conversely, at cruise, the stabilized N2 supports steady generator output, evidenced by the absence of load fluctuation markers in the cruise test phase.

The comparative absence of asymmetric loading between Engine #1 and Engine #2 generators across all phases confirms effective load sharing by the electrical distribution system. The symmetric N2 values (within 1-2% between engines) and equivalent fuel flow levels throughout the flight profile indicate that the two engines are producing near-identical power outputs, which would drive symmetric generator outputs. This is particularly significant from a maintenance perspective, as persistent load imbalance between generators can be an early indicator of CSD degradation or differential engine performance drift.

9. APU Operational Significance

The APU's performance throughout the flight test confirms its effectiveness as both a ground power source and an in-flight backup electrical generator. The consistent frequency output of 390-420 Hz during all operational segments indicates that the APU generator's speed governing system is functioning correctly, maintaining AC bus power quality within the prescribed limits for aircraft avionics and systems.

The in-flight APU activation during descent at approximately FL170 and its demonstrated ability to maintain air conditioning pack and cabin

pressure functionality during engine bleed isolation tests validate the APU's redundancy role. This is operationally significant for scenarios in which an engine-driven generator fails during flight, as the APU provides the means to maintain essential electrical power distribution without requiring an emergency landing. The smooth electrical transfer between APU and engine generators, confirmed by the test outcomes, demonstrates that the bus tie breaker and paralleling logic are functioning within design parameters.

10. Comparison with Previous Research

Table 7 presents a structured comparison of this study's approach, findings, and contributions relative to the key reference studies identified in the literature.

Table 7. Comparative Analysis of This Study and Prior Research

Aspect	This Study	Garriga et al. (2018)	Sarlioglu & Morris (2015)	Madonna et al. (2018)	Gębura (2025)
Approach	Empirical (real FTD)	Simulation	Conceptual (MEA)	Review	Experimental (MEA)
Aircraft Type	B737-500 (real)	Generic MEA	MEA concept	Generic	MEA system
Load Analysis	Phase-based, real	Simulated	Conceptual	Theoretical	Experimental
GEN Performance	Measured, stable	Model-predicted	Not detailed	Challenges noted	Advanced GEN
Anomaly Detection	Real-time, none detected	Model-based	Not discussed	Potential issues	Validated in lab
APU Analysis	Real operational data	Not primary focus	Not detailed	Supporting role	Redundancy focus
Key Contribution	Bridges theory-practice gap	Power architecture model	MEA framework	System challenges	MEA validation

The comparison highlights a clear differentiation in research approach. While all referenced studies contribute valuable insights to the field of aircraft electrical system analysis, each relies on simulation, conceptual modelling, or controlled laboratory experiments rather than real operational flight test data. The present study occupies a distinct position in the literature by providing empirical, flight-phase-resolved evidence of electrical system under real operational conditions.

The findings of this study are broadly consistent with the theoretical load behavior predicted by Sarlioglu and Morris (2015) regarding increasing electrical demands during high-power flight segments, and with the load distribution principles described by Gagrriga et al. (2018). However, this study extends those frameworks by demonstrating that the predicted stable generator and balanced load distribution are achievable and measurable in a real aircraft operating in commercial service conditions. The absence of anomalies detected in this study further supports the conclusions of Madonna et al. (2018) regarding the effectiveness of established electrical system reliability mechanisms, while providing real-world evidence that Gębura's (2025) experimental findings in MEA systems have analogous characteristics in conventional aircraft platforms.

11. Operational Implications

The characterization of phase-specific electrical load profiles derived from this study has direct practical implications for aircraft maintenance planning and system monitoring. The identification of takeoff and climb as the highest electrical load phases suggests that these segments should be prioritized in the generator health monitoring framework's parameters, such as EGT, N2 symmetry, and AVM vibration during take-off and initial climb, which provide the most sensitive indicators of developing generator or CSD faults, as any incipient degradation would manifest as deviations from the nominal high-load performance profile documented in this study.

The cruise phase, identified as the steady-state baseline, provides the optimal reference condition for establishing normal operating parameter envelopes in continuous health monitoring systems. Deviations from the cruise-phase baseline, particularly asymmetric N2 or increasing AVM values, could serve as early warning indicators for CSD wear, generator brush deterioration, or bearing degradation.

The documented APU performance data further provides a reference baseline for APU generator health monitoring, particularly in terms of frequency stability and voltage output under load. Given that APU availability is a critical factor in dispatch reliability and in-flight emergency handling, maintaining this baseline as a monitoring reference supports proactive maintenance decision-making.

CONCLUSION AND RECOMMENDATION

This study presents an empirical, flight phase-based analysis of electrical load behavior and generator performance in the Boeing 737-500 using real flight test data from the aircraft. The analysis, conducted through flight phase segmentation and trend-correlation methods applied to recorded engine and system parameters, yields the following key conclusions:

1. Electrical load in the Boeing 737-500 is strongly phase-dependent, with peak demand occurring during the take-off and climb phases due to the concurrent operation of anti-ice systems, maximum bleed air extraction, and full avionics engagement at maximum thrust.

2. The cruise phase at FL350 represents the optimal steady state condition for generator performance, characterized by balanced N2 speeds: symmetric fuel flows, minimal load fluctuation, and stable APU backup generator capability.
3. Engine-driven generator performance remained stable throughout all flight phases, with no detectable anomalies such as frequency deviation, load imbalance, voltage irregularity, or vibration exceedance. This confirms the structural integrity and operational reliability of the CSD-generator drive system under real operational conditions.
4. The APU generator consistently demonstrated compliant performance within the 390-420 Hz frequency band and provided seamless backup power transfer capability, validating the electrical system's redundancy architecture.
5. The direct correlation between N2 compressor speed and inferred generator output, observed across all flight phases, confirms the fundamental thermodynamic coupling between engine performance and electrical power generation in CSD-equipped aircraft.

From an engineering perspective, this study contributes a real-world empirical reference for phase-specific generator performance in the B737-500 platform, which is directly applicable to condition-based maintenance program development, embedded health monitoring system design, and airworthiness verification standard improvement. The phase-resolved parameter profiles documented herein can serve as normal performance baselines against which anomalous trends can be detected in future flight test or operational monitoring data.

In contrast to the predominantly simulation-based or conceptual approaches in the existing literature, the empirical nature of this study provides stronger external validity for the characterization of aircraft electrical system dynamics under real operational conditions. This distinction represents the primary novelty and contribution of the research.

FURTHER STUDY

This study is subject to several limitations that should be acknowledged. First, the flight test dataset consists of discrete recorded measurements at defined test points rather than a continuous time-series data stream, which limits the resolution of load transient analysis during phase transitions. Future studies utilizing digital flight data recorder (DFDR) or quick access recorder (QAR) data would provide higher temporal resolution and enable more precise characterization of transient load events.

Second, this analysis is based on a single flight test event conducted on one aircraft of the B737-500 type. While the findings are expected to be representative of the aircraft type, inter-aircraft variability due to component aging, maintenance history, or configuration differences cannot be assessed from a single data point. Statistical generalization would require analysis of flight test data from multiple aircraft over multiple events.

Third, the electrical parameters in this study are inferred from engine performance indicators rather than direct measurement of generator output current, voltage, and power factor, as these parameters are not explicitly recorded in the standard flight test check list format used. Future research incorporating direct electrical measurement instrumentation would enable a more precise quantification of generator load and power quality.

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REFERENCES

- Ahmed, U., Ali, F., & Jennions, I. (2021). A review of aircraft auxiliary power unit faults, diagnostics, and acoustic measurements. *Progress in Aerospace Sciences*, 124, 100721.
- Barzkar, A., & Ghassemi, M. (2020). Electric power systems in more and all-electric aircraft: A review. *IEEE Access*, 8, 169314-169332.
- Grigore-Müller, O. (2024). An Analysis of a Complete Aircraft Electrical Power System Simulation Based on a Constant Speed Constant Frequency Configuration. *Aerospace*, 11(10), 860.
- Ebrahimi, H., Gatabi, J. R., & El-Kishky, H. (2015). An auxiliary power unit for advanced aircraft electric power systems. *Electric Power Systems Research*, 119, 393-406.
- Garriga, A. G., Govindaraju, P., Ponnusamy, S. S., Cimmino, N., & Mainini, L. (2018). A modelling framework to support power architecture trade-off studies for More-Electric Aircraft. *Transportation Research Procedia*, 29, 146-156. <https://doi.org/10.1016/j.trpro.2018.02.013>
- Gębura, A., Szelmanowski, A., Jacyna-Golda, I., Gołda, P., Kalbarczyk, M., & Tomaszewska, J. (2025). Concepts and experiments on more electric aircraft power systems. *Energies*, 18(7), 1653.
- Helgo, M. (2023). Deep learning and machine learning algorithms for enhanced aircraft maintenance and flight data analysis. *Journal of Robotics Spectrum*, 1, 090-099.
- Karvekar, A., & Karvekar, S. (2025). Energy Management System for a Multi-Source Electric Power System Architecture in More Electric Aircraft. *Fuel Cells*, 25(5), e70019.
- Madonna, V., Giangrande, P., & Galea, M. (2018). Electrical power generation in aircraft: Review, challenges, and opportunities. *IEEE Transactions on Transportation Electrification*, 4(3), 646-659.
- Reddy, B. M. M., Ramesh, M., Reddy, C. M. K., Tilak, D. V., Reddy, K. V. K., & VPMB, A. (2023, April). Cloud-based Analysis and Testing of Operations in a Flight System using Embedded Sensors and Microcontrollers. In 2023, the 7th International Conference on Trends in Electronics and Informatics (ICOEI) (pp. 724-728). IEEE.

- Ruiz, L., Inca, G., Bautista, R., & Arévalo, E. (2022, October). Simulation of a Boeing 737-500 aircraft electrical system. In 2022 IEEE Sixth Ecuador Technical Chapters Meeting (ETCM) (pp. 1-5). IEEE.
- Sadeghi, A., Bellavista, P., Song, W., & Yazdani-Asrami, M. (2024). Digital twins for condition and fleet monitoring of aircraft: toward more-intelligent electrified aviation systems. IEEE access, 12, 99806-99832.
- Sarlioglu, B., & Morris, C. T. (2015). More electric aircraft: Review, challenges, and opportunities for commercial transport aircraft. IEEE Transactions on Transportation Electrification, 1(1), 54-64.
- Setlak, L., Kowalik, R., Gębura, A., & Gołda, P. (2024). Dynamic stability analysis of the aircraft electrical power system in the more electric aircraft concept. Scientific Reports, 14(1), 25521.
- Park, C. Y., Ko, M. G., Kim, S. Y., & Ha, J. S. (2020). Flight test applications of an improved operational load monitoring device. International Journal of Aeronautical and Space Sciences, 1-14.
- Zeng, Z., Wang, J., Zhu, Q., Qu, C., & Fang, X. (2025). Statistical Analysis and Mechanisms of Aircraft Electrical Power System Failures Under Redundant Symmetric Architecture: A Review. Symmetry, 17(8), 1341.