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MATHEMATICAL RELIABILITY MODEL OF THE AERODROME POWER SUPPLY SYSTEM

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Abstract—*The article is devoted to the modeling of the reliability of the power supply system at civil aviation aerodromes. ICAO standards and recommended practices establish a specific set of requirements for the power supply systems of modern civil aviation aerodromes. Every new project or modernization/reconstruction of aerodrome equipment, on which flight safety depends, must be accompanied by the determination and evaluation of its reliability indicators. This requirement is explained by the fact that failures of such equipment pose threats and can create risks to flight safety during the technological processes with aircrafts at civil aviation aerodromes. In accordance with ICAO safety management standards, all risks at the aerodrome must be controlled and reduced to an acceptable level. The proposed mathematical model of the reliability of the aerodrome lighting system's power supply allows for the determination of its reliability indicators under various failure criteria, assessing the impact of the power supply system on flight safety, and developing a set of organizational and technical measures to ensure and enhance the reliability of the system as a whole, which will undoubtedly have a positive impact on the safety of aircraft during all phases of visual piloting.*

Index Terms—Aerodrome; power supply system; reliability measures; failure criteria.

I. INTRODUCTION

The analysis of statistical data on the number of aviation incidents and accidents occurring during different phases of aircraft's flight indicates that the visual piloting phase poses the highest risks to flight safety, [1].

The visual piloting phase begins with the aircraft taxiing before the takeoff, continues through the takeoff roll along the runway until liftoff, and includes the final stage of approach from the height of visual assessment, landing and taxiing to the parking position. The pilot's determination of the aircraft's position relative to the runway centerline during visual piloting at night, twilight, and daytime, as well as in adverse meteorological conditions, is guided by the visual cues created by ground-based visual navigation aids, which are the lights of the aerodrome lighting system (ALS).

A modern ALS ensures aircraft takeoff in runway visual range (RVR) conditions from 550 meters to 150 meters, and provides the visual navigation during final approach, landing, run and taxiing to the aircraft parking position under the operational minima of aerodromes in Cat. I, II, and III. The aerodrome lighting system is a complex, topological, multi-element system that includes up to a thousand aerodrome lights and markers of various functional purposes, positioned throughout and beyond the airfield. This set of lights and markers forms a standardized lighting picture of specific configuration and color, enabling the pilot to define the aircraft's position during the visual piloting phase in adverse meteorological conditions during the day, twilight, and night.

The operability and proper functioning of the ALS are key guarantees in ensuring an acceptable level of flight safety risk during the visual piloting phase of operations at an every aerodrome. The complexity of the ALS necessitates the formulation of specific criteria under which it performs its functions. These criteria are outlined in the requirements of the ICAO International Standards and Recommended Practices (SARPs) [2] and include two main indicators – quantitative and topological. In other words, an ALS failure occurs when a certain number of lights failed or when non-operational lights are positioned in specific manner (i.e. two in a raw). Additionally, the ALS may operate in a reduced functionality state or progress to a full failure depending on its composition, the structure of the power supply system, and the meteorological conditions under which flights are conducted.

The modern ALS includes highly reliable components such as LED light sources, high-voltage and low-voltage cables, AGL (airfield ground light) transformers, and constant current regulators. Analysis of failure statistics for ALS components indicates that, due to the high reliability of LED lights, the overall reliability of the system is largely influenced by the reliability of its power supply system.

II. Problem Statement

International ICAO SARPs in document [2] emphasize the importance of designing a "highly reliable" power supply system for all aerodrome consumers in general, and for the lighting system in particular: "The safety of operations at aerodromes depends on the quality of the supplied power".

Failure of the ALS power supply system, depending on its type, typically leads to the failure of at least half of all aerodrome lights connected to the respective power source (which may include one or several functional ALS subsystems). In such cases, the visual pattern provided by the lighting system will be distorted, potentially causing the pilot to lose visual contact or, even worse, to establish false visual contact. In the first scenario, according to flight operation procedures, the pilot is required to abort the landing and execute a go-around maneuver. In the second scenario, where false visual contact is established, predicting the pilot's actions becomes nearly impossible. However, it is clear that the situation on board the aircraft is likely to escalate from an incident to an aviation accident.

From the above, it can be concluded that ensuring high levels of reliability in the power supply system at the aerodromes is extremely important, especially since there are other consumers at the aerodrome that ensure the safety of technological operations with aircraft.

Therefore, the problem lies in developing a mathematical model to determine the reliability indicators of the power supply system and its normalization, based on criteria for ensuring an acceptable level of flight safety risks.

To develop a mathematical model for the reliability of the power supply system it is necessary to conduct an engineering analysis of the system, formulate failure criteria, and substantiate the input data and failure models for the system's components.

As a result, we aim to derive an analytical relationship between the reliability indicators of the system's elements ($K_{\text{A G1}}$, $K_{\text{A G2}}$, $K_{\text{A SPS}}$, $K_{\text{A SPS AC}}$) and the system as a whole ($K_{\text{A PS ALS}}(t)$):

$$K_{\text{A PSS ALS}}(t) = f\left(K_{\text{A G1}}, K_{\text{A G2}}, K_{\text{A SPS}}, K_{\text{A SPS AC}}, t\right),$$

where $K_{\text{A PSS ALS}}(t)$ is the non-stationary (or stationary) availability coefficient of the ALS power supply system (PSS); $K_{\text{A G1}}$, $K_{\text{A G2}}$, $K_{\text{A SPS}}$, $K_{\text{A SPS AC}}$ are non-stationary (or stationary) availability coefficients of the ALS primary power supply system elements (primary independent power supply system inputs G1, G2; secondary power supply system unit (SPS) and secondary power supply automatic connector (SPS AC); t is the time period, within which the reliability indicators of the system must be determined, is typically the interval between two maintenance operations.

In turn, the non-stationary (or stationary) availability measures of the components of the ALS power supply system, as restorable system, are determined by the failure rate parameters of their elements ω_i:

$$K_{\text{A G1}}(t) = f(\omega_{\text{G1}}, t), \quad K_{\text{A G2}}(t) = f(\omega_{\text{G2}}, t),$$

$$K_{\text{A SPS}}(t) = f(\omega_{\text{SPS}}, t), \quad K_{\text{A SPS AC}}(t) = f(\omega_{\text{SPS AC}}, t),$$

where ω_i is the failure rate parameter of the corresponding element of the power supply system of ALS.

The "reliability function" of elements of the ALS power supply system over time t, as for most technical systems, will be assumed to follow an exponential distribution, where the failure rate parameter remains constant (ω = const):

$$R_i(t) = e^{-\omega_i t}.$$

The relevance of the problem is confirmed by ICAO requirements [3, p. 18.3.5]: "…Reliable indications of the levels of serviceability should be an integral part of any system design".

The goal of this article is to develop a reliability model for the power supply system under various failure criteria, aimed at determining the reliability indicators of the system during its design, modernization/reconstruction, or operational phases.

III. Problem Solution

National standards and literary sources [4], [5], as well as international standards [2], [6], require that an aerodrome should have at least one primary (public source) and a secondary (interruptible) power supply source to ensure the electrical energy supply for the elements of the ALS (Fig. 1). These power sources must be integrated in such a way as to ensure that power interruptions for consumers, which are regulated at levels ranging from 15 to 1 second for various categories and subsystems of the ALS power supply system, as specified in the documentation [2], [4].

The analysis of the literature sources [2] – [6] has demonstrated that specific requirements are imposed on the aerodrome power supply system. According to ICAO standards [2, p.18.3.5]: The requirements of Annex 14, Volume I, Chapter 8, clearly indicate that, to achieve the high levels of reliability necessary for the visual aids to properly support operations, attention must be given to the design, operation and monitoring of the electrical supplies. Strict limits are set on the levels of availability of the various aids.

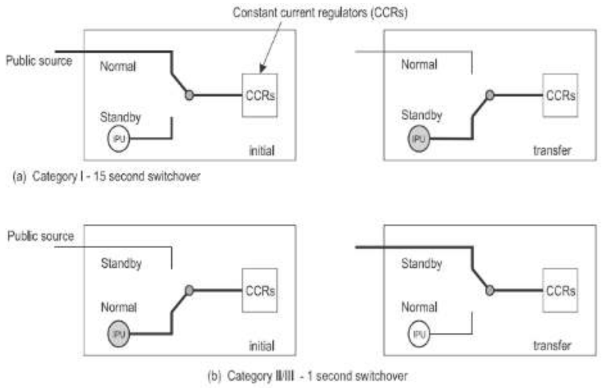

Fig. 1. Normal and standby aerodrome power supply for Cat. I – III operation

At the modern Ukrainian aerodromes, as well as abroad, the most common power supply configuration consists of at least two independent public power sources and one or more autonomous power sources – secondary (interruptible) PSS (mostly diesel generator). Additionally, the use of uninterruptible power supplies (UPS) has become increasingly prevalent in recent years, as they guarantee the provision of maximum value of "switch-over time" for critical systems. Under normal conditions, all consumers receive electricity from the two independent public power sources. In case of a failure of one public source, the second (operational) public source takes the load of the first one (via the power supply system automatic connector (PSS AC), while simultaneously triggering the command to start the SPS. Once the SPS starts and reaches operational mode, it takes the load of the consumers previously served by the failed public source or, if necessary, can take over the load for all consumers if the reliability of the second public source is in doubt. In this case, the second public power source remains in a standby mode without load.

ICAO standards and national regulatory documents [2], [4] specify not the interruption time in power supply, as it was previously, but the switch-over aerodrome lights of different subsystems. The Switch-over time (light) is the defined as the time required for the actual intensity of a light measured in a given direction to fall from 50 per cent and recover to 50 per cent during a power supply changeover, when the light is being operated at intensities of 25 per cent or above [2]. Modern secondary power supply automatic connector and appropriate fast-acting switches perform rapid switching.

The diagram of a typical aerodrome transformer substation with power distribution system to the consumer is presented in Fig. 2. It includes two independent public power sources G1 and G2, as well as one autonomous source – a diesel generator G3, with automation levels II-III. The power supply of ALS is provided via two sections of guaranteed power supply buses (GPSB) – GPSB 1 and GPSB 2. Each of the power transformers (T1/T2) operates on its respective section of the busbars (BB1/BB2) which are connected through connectors of PSS AC to corresponding GPSB, ensuring load redundancy for both sections.

The GPSB redundancy is provided on the low-voltage side by the section circuit breaker QF8 of the power supply AC.

The autonomous power supply source G3 utilizes the PSS AC to provide unloaded redundancy for both sections of the GPSB. The activation of backup power supply from the soured G3 (mostly diesel generators) in the event of a failure of the primary public power source is carried out automatically within approximate time period 15,0 sec. (the startup and stabilization time for modern diesel generators).

The functioning algorithm of the power supply system is as follows:

1) Both independent public power sources, G1 and G2, operate on their respective bus sections: GPSB 1 and GPSB 2.

2) The section circuit breaker of PSS AC QF8, is in the open state. The autonomous power supply source G3 is in unloaded reserve.

3) In case of a failure, for example, of public power source G1, it is disconnected from the bus section GPSB 1 by circuit breaker QF3 and contactor CN1. Subsequently, the PSS AC is triggered (closing the section circuit breaker QF8). Power supply to the consumers of the GPSB 1 is provided by public source G2 from the GPSB 2.

4) Simultaneously with the activation of the PSS AC, a command is generated to start the autonomous power source G3 (diesel generator). The power source G3 starts within approximately 15.0 seconds, and after reaching nominal operating mode, a command is generated to connect it to the GPSB 1, along with the operation of the PSS AC, which means opening the section circuit breaker QF8 of the PSS AC.

5) Thus, power source G3 supplies the GPSB 1, while public source G2 supplies GPSB 2. Consequently, the source G3 backs up source G2, and conversely, source G2 backs up G3 in the case of its failure.

6) Upon the restoration of public source G1, after a 3–5 second pause, diesel generator G3 disconnects from the GPSB 1, the PSS AC activates (sectional circuit breaker QF8 of PSS AC opens), and the public source G1 is connected to bus section GPSB 1. After a 5.0–7.0 second pause, source G3 shuts down and went back to standby mode.

7) In case of the source G3 failure, it disconnects from bus section GPSB 1, and the PSS AC is activated again – sectional circuit breaker QF8 of PSS AC closes. The power supply to consumers of GPSB 1 is provided by public source G2, through bus section GPSB 2.

8) In case of a failure of public source G2, it disconnects via circuit breaker QF2 and contactor CN4, the PSS AC activates (sectional circuit breaker QF8 closes), and the power supply to both bus sections GPSB 1 and GPSB 2 is provided by diesel generator G3.

9) Upon the restoration of public source G1 (or source G2), after a 3.0–5.0 second pause, the PSS AC activates (sectional circuit breaker QF8 of PSS AC opens), and public source G1 (or G2) is connected to the corresponding bus section GPSB 1 or GPSB 2.

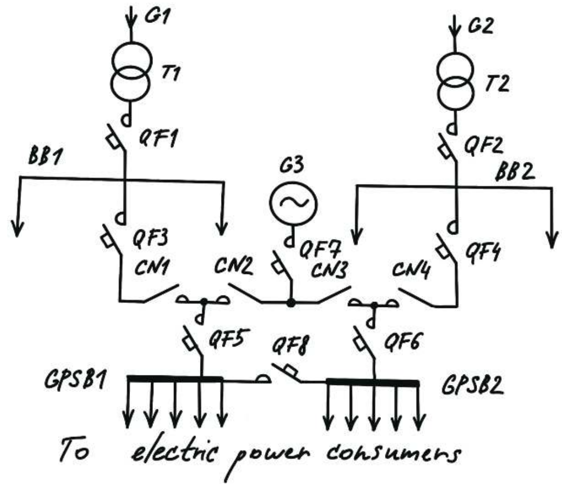

Fig. 2. Typical aerodrome power supply system

The PSS AC switching time (sectional circuit breaker QF8 of PSS AC) must not exceed 1 second.

Currently, some regional aerodromes have a different algorithm for the automatic transfer of backup power supply, which is as follows.

In case of a failure of either of the two public power sources, G1 or G2, and upon reaching nominal operating conditions of diesel generator G3, the second public power source is disconnected from the guaranteed power supply bus sections. The section circuit breaker of the PSS AC remains closed, and power source G3 is connected to both sections of the guaranteed power supply buses.

In this case, the operational public power source is in unloaded reserve mode relative to the power source G3. Although the reliability of this algorithm is not different from the first, it has a drawback that raises doubts about its practicality. When the power source G3 operates on both sections of the GPSB, its load approaches nominal values, resulting in nearly double fuel consumption. Additionally, the lifetime of the diesel generator is significantly reduced, making this algorithm impractical.

For the development of the reliability model of the power supply system, is more practicably choose the first algorithm of power supply system operation, as it is more common.

Thus, for the development of a mathematical model of the reliability of the power supply system, it is necessary to consider all possible technical states of the following key elements:

- first public (primary) power source G1;
- second public (primary) power source G2;
- secondary (backup / interruptible) power source G3;
- PSS AC device.

The availability and technical state of UPS will not be considered in the model, as they may not be installed for all subsystems or may not be used at all.

Let's assume that all the aforementioned elements of the power supply system may be only in two technical states – operational and non-operational, i.e., failure state.

The indicator of the operational state of the entire system will be the availability of power supply to for aerodrome consumers. However, we will consider two cases.

1) Case of availability of backup power source – "normal conditions": in this scenario, the system can be utilized as intended without any time restrictions.

2) Case of absence of backup power source – "critical aircraft" case": this pertains to a situation where an aircraft requires immediate landing due to certain issues on board. In this case, the system can only be used for a limited period, necessary to ensure landing and safe arrival for all aircrafts in need.

With this formulation of the criterion of operational state of the PSS, the probability of the PSS being unavailable by any aircraft is equal to zero.

Let's examine all possible types of technical states, their combinations, and the corresponding scenarios that may arise in a PSS with four mentioned above elements.

First scenario – the number of failed elements in the system is equal to zero. All four elements of the power supply system are in an operational state. Such a scenario can occur only once. The probability of this scenario at a given time t is determined as the product of the probabilities of the operational states of each system element. Let's denote them conditionally as R_{G1}, R_{G2}, R_{G3}, $R_{PSS\ AC}$.

For the simplicity of the presentation, we will omit the time dependence of the probabilities of the operational states of the elements.

$$n = 0,\ P_0 = R_{G1} \cdot R_{G2} \cdot R_{G3} \cdot R_{PSS\,AC}.$$

Second scenario – one element out of four has failed. There are four such cases possible (combinations of one failure out of four elements): either G1 (F_{G1}), or G2 (F_{G2}), or G3 (F_{G3}), or ABP ($F_{PSS\ AC}$). The probability of this scenario occurring within a given time t is determined as the sum of the products of the probabilities of the operational and failed states of the respective system elements:

$$n = 1,\ P_1 = F_{G1} \cdot R_{G2} \cdot R_{G3} \cdot R_{PSS\,AC} + R_{G1} \cdot F_{G2} \cdot R_{G3} \cdot R_{PSS\,AC} + R_{G1} \cdot R_{G2} \cdot F_{G3} \cdot R_{PSS\,AC} + R_{G1} \cdot R_{G2} \cdot R_{G3} \cdot F_{PSS\,AC}.$$

Third scenario – two elements have failed. There are exactly six cases (combinations of two failures out of four elements). This includes situations where either both external sources fail (F_{G1} and F_{G1}), or one of the public power sources and diesel generator (F_{G1} and F_{G3} or F_{G2} and F_{G3}), or one of the public power sources and PSS AC (F_{G1} and $F_{PSS\ AC}$, or F_{G2} and $F_{PSS\ AC}$) or diesel generator and PSS AC fail (F_{G3} and $F_{PSS\ AC}$). The probability of this scenario occurring within a given time t is determined as follows:

$$n = 2,\ P_2 = F_{G1} \cdot F_{G2} \cdot R_{G3} \cdot R_{PSS\,AC} + F_{G1} \cdot R_{G2} \cdot F_{G3} \cdot R_{PSS\,AC} + F_{G1} \cdot R_{G2} \cdot R_{G3} \cdot F_{PSS\,AC} + R_{G1} \cdot F_{G2} \cdot F_{G3} \cdot R_{PSS\,AC} + R_{G1} \cdot F_{G2} \cdot R_{G3} \cdot F_{PSS\,AC} + R_{G1} \cdot R_{G2} \cdot F_{G3} \cdot F_{PSS\,AC}.$$

Fourth scenario – three elements of the system have failed. There are four such a possible cases (combinations of three failures out of four elements). These include situations where both primary sources and the diesel generator fail (F_{G1}, F_{G2} and F_{G3}), or both primary sources and the PSS AC fail (F_{G1}, F_{G2} and $F_{PSS\ AC}$) or one of the public sources and the diesel generator together with PSS AC (F_{G1}, F_{G3} and $F_{PSS\ AC}$ or F_{G2}, F_{G3} and $F_{PSS\ AC}$). The probability of this scenario occurring within a given time t is determined as follows:

$$n = 3,\ P_3 = F_{G1} \cdot F_{G2} \cdot F_{G3} \cdot R_{PSS\,AC} + F_{G1} \cdot F_{G2} \cdot R_{G3} \cdot F_{PSS\,AC} + R_{G1} \cdot F_{G2} \cdot F_{G3} \cdot F_{PSS\,AC} + F_{G1} \cdot R_{G2} \cdot F_{G3} \cdot F_{PSS\,AC}.$$

Fifth scenario – all four elements have failed, meaning the entire power supply system is inoperative. This situation occurs in one case (a combination of all four failed elements) and characterizes the complete failure of the power supply system. The probability of this scenario is defined as

$$n = 4,\ P_4 = F_{G1} \cdot F_{G2} \cdot F_{G3} \cdot F_{PSS\,AC}.$$

The sum of the probabilities of all the above scenarios is equals to unity, as they form a complete group of events.

From the above scenarios, we select the cases that fit the description of the "operational state of the system" according to the failure criterion.

Let's consider the first formulation of the criteria for the system's operational state – "normal conditions," where a backup power source is always available and can automatically connect to the consumers. This includes the first scenario and three cases from the second scenario (those that account for the operational state of two out of three sources and the PSS AC). The probability of the situation falling under the description of "normal conditions" is described by the following formula:

$$P_{\text{"norm. cond."}} = R_{G1} \cdot R_{G2} \cdot R_{G3} \cdot R_{PSS\,AC} + F_{G1} \cdot R_{G2} \cdot R_{G3} \cdot R_{PSS\,AC} + R_{G1} \cdot F_{G2} \cdot R_{G3} \cdot R_{PSS\,AC} + R_{G1} \cdot R_{G2} \cdot F_{G3} \cdot R_{PSS\,AC}.$$

For the second formulation of the system's operational state criteria – "critical aircraft case," the only condition is the presence of at least one power source that can supply at least half of the consumers. The relevant cases from the previously described scenarios are:

- first scenario – all elements of the system are operational;
- second scenario – one out of four system elements has failed – all cases;
- third scenario – two out of four system elements have failed – all cases;
- fourth scenario – three out of four system elements have failed – all cases except the first one

(where only the PSS AC is operational), assuming that in a scenario where the diesel generator is operational but the PSS AC fails, consumers can be manually connected.

For the second formulation, it is easier to establish the failure criterion for the system, find the probability of it being in an failed state ($F_{\text{"cr. acrf."}}$), and then determine the probability of the system being operational at a given time t by inverse calculation. The failure criterion can be formulated as follows: "The system fails when all three power sources fail."

$$P_{\text{"cr. acrf."}} = 1 - F_{\text{"cr. acrf."}} = 1 - (F_{\text{G1}} \cdot F_{\text{G2}} \cdot F_{\text{G3}} \cdot F_{\text{PSS AC}} + F_{\text{G1}} \cdot F_{\text{G2}} \cdot F_{\text{G3}} \cdot R_{\text{PSS AC}}).$$

Thus, we have a mathematical model for determining the probabilities of the power supply system's operational state, consisting of four elements, based on two different formulations of failure criteria.

Given that all elements of the power supply system are renewable, the system's reliability measures should be calculated using the steady-state availability coefficients (K_{A}) of its elements. These coefficients describe system's availability – the probability that the system is in an operational state at any random moment, except during restoration periods. The coefficient of non-availability K_{NA} is the reciprocal parameter to K_{A}.

$$K_{NA} = 1 - K_{A}.$$

The probability of the system being operational under "normal conditions" is then determined as follows:

$$K_{\text{A"norm. cond."}} = K_{\text{A G1}} \cdot K_{\text{A G2}} \cdot K_{\text{A G3}} \cdot K_{\text{A PSS AC}} + K_{\text{NA G1}} \cdot K_{\text{A G2}} \cdot K_{\text{A G3}} \cdot K_{\text{A PSS ACBP}} + K_{\text{A G1}} \cdot K_{\text{NA G2}} \cdot K_{\text{A G3}} \cdot K_{\text{A PSS AC}} + K_{\text{A G1}} \cdot K_{\text{A G2}} \cdot K_{\text{NA G3}} \cdot K_{\text{A PSS AC}}.$$

The probability of the system being operational in the "critical aircraft" scenario is determined as follows:

$$K_{\text{A"cr. acrf."}} = 1 - K_{\text{NA"cr. acrf."}} = 1 - (K_{\text{NA G1}} \cdot K_{\text{NA G2}} \cdot K_{\text{NA G3}} \cdot K_{\text{NA PSS AC}} + K_{\text{NA G1}} \cdot K_{\text{NA G2}} \cdot K_{\text{NA G3}} \cdot K_{\text{A PSS AC}}).$$

Given the initial data on the failure rates of power sources G1, G2, G3, the reliability measures of the power supply system can be determined in accordance with the formulated system failure criterion – either the steady-state or non-steady-state availability coefficient, or the probability of failure-free operation for a given time.

IV. CONCLUSIONS

Modern aerodrome power supply systems must meet strict reliability standards during operation, as the quality of power supply directly impacts aircraft safety performance during visual piloting phase at twilight, night and day in adverse weather conditions.

National and international regulations regarding the composition and functioning principles of ALS power supply systems have been analyzed.

The most common operational algorithm of ALS power supply systems has been examined in detail, and a mathematical model has been developed to determine reliability measures. This model can be practically applied to assess and optimize system reliability during design, as well as in operation, to evaluate the need for upgrades or additional elements, such as UPS.

The reliability measures of ALS power supply systems can also be used for flight safety risk assessments during visual piloting phase at civil aviation aerodromes.

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С. С. Дев'яткіна, Т. І. Яреміч. Математична модель надійності системи електропостачання аеродрому

Статтю присвячено моделюванню надійності системи електропостачання аеродромів цивільної авіації. Стандарти та рекомендована практика ICAO ставлять перелік вимог до систем електропостачання сучасних аеродромів цивільної авіації. Кожний новий проект або модернізація / реконструкція аеродромного обладнання, від функціонування якого залежить рівень безпеки польотів, повинен супроводжуватися визначенням та оцінкою його показників надійності. Така вимога пояснюється тим, що відмови такого обладнання являють собою загрози та можуть створювати ризики щодо безпеки польотів при забезпеченні технологічних процесів обслуговування повітряних суден на аеродромі цивільної авіації. Відповідно до вимог стандартів ICAO в сфері керування безпекою польотів, всі ризики на аеродромі мають контролюватися та знижуватися до прийнятного рівня. Запропонована математична модель надійності системи електропостачання аеродрому дозволяє визначати показники її надійності при різних формулюваннях критеріїв відмови, оцінювати вплив системи електропостачання на рівень безпеки польотів та розробляти комплекс організаційно технічних заходів для забезпечення та підвищення надійності системи в цілому, що безумовно матиме позитивний вплив на рівень безпеки польотів повітряних суден.

Ключові слова: аеродром; система електропостачання аеродрому; показники надійності; критерії відмови.

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Напрям наукової діяльності: надійність аеродромних наземних навігаційних засобів забезпечення польотів та систем їх електропостачання, керування ризиками щодо безпеки польотів на етапі візуального пілотування.
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Напрям наукової діяльності: світлотехніка і джерел світла, підвищення ефективності світлотехнічних установок та систем, авіаційна світлотехніка, аеродромні засоби забезпечення польотів та системи їх електропостачання.
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