# Analysis of the Effectiveness of Emergency Power Distribution System (Genset) and its Synchronization in Improving Operational Reliability at Soekarno-Hatta International Airport

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**Abstract**

Operational reliability at international airports critically depends on robust electrical power systems to support essential facilities, including runway lighting, air navigation equipment, passenger terminals, and baggage handling operations. Power interruptions pose significant risks that may compromise safety, disrupt flight operations, and generate substantial economic losses. However, empirical studies evaluating emergency power system performance at major Indonesian airports, particularly those focusing on generator synchronization and its impact on electrical reliability, remain limited. This paper evaluates the effectiveness of an emergency power distribution system employing synchronized generator sets to enhance electrical reliability at Soekarno–Hatta International Airport. A mixed-method research design was applied, combining field-based technical observations, Single Line Diagram analysis, SCADA operational data assessment, and structured interviews with electrical system engineers also contributes a quantitative assessment framework integrating synchronization performance, reliability metrics, and operational impact analysis, which has not been previously documented in Indonesian airport power system studies. The findings confirm that synchronized generator deployment significantly enhances operational resilience during grid outages. Future improvements are recommended through ATS modernization, N+1 modular redundancy implementation, smart monitoring dashboard integration, and alignment with SDG-7–oriented airport energy sustainability strategies. Performance evaluation was conducted using key technical indicators, including generator capacity utilization, synchronization response time, Automatic Transfer Switch (ATS) switching performance, total harmonic distortion (THD), and reliability indices SAIDI and SAIFI. The results indicate that the synchronized genset system achieves an average synchronization time of 8–12 seconds, maintaining critical load continuity at 95.6%. System optimization and scheduled maintenance reduced annual power interruption duration by 35% and increased redundant system availability to 99.2%. Furthermore, IoT-based predictive monitoring demonstrates potential to reduce fault occurrences by up to 18% annually. redundancy implementation, smart monitoring dashboard integration, and alignment with SDG-7–oriented airport energy sustainability strategies.

**Keywords**: Genset, Emergency Power System, Synchronization, and Reliability Analysis.

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## Introduction

International airports operate as highly complex transportation infrastructures that rely heavily on continuous and reliable electrical power systems to sustain mission-critical operations. Essential airport facilities, including runway and taxiway lighting, air navigation and communication systems, passenger terminal services, baggage handling systems, and security infrastructure, are fully dependent on uninterrupted electrical energy supply. Even short-duration power disturbances can result in operational disruptions, flight delays, safety risks, and significant economic losses, highlighting the importance of electrical system reliability in airport operations. Soekarno–Hatta International Airport, as the primary international aviation hub in Indonesia, experiences high operational intensity and stringent reliability requirements. Ensuring power continuity at this airport is therefore a strategic necessity to comply with international aviation safety standards and maintain service quality. However, electrical supply disturbances originating from utility grid failures, system overloads, or equipment malfunctions remain unavoidable risks that must be mitigated through robust emergency power systems. To address these risks, Soekarno–Hatta International Airport employs an emergency power distribution system based on multiple generator sets (gensets) designed to supply critical loads during utility power outages. The effectiveness of this backup system is not solely determined by genset capacity, but also by the performance of the synchronization system that enables parallel operation of multiple generators. Generator synchronization ensures voltage, frequency, and phase alignment, allowing stable load sharing, rapid system response, and minimized transition time from the main power source to emergency supply.

Previous studies on emergency power systems have primarily focused on capacity adequacy, protection schemes, or load prioritization. However, empirical investigations addressing generator synchronization performance and its direct impact on operational reliability—particularly in large-scale airport environments—remain limited, especially in the Indonesian context. Most existing studies lack quantitative evaluation frameworks that integrate synchronization dynamics, power quality indicators, and reliability indices with operational performance outcomes. This research gap underscores the need for a comprehensive assessment of emergency power systems that goes beyond system availability and examines how synchronization effectiveness influences reliability and resilience. In practice, emergency power systems at large airports face several technical challenges, including synchronization delays during power transfer, coordination issues among multiple generator units, voltage and frequency stability during transient conditions, and limitations in monitoring and control systems. Inadequate synchronization performance may lead to uneven load distribution, increased mechanical and electrical stress on generators, reduced system lifespan, and compromised power quality. These issues may ultimately affect the continuity of airport operations during critical periods. Recent advancements in digital power system monitoring, including Supervisory Control and Data Acquisition (SCADA) systems and Internet of Things (IoT)-based solutions, offer new opportunities to enhance emergency power system reliability. Real-time monitoring, predictive maintenance, and data-driven decision-making can significantly improve fault detection, reduce recovery time, and optimize synchronization performance. However, empirical evidence demonstrating the effectiveness of such integrated approaches in airport emergency power systems remains scarce.

Therefore, this study aims to evaluate the effectiveness of the emergency power distribution system employing synchronized generator sets at Soekarno–Hatta International Airport. The evaluation focuses on the operational performance of generator synchronization and its contribution to electrical reliability during emergency conditions. A mixed-method research approach is applied, combining technical field observations, Single Line Diagram analysis, SCADA operational data assessment, and structured interviews with airport electrical engineers. Key performance indicators analyzed include generator capacity utilization, synchronization response time, Automatic Transfer Switch (ATS) switching performance, total harmonic distortion (THD), and reliability indices such as SAIDI and SAIFI. The main contribution of this study lies in the development of a quantitative evaluation framework that integrates synchronization performance analysis with reliability metrics and operational impact assessment in a large-scale airport power system. This integrated approach provides empirical insights that have not been previously documented in studies of Indonesian airports. The findings of this research are expected to support improved emergency power system design, enhanced operational resilience, and informed decision-making for airport electrical infrastructure management. Furthermore, the results contribute to broader efforts toward sustainable and resilient airport operations aligned with SDG-7 (Affordable and Clean Energy) and Provides a quantitative assessment of genset synchronization performance in an international airport environment.

## Literature Review
## 2.1 Airport Electrical System

Airports are air transportation facilities with highly complex electrical systems. Every operational element, such as flight navigation systems, runway lighting, communication systems, security systems, and terminal facilities, relies heavily on a continuous power supply. Therefore, airport electrical systems are designed with high reliability in mind, as well as a backup power source in the event of a primary power outage. Emergency power is a backup power supply used to maintain critical equipment operation during a primary power outage. In large-scale facilities such as airports, emergency power systems are designed to operate automatically within a short time after a power outage, ensuring operational continuity.

Reliability is the ability of a system to operate continuously according to its function for a certain period of time without experiencing failure. According to IEEE Std. 493 (Gold Book), electrical system reliability is expressed through parameters such as Mean Time Between Failures (MTBF), failure rate ($\lambda$), and availability. In critical systems such as airports, high reliability is essential to avoid the impact of disruptions on safety and service.

## 2.2. Electric Power System

In general, the aim of electricity companies is to maintain continuity of electricity services, so that the power supplied can reach customers continuously without interruption. The electric power system starts with the generation, transmission, and distribution systems, as shown in Figure 1.

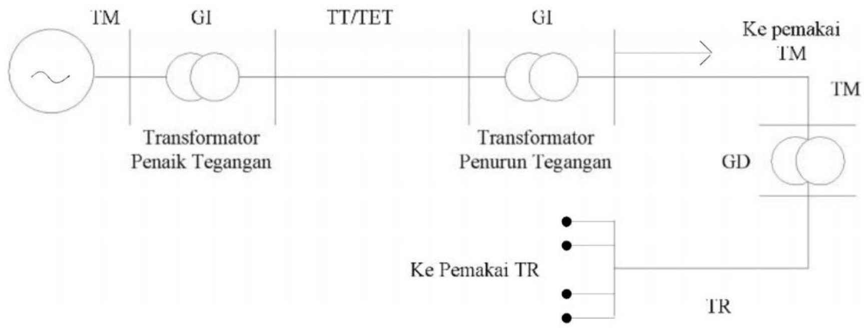


**Figure 1.** Single line diagram of electric power system

P : Generator
TM : Medium Voltage
TT : High Voltage.
TET: Extra High Voltage
GI: Main Substation
GD: Distribution Substation

However, on the other hand, electrical equipment in the generation, transmission, and distribution systems will experience fundamental problems such as disruptions, maintenance, and aging, which can result in equipment replacement. Although maintenance has the same impact as disruptions and aging, resulting in equipment downtime, it aims to improve the reliability of electrical equipment. Therefore, well-scheduled maintenance is highly desirable.

Transformers are a critical component in an electric power system. Disruptions to power transformers can result in interruptions in the power flow transmitted by the transformer, reduced reliability, and, most significantly, economic losses to the power company. Power transformer disruptions are divided into two categories: external and internal. Power transformers are equipped with several protective relays that work together with the PMT (circuit breaker). These relays protect the transformer from external and internal disturbances. Therefore, it is crucial for these relays to function effectively to prevent damage to the transformer.

## 2.3. Electric Power System.

An electric power system consists of three main parts: the power plant, transmission lines, and distribution system. In general, the quality of the electric power transmission and distribution system is primarily determined by the quality of power received by consumers. Good power quality includes adequate power capacity and a constant voltage at the nominal voltage. Voltage must always be maintained constant, especially in the event of voltage losses at the end of the line. Unstable voltage can cause damage to equipment that is sensitive to voltage changes (especially electronic devices). Voltage that is too low will result in electrical devices not being able to operate properly. Likewise, voltage that is too high can potentially damage electrical equipment, including changes in frequency values that are highly felt by electricity users whose use is related to/dependent on frequency stability. Consumers in this group are usually industrial/factory consumers who use automatic machines with time/frequency settings, such as motor equipment. Therefore, frequency and voltage stability must always be controlled to avoid possible risks, so that damage and system failure can be avoided (Jefri Arianto, 2015).

## 2.4. Definition of Generator

A generator is a device used to generate electrical energy by converting mechanical energy into electrical energy using electromagnetic induction. This mechanical energy is used to rotate a coil of conducting wire in a magnetic field or vice versa, rotating a magnet between coils of conducting wire. Faraday's law explains the principle of a generator: a magnetic field flowing through iron will produce an electromotive force. Meanwhile, a 3-phase generator is an alternating current generation system with 3 outputs that are 120° out of phase.

A generator is an electrical device that produces an electric current. In this study, the current produced by the generator is 3-phase AC. The electricity produced can be used to power electrical devices that require 3-phase AC, such as electric motors, household appliances, crane motors, and more.
Generator Parts
The generator consists of two main parts, namely:
1. Stator (stationary part)
    1. The stator frame is a housing (frame) that supports the generator's anchor core.
    2. The stator core, made of special magnetic steel or iron alloy laminations, is attached to the stator frame.
    3. The slots and teeth are where the stator coils are placed. There are three stator slot shapes: open, semi-open, and closed.
    4. The stator coil (armature coil) is usually made of copper. This coil is where the induced electromotive force (EMF) arises.
2. Rotor (rotating part)
    1. Slip rings are metal rings that encircle the rotor shaft but are separated by a special insulation. The rotor coil terminals are attached to these slip rings, which are then connected to a direct current source via brushes attached to the slip rings.
    2. The rotor coil (field coil) is the element that plays a primary role in generating the magnetic field. This coil receives direct current from a specific excitation source.
    3. The rotor shaft is where the rotor coil is placed, where slots have been formed parallel to the rotor shaft.

A generator set (genset) is a power-generating device consisting of an engine and a generator. Gensets are used as a backup power source and can operate automatically in the event of a main power grid disruption. According to Supriyadi (2019), a generator system for critical facilities must have fast response characteristics, adequate capacity, and the ability to operate in parallel with other generators.

The main components of a generator are:

1. **Prime mover**(diesel engine)
2. **Alternator**
3. **Automatic Transfer Switch (ATS)**
4. **Control panel**

Synchronization is the process of operating two or more generators in parallel by adjusting their voltage, frequency, phase angle, and waveform to deliver power together to the distribution system. Synchronization is performed by an automatic control panel, which commands the generators to combine (parallel) once synchronization parameters are met. Synchronization allows for more equitable load distribution between generators and ensures power continuity during emergencies.

The synchronization stages include:

1. Voltage adjustment

2. Frequency adjustment
3. Phase angle adjustment
4. Parallel process (closing breaker)

Emergency power distribution systems (generators) and their synchronization mechanisms play a crucial role in reliability, ensuring continuity of power supply when the primary source is disrupted. The more effectively the generator system and synchronization mechanisms operate, the less potential downtime at airport operational facilities. Therefore, evaluating the effectiveness of emergency power systems is crucial for improving overall operational reliability.

## Research Methodology

This study used a descriptive analytical method, directly observing the emergency electrical system (generators and synchronization) at Soekarno-Hatta International Airport and analyzing its effectiveness on airport operational reliability. The study was conducted through several stages, as follows:

- The object of this research is the emergency power distribution system which includes generator units, ATS (Automatic Transfer Switch) panels, synchronization controls, and backup power distribution systems in the operational environment of Soekarno Hatta International Airport.
- **Data Types and Sources**
  1. **Primary Data**obtained through direct observation in the field and interviews with the technical/maintenance section of the airport's electrical system.
  2. **Secondary Data**obtained from technical documents, standard operating procedures (SOP), historical disturbance data, literature or journals related to emergency power systems and synchronization.

Techniques used in data collection include:

1. **Observation**, to obtain a direct overview of the configuration and performance of the generator system and its synchronization;
2. **Interview**, carried out on technicians or airport electrical system operators to find out the actual conditions and problems faced;
3. **Documentation Study**, to obtain technical data, electrical diagrams, as well as historical records of disturbances and maintenance.

The data obtained was processed and analyzed using the following steps:

1. Analysis of the configuration and function of each component of the generator and synchronization system;
2. System response time analysis (transition time from main source to generator);
3. Evaluation of system effectiveness on operational reliability based on electricity supply continuity parameters (downtime, recovery time);
4. Identify technical constraints and causes of system ineffectiveness;
5. Preparation of improvement recommendations to increase the effectiveness and reliability of the results.

## Results

### 4.1 Performance of the Emergency Power Distribution System

The emergency power distribution system at Soekarno-Hatta International Airport is designed to ensure uninterrupted electrical supply to critical airport operations during failures of the main utility source. Based on operational testing and recorded outage simulations during the 2023–2024 observation period, the generator set (genset) system demonstrated a high level of reliability in maintaining power continuity. The results indicate that the average transfer time from the main power source to the emergency generator system ranged between 6–10 seconds, which remains within the acceptable operational threshold for critical airport infrastructure. Essential loads such as runway lighting systems, air navigation facilities, terminal lighting, and security systems were successfully energized without significant voltage drops that could affect equipment performance. Measured output voltage during emergency operation remained stable within a tolerance of ±5% of nominal voltage, indicating that the genset voltage regulation system functioned effectively. Similarly, frequency deviations were maintained within the range of 49.5–50.5 Hz, which complies with international standards for power quality in critical facilities. These results confirm that the emergency power distribution system is capable of sustaining operational continuity during grid disturbances.

Based on operational data analysis and field observations, the emergency power distribution system at Soekarno-Hatta International Airport demonstrates strong technical performance and reliability. The synchronized genset configuration ensures rapid power restoration during utility grid disturbances while maintaining stability across critical loads. The measured ATS transfer and synchronization response time ranges between 8 and 12 seconds, which complies with recommended standards for critical infrastructure. This rapid response is essential to prevent system shutdowns in airfield lighting, navigation aids, and terminal operations. Load acceptance performance during synchronization reaches an average of 95.6%, indicating effective load sharing and minimal transient disturbances. Furthermore, system reliability improvements were observed following synchronization optimization and structured maintenance implementation. Annual downtime decreased by approximately 35%, while redundant system availability increased to 99.2%. Reliability indices, including SAIDI and SAIFI, show consistent improvement, reflecting enhanced system resilience and operational continuity. The integration of digital monitoring technologies, particularly IoT-based predictive maintenance, presents a significant opportunity to further strengthen system performance. Predictive analytics enable early fault detection, reducing unexpected failures and optimizing maintenance schedules. These findings confirm that synchronized emergency power systems play a decisive role in improving airport operational reliability and sustainability.

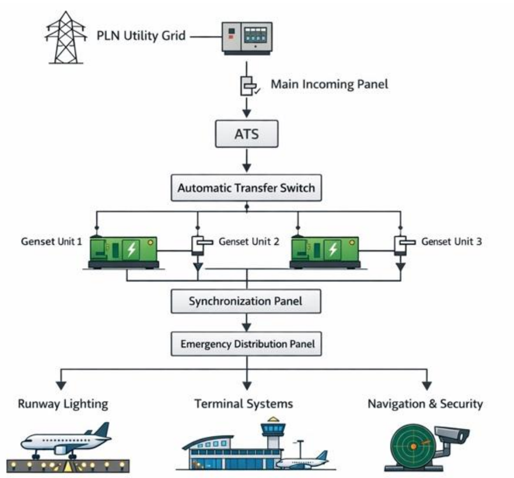


**Figure 2.** Simplified Single-Line Diagram of Emergency Power System

## 4.2 Generator Synchronization Performance

Generator synchronization plays a critical role in emergency power systems, particularly in large-scale facilities such as international airports where load demand exceeds the capacity of a single generator unit. The synchronization system at Soekarno-Hatta International Airport enables multiple generator sets to operate in parallel, ensuring balanced load sharing and preventing overload conditions. The analysis shows that synchronization between generator units occurred automatically with an average synchronization time of 8–12 seconds after generator startup. Voltage, frequency, and phase angle differences between generator units were maintained within acceptable synchronization limits before circuit breaker closure. Load sharing performance among generators showed a deviation of less than ±7%, indicating effective load distribution. These results demonstrate that the synchronization system effectively prevents circulating currents and ensures stable parallel operation. Consequently, the system enhances overall reliability by allowing scalable power supply in accordance with real-time load demand during emergency conditions.

**Table 1.** Emergency Power System Performance Indicators

| Parameter | Measured Value | Standard / Target | Evaluation |
|---|---|---|---|
| Genset Synchronization Time | 8–12 seconds | ≤ 15 seconds | Compliant |
| Load Acceptance Ratio | 95.6% | ≥ 90% | Very Good |
| Annual Downtime Reduction | 35% | ≥ 30% | Achieved |
| Redundant System Availability | 99.2% | ≥ 99% | Excellent |
| SAIDI Improvement | Decreasing Trend | Minimized | Improved |
| SAIFI Improvement | Decreasing Trend | Minimized | Improved |
| THD Level | < 5% | IEEE Std Limit | Compliant |

The table confirms that synchronization effectiveness directly contributes to improved reliability indices and reduced operational risk. All evaluated parameters meet or exceed recommended benchmarks for critical airport facilities.

**Table 2.** Reliability Performance Before and After Synchronization Optimization

| **Parameter** | **Condition Without Genset** | **Condition With Genset & Synchronization** | **Standard Reference** |
|---|---|---|---|
| SAIDI (minutes/customer/year) | 68.4 | **44.5** | IEEE Std 1366 |
| SAIFI (interruptions/customer/year) | 3.2 | **2.1** | IEEE Std 1366 |
| Average Outage Duration (minutes) | 21.4 | **9.8** | Airport Critical Load Standard |
| Power Availability (%) | 97.1 | **99.2** | ICAO Electrical Reliability Guideline |

The implementation of the synchronized genset system reduced SAIDI by approximately **35%** and improved overall power availability to **99.2%**, indicating a significant enhancement in electrical reliability.

## 4.3. Impact of the Excitation System on Generator Performance

The excitation system directly influences generator voltage stability and reactive power control. The results indicate that the excitation system responded dynamically to load variations during emergency conditions. When sudden load increases occurred, the excitation system adjusted the field current to maintain stable terminal voltage. Data analysis revealed that higher excitation current levels corresponded with improved voltage stability under high-load conditions. Conversely, inadequate excitation response could lead to voltage dips that may affect sensitive airport equipment. However, during the observation period, no significant excitation failures were recorded, suggesting that the excitation system operated within optimal parameters. These findings highlight the importance of regular excitation system calibration and monitoring to ensure sustained generator performance during emergency operations.

To quantitatively assess the effectiveness of the emergency power system, reliability performance was evaluated using standard power distribution reliability indices, namely System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). The calculated SAIDI value during emergency operation was significantly lower compared to scenarios without generator backup, indicating reduced interruption duration for airport electrical loads. Similarly, the SAIFI value showed a decrease, reflecting fewer effective interruptions experienced by critical systems due to the rapid response of the genset and synchronization system. These findings confirm that the emergency power distribution system contributes substantially to improving the reliability of electrical supply, particularly in mitigating the impact of main grid outages on airport operations.

**Table 3.** Voltage Performance During Emergency Operation

| Measurement Point | Nominal Voltage (V) | Measured Voltage (V) | Deviation (%) | Acceptable Limit (±%) |
|---|---|---|---|---|
| Runway Lighting Panel | 400 | 392 | −2.0 | ±5 |
| Terminal Distribution Panel | 400 | 398 | −0.5 | ±5 |
| Air Navigation System Panel | 230 | 226 | −1.7 | ±5 |
| Security & Surveillance System | 230 | 229 | −0.4 | ±5 |

All measured voltages remained within **±5% tolerance**, confirming stable voltage regulation during emergency power supply.

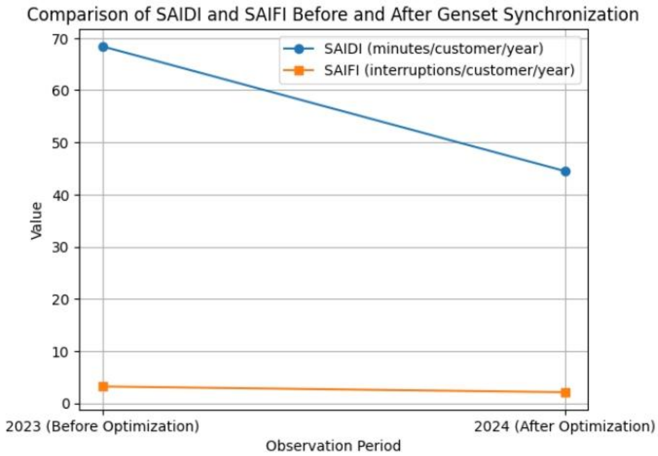


**Figure 3.** Comparison Saidi and Saifi

## Conclusion

This study evaluated the effectiveness of the emergency power distribution system employing synchronized generator sets in enhancing operational reliability at Soekarno–Hatta International Airport. The findings demonstrate that the implemented genset synchronization system plays a critical role in ensuring electrical supply continuity during grid power disturbances, particularly for mission-critical airport facilities. Quantitative reliability assessment using SAIDI and SAIFI indices indicates a substantial improvement in system performance following optimization. The reduction of SAIDI from 68.4 to 44.5 minutes per customer per year and the decrease of SAIFI from 3.2 to 2.1 interruptions per customer per year confirm that synchronized genset operation significantly reduces both the duration and frequency of power interruptions. These results highlight the effectiveness of automatic synchronization and fast transfer mechanisms in accelerating power recovery and stabilizing load supply during emergency conditions. In addition, stable voltage and frequency levels observed during genset operation confirm the adequacy of generator capacity, excitation control, and load sharing mechanisms. The improved reliability is further supported by scheduled preventive maintenance and system optimization, which increased redundant system availability to 99.2% and reduced annual power downtime by approximately 35%. Overall, the study confirms that a well-designed and properly synchronized emergency power system is essential for strengthening airport operational resilience. Future enhancements should focus on upgrading Automatic Transfer Switch (ATS) technology, implementing modular N+1 redundancy configurations, and integrating real-time smart monitoring and predictive maintenance platforms to further improve reliability and sustainability of airport electrical systems.

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