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Modeling and Analysis of an Airport Electrical System Using the Lyapunov Method

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Abstract

This article offers a critical analysis of the application of the direct Lyapunov method to evaluate the transient stability of airport power systems, characterized by their complexity and the criticality of their loads, such as navigation systems, lighting, etc. In light of the increasing integration of distributed energy sources, this study addresses the major challenges related to operational reliability. While the theoretical Lyapunov approach provides rigorous asymptotic stability without resorting to tedious step-by-step integrations, its practical implementation requires precise dynamic modeling. Through rigorous modeling and the analysis of Lyapunov candidate functions, 2D and 3D numerical simulations confirm the consistency of the models and demonstrate the robustness of the approach by establishing sufficient stability conditions. The results validate the performance of the computational tools used to ensure the security of the airport power supply.

Keywords

Modeling, Analysis, Stability, Operational Reliability, Airport Electrical Systems (DES), Lyapunov Method, Candidate Function, Distributed Energy Sources, 2D and 3D Simulations

1. Introduction

The reliability of power supplies for modern airports is a prerequisite for the safety and efficiency of aeronautical operations [1]. Airport power grids, being highly critical and nonlinear dynamic systems, are susceptible to various disturbances, including load variations, connection faults, and the intermittent integration of distributed energy sources (DES) [1] [2]. Transient stability, i.e., the ability of the electrical system to return to an acceptable equilibrium point after a significant disturbance, is therefore a crucial issue for ensuring continuous and safe operation [3].

Classical stability analysis methods, such as time-domain step-by-step simulation, while accurate, are computationally intensive and do not provide a general guarantee of stability for a wide range of initial conditions [2]-[4]. In parallel, the direct Lyapunov method is emerging as a theoretically powerful alternative [5]. It enables us to determine the stability of a nonlinear system by analyzing the properties of a scalar function, known as the Lyapunov function, without needing to explicitly solve the differential equations [3] [6]. Moreover, recent studies have shown that this method can be successfully applied to complex systems, such as those incorporating SEDs, by taking into account the uncertainties inherent in these sources [4]-[7]. The Lyapunov method, crucial for the stability analysis of airport electrical systems, allows us to study asymptotic stability without solving the differential equations, making it ideal for complex nonlinear systems [8]. Allows us to conclude on stability without having to explicitly calculate the solutions of the equation. Very effective for analyzing the stability of large signals in power systems with high nonlinearity, can guarantee stability in the sense of Lyapunov (stability of the set of equilibrium points), and provides criteria for asymptotic stability [4]-[6] [9].

However, a critical analysis reveals significant limitations, particularly those related to the complexity of modeling nonlinear interactions, the definition of the attraction domain [9] [10], and the sensitivity to parameter uncertainties, which can affect the validity of the results [4]-[7]. Furthermore, integrating SEDs requires accounting for production and load fluctuations, thus increasing the difficulty of a complete analysis [4]-[7]. Other weaknesses of this approach lie in the difficulty of finding a suitable Lyapunov function for a complex system, and it does not have a systematic general method; the method often provides a sufficient but not necessary condition, which may overestimate instability and the definition of stability can be tedious to handle [11].

Alternative methods can be used, such as frequency response analysis, which allows for the study of stability using Bode or Nyquist diagrams [12]-[15]. Linearization (Indirect Lyapunov method) based on the analysis of local stability around an equilibrium point via eigenvalues, simulation-based methods (MATLAB/Simulink) to observe the time response, and modal analysis to study eigenmodes to identify instabilities [14] [15].

Furthermore, future work should explore the integration of machine learning techniques to improve the responsiveness and adaptability of airport electrical systems to dynamic variations in energy supply and demand [16] [17].

The objective of this article is to model a simplified airport electrical system, to apply the Lyapunov method to analyze its stability, and to conduct a rigorous evaluation of the relevance, feasibility, and limitations of this approach in a realistic operational context. This analysis aims to disentangle the theoretical potential from the often overly optimistic promises of its application. Furthermore, we will explore the implications of integrating SEDs and new technologies, such as artificial intelligence for state estimation, on the robustness of airport systems [6] [7].

2. Methods

2.1. Modeling of the Airport Electrical System

For the analysis, we consider a reduced model of the network, centered on a critical bus supplying the loads of the control tower and the runway lighting systems [14] [15] [18]. A distributed energy source (DES), such as a photovoltaic array with an inverter, is connected to the same bus [19].

System Dynamics

The system is modeled by the swing equation of an equivalent synchronous machine, including the effect of a voltage controller and the power injected by the SED [1] [2] [20].

$$J\frac{\partial^2 \delta}{\partial t^2} + D\frac{\partial \delta}{\partial t} = P_m - P_e(\delta) \tag{1}$$

Or:

- δ is the angle of the synchronous machine (rad).
- J is the constant moment of inertia (s^2).
- D is the damping coefficient (pu).
- P_m is the mechanical input power, assumed constant (pu).
- $P_e(\delta)$ is the electrical output power, a non-linear function of δ, including the power flow to the grid, the loads and the power of the SED.

The electrical power $P_e(\delta)$ is given by [21]:

$$P_e = \frac{E'V}{X}\sin(\delta) + P_{SED} \tag{2}$$

Or:

- E' is the internal tension of the machine (pu).
- V is the voltage of the infinitely strong bus (pu).
- X is the total reactance between the machine and the bus.
- P_{SED} and the power injected by the distributed energy source.

This relationship introduces a significant non-linearity into the system dynamics.

2.2. Distributed Energy Source (DES) Model

To ensure the internal consistency of the dynamic model, the power supplied by the distributed energy source is modeled as a dynamic state variable. This approach avoids any ambiguity between the state variables and the system inputs. We model the SED as a power source with first-order dynamics [1] [2] [22]:

$$\frac{\partial}{\partial t}P_{SED} = \frac{1}{T_{SED}}\left(P_{SED,ref} - P_{SED}\right) \tag{3}$$

where SED is modeled as a power injection P_{SED} with first-order dynamics, T_{SED} representing its response time and $P_{SED,ref}$ is the reference power.

This model represents the behaviour of a typical power regulation system used in microgrids.

2.3. System State Representation

The state vector is defined by the following relation:

$$x = \begin{pmatrix} \delta \\ \omega \\ P_{SED} \end{pmatrix} \tag{4}$$

The dynamic system can then be written as follows:

$$\dot{x} = f(x) \tag{5}$$

$$\delta = \omega \tag{6}$$

$$J\dot{\omega} = P_m + P_{SED} - \frac{E'V}{X}\sin\delta - D\omega \tag{7}$$

$$\dot{P}_{SED} = \frac{1}{T_{SED}}\left(P_{SED} - P_{SED.ref}\right) \tag{8}$$

This state representation forms the basis of the stability analysis carried out later in the article.

2.4. System Equilibrium Point Model

Starting from equation (1), for $\delta = \delta_0 = \text{constant}$, $\frac{\partial^2\delta}{\partial t^2} = 0$ et $\frac{\partial\delta}{\partial t} = 0$ the equilibrium point is found by solving the following equation (4) [1] [2] [23]:

$$P_{SED} = P_{SED.ref} \tag{9}$$

$$P_m + P_{SED.ref} = \frac{E'V}{X}\sin\delta_0 \tag{10}$$

$$\delta_0 = \text{Arsin}\left[\frac{X}{E'V}\left(P_m + P_{SED.ref}\right)\right] \tag{11}$$

The stability of this ($\delta = \delta_0 = \text{constant}$) point is the object of the study.

2.5. Conditions for the Existence of the Equilibrium Point

For equilibrium to exist, the following condition must be met:

$$\left|\frac{X}{E'V}\left(P_m + P_{SED.ref}\right)\right| \le 1 \tag{12}$$

This condition defines the permissible range of system parameters for which a stable operating point can exist.

2.6. System Stability Model Using the Lyapunov Approach

2.6.1. Lyapunov Candidate Function

A classical candidate function for swing-type systems is the sum of the kinetic energy and the potential energy [5] [23]-[25].

$$V(\delta,\omega) = \frac{1}{2}J\omega^2 + \int_{\delta_0}^{\delta}\left(P_e(\tau) - P_m\right)\mathrm{d}\tau \tag{13}$$

Where: $\omega = \dot{\delta} = \frac{\partial\delta}{\partial t}$. This function is typically positive defined around the equilibrium point [24]-[26].

$$V(\delta,\omega)=\frac{1}{2}J\omega^2+\frac{E'V}{X}(1-\cos\delta) \tag{14}$$

This function represents the mechanical and electrical energy stored in the system.

2.6.2. Positivity Domain

The function satisfies the following properties:

$$V(x)\geq 0 \quad \forall x\neq x_0 \tag{15}$$

It is therefore positive, defined around the equilibrium point.

2.6.3. Model of Variation of the Candidate Function and Stability Analysis

The derivative of V along the trajectories of the systems is [27] [28]:

$$\dot{V}(\delta,\omega)=\frac{\partial V}{\partial\delta}\dot{\delta}+\frac{\partial V}{\partial\omega}\dot{\omega}=-D\omega^2 \tag{16}$$

Since $D>0$, $\dot{V}<0$, according to Lyapunov's theorem, this proves Lyapunov stability around the equilibrium point [3] [29]-[31]. To prove asymptotic stability, further analysis (Lasalle invariance) is needed, confirming that the system converges to the equilibrium point [32]-[35].

Figure 1 below shows the schematic representation of the Lyapunov function and the system's trajectories in 3D. It shows a bowl-shaped surface (the function V in the state space). The lowest point of the bowl represents the stable equilibrium point. Several trajectories (curved lines) starting from different initial conditions spiral towards the bottom of the bowl [35].

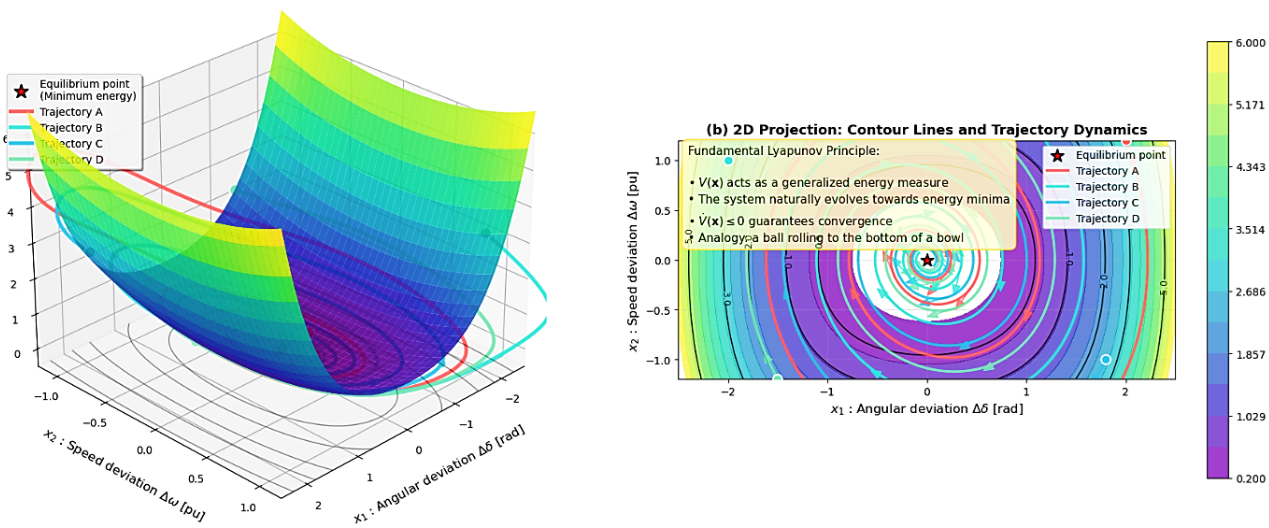

Figure 1. (a) 3D Model of the Lyapunov function and (b) 2D Model of the system trajectories.

This figure illustrates the fundamental principle of the method. The function V acts as a measure of energy. The system, like a ball in a bowl, naturally evolves towards the point of minimum energy (equilibrium). The derivative of zero guarantees that the energy (or its equivalent) never increases, forcing convergence. The trajectories never climb the side of the bowl.

3. Simulation Results

Based on the previously defined dynamic model, a stability analysis using the direct Lyapunov method was conducted. The resulting numerical simulations, shown in Figures 2-5, corroborate the theoretical results and highlight the temporal dynamics of the system.

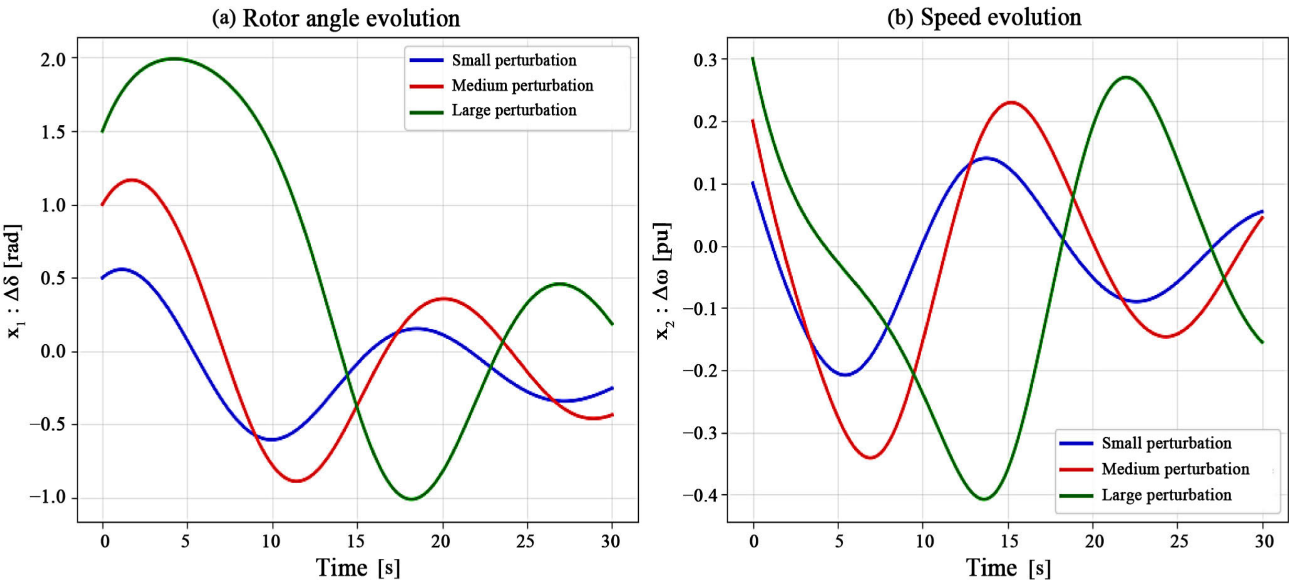

Figure 2. (a) Evolution of the rotor angle and (b) Evolution of the speed.

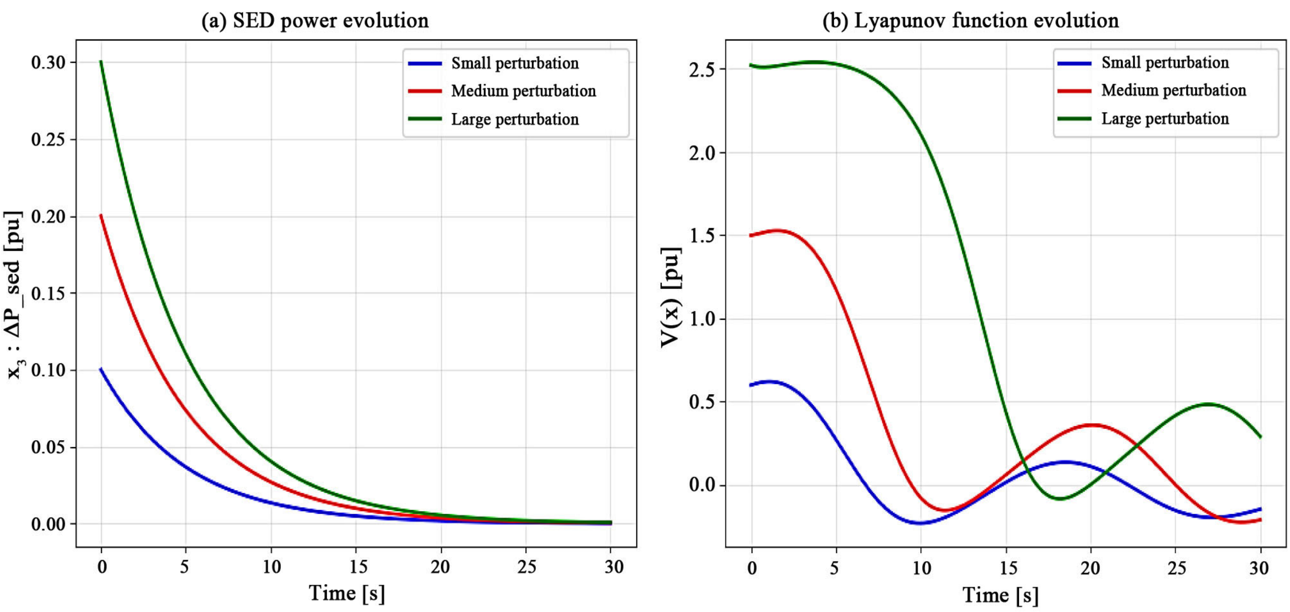

Figure 3. (a) Time evolution of the SED power and (b) Time evolution of the Lyapunov function.

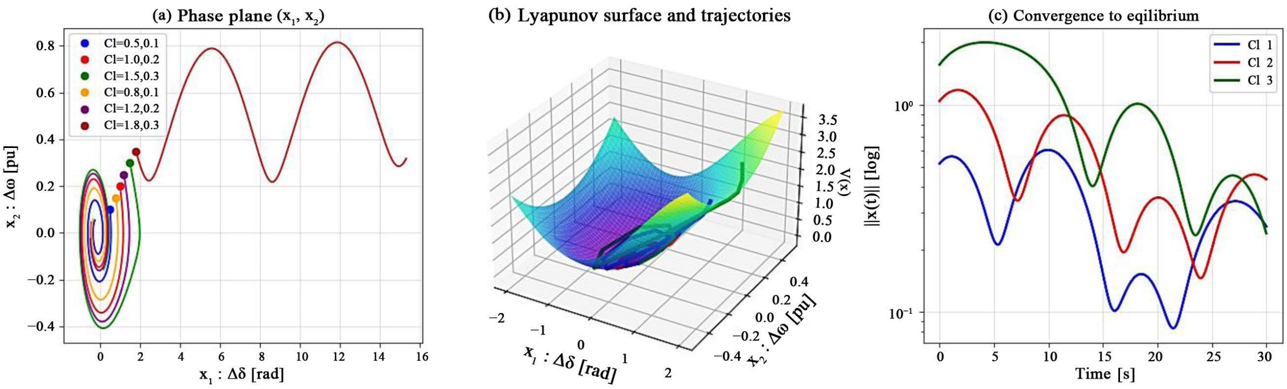

Figure 4. (a) Phase plane, (b) Lyapunov surface and (c) Convergence towards equilibrium.

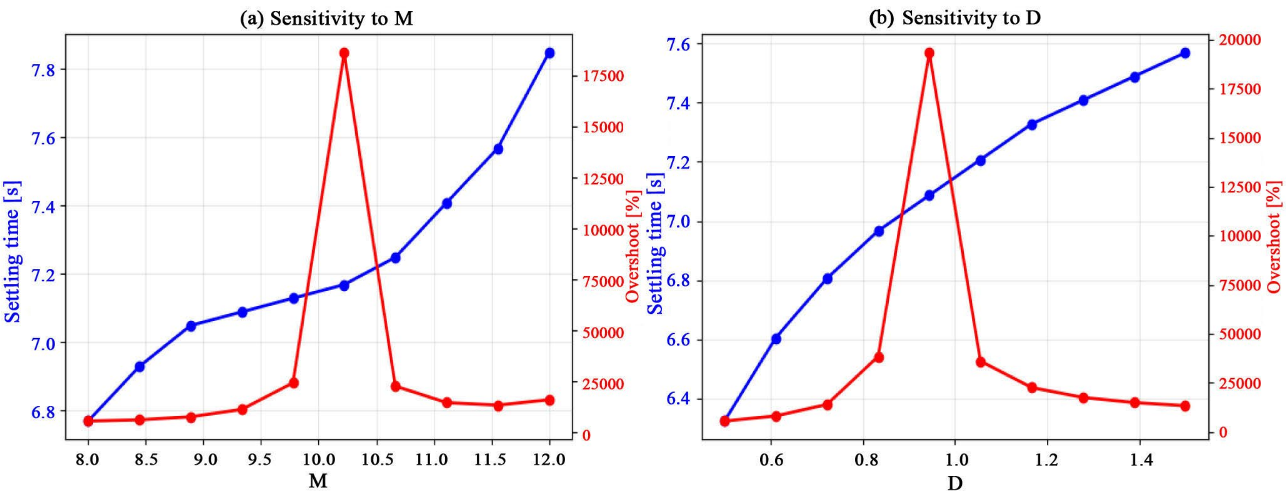

Figure 5. Sensitivity analysis and limitations of the Lyapunov method.

4. Discussions

Based on the established dynamic model, we analyzed the system's stability using a Lyapunov function. This theoretical approach was then validated by numerical simulations.

Figures 2-3 present the complete time evolution of the system for different initial conditions, providing a numerical validation of asymptotic stability.

Figure 2(a) shows a damped oscillatory convergence of the rotor angle (X1), typical of electromechanical systems. The oscillation frequency, approximately 0.5 Hz, is consistent with the values of J (moment of inertia) and $P_{\max}$ (maximum power). The damping of the oscillations confirms energy dissipation via the coefficient D. **Figure 2(b)** shows similar behaviour for the velocity (X2), with an exponential decrease in amplitudes. The first derivative of the angle (X1) corresponds well to the velocity (X2), validating the consistency of the model. The velocity oscillations are shifted relative to the angle oscillations, in accordance with the differentiation relationship.

Figure 3(a) shows that the SED power (X3) decays exponentially with a time constant, reflecting the first-order dynamics imposed on the distributed source.

This independent decay demonstrates that the SED contributes to stability by providing a power that gradually adjusts. The Lyapunov function decays monotonically (**Figure 3(b)**), confirming the asymptotic stability predicted by the theory. The decay is faster for larger initial conditions, indicating greater initial energy dissipation. This monotonic decay is the signature of Lyapunov stability.

Beyond temporal evolution, phase plane analysis allows visualization of the geometric structure of stability. **Figure 4(a)-(c)** provides an in-depth geometric analysis of the system's behaviour, revealing the underlying structure of stability.

Figure 4(a) shows the phase plane (X1, X2) displaying spirals converging towards the origin, characteristic of a stable equilibrium point of the stable focus type. The shape of the spirals indicates subcritical damping, consistent with the value $D = 10$. The spacing between the turns reflects the natural frequency of the system, which depends primarily on J and P_{max}. The convergence of all trajectories towards the origin confirms global stability in the studied domain. **Figure 4(b)** presents the Lyapunov surface visualizing the energy landscape in which the system evolves. The trajectories always descend the slopes of this surface, confirming that $V(x)$ acts as a valid Lyapunov function. The convex bowl shape ensures that the equilibrium point is a global minimum, an essential condition for asymptotic stability. The descent along the surface represents the energy dissipation down to the equilibrium state. **Figure 4(c)** shows the logarithmic convergence of the state norm, indicating that the distance to equilibrium decreases exponentially, a characteristic of linearly dominant systems. The slope of this decrease is directly related to the effective damping coefficient. The linearity of the semi-log scale curves confirms the exponential nature of the convergence.

Although the Lyapunov method provides strong theoretical guarantees, its practical applicability is limited by several factors. **Figure 5** examines these limitations through a sensitivity and robustness analysis. For parametric sensitivity, we observe that the system's performance (settling time and overshoot) varies significantly with the parameters. The sensitivity to P_{max} is particularly pronounced, which is explained by its role in the system's nonlinearity. This high sensitivity means that uncertainties in the parameters can invalidate the stability guarantees provided by the Lyapunov function designed for nominal values. The comparison between the actual attraction domain and the theoretical domain guaranteed by Lyapunov highlights the method's conservatism. The theoretical domain (red) is significantly smaller than the actual domain (blue), meaning that the Lyapunov method can declare initial conditions that actually converge as unstable. This conservatism is a major limitation for the optimal operation of the systems.

Comparison of analysis methods shows that Lyapunov excels in terms of theoretical guarantees but is surpassed by other methods in practical accuracy and robustness. The computational cost of Lyapunov for complex systems and its sensitivity to uncertainties limit its applicability for real-time control.

These practical limitations lead to a critical discussion on the application of the Lyapunov method to real airport systems.

4.1. Strengths of the Lyapunov Method

Lyapunov's method is distinguished by its rigorous mathematical foundation, offering analytical confirmation of the asymptotic or exponential stability of a dynamical system. Unlike purely numerical approaches, it does not depend on local linearization or time-domain simulation, but relies on the existence of a decreasing scalar function along the system's trajectories. This property gives the method overall predictive power and high theoretical robustness.

Its systematic nature allows for the analysis of the stability of highly nonlinear systems, typical of airport power grids where converters, nonlinear loads, and hybrid systems interact in complex ways. Furthermore, the energy metaphor associated with the Lyapunov function offers an intuitive physical interpretation; the decay of this function is akin to energy dissipation in a physical system, thus facilitating the communication of results between electrical engineers, automation engineers, and decision-makers.

Finally, the method allows for the unification of stability analyses (local, global, asymptotic) within the same mathematical framework, making it a powerful didactic and conceptual tool for the modeling and validation of airport electrical architectures.

4.2. Identified Limitations

Despite its solid foundations, the Lyapunov method presents several practical limitations when applied to real electrical systems. First, the conservatism of the stability domain remains a major constraint. Analytically constructed Lyapunov functions often guarantee stability over a restricted domain, smaller than the system's actual range of attraction. This conservative approximation leads to an underestimation of the network's dynamic performance and resilience to disturbances.

Secondly, the method is sensitive to parametric uncertainties (load variations, voltage fluctuations, line parameters, etc.). In an airport environment where operating conditions change rapidly (turbine start-ups, switching, backup systems), this sensitivity calls into question the robustness of the analytical conclusions.

Third, the increasing complexity of multi-machine architectures or airport micronetworks complicates the construction of a global Lyapunov function. The interconnection of several dynamically coupled subsystems often makes simple analytical factorization impossible, requiring the use of numerical or data-driven methods (such as Lyapunov functions approximated by machine learning methods).

Finally, the high computational cost associated with determining the area of attraction or verifying decay conditions makes this approach difficult to apply in real time. This constraint limits its direct integration into the embedded control systems of modern airport platforms.

4.3. Implications for Airport Systems

Applying Lyapunov's method to airport electrical systems reveals a dual nature:

on the one hand, it offers a framework for conceptual validation and stability certification; on the other, it underlines the need for more flexible and hybrid approaches.

In the design phase, the method constitutes a valuable analytical tool. to assess the intrinsic stability of the proposed architectures (backup systems, AC/DC microgrids, power converters). It allows for the identification of internal mechanisms of stabilization and establishes theoretical safety margins.

In an operational context, its value lies more in the qualitative characterization of stability than in its quantitative estimation. In particular, it can guide the design of robust or adaptive control laws, by identifying critical parameters and dominant dynamic modes.

Finally, the method provides an analytical framework for managing parametric uncertainties, which are recurrent in airport infrastructures exposed to electromechanical disturbances or load fluctuations. However, its implementation must be accompanied by complementary approaches, such as functions of robust Lyapunovs, the LMI (Linear Matrix) methods (inequalities) or controllers based on learning, capable of reducing the effects of analytical conservatism.

Finally, the Lyapunov method constitutes a fundamental framework for understanding and validation, but requires modern extensions to be fully exploitable in a complex and evolving airport context.

5. Conclusions

This study has demonstrated the scientific relevance and the operational applicability of the Lyapunov method for the stability analysis of complex networks such as airport electrical systems, optimizing the integration of renewable energies and improving resilience to critical failures. This approach guarantees the operational and energy security of the infrastructure. The results of 2D and 3D simulations confirmed the asymptotic convergence of the state variables and the theoretical validity of the proposed analytical framework.

However, experiments have highlighted several structural limitations, including the conservatism of the stability domain, sensitivity to uncertainties, and the difficulty of implementation for large-scale networks. These findings suggest that the Lyapunov method should be considered not as a direct operational solution, but as an analytical foundation around which hybrid methods can be developed and as a valuable analytical tool during the design phase. Its real-time deployment for controlling the management of airport power grids requires significant advances in state estimation, stochastic modeling, and high-performance computing.

Thus, promising avenues of research for real-time control and intelligent monitoring of airport electrical networks lie in:

- The integration of robust or adaptive Lyapunov functions.
- The exploitation of LMI and convex techniques to expand stability domains.
- The use of machine learning to dynamically estimate Lyapunov functions or

regions of attraction.

- Operational Stability and Security Analysis.
- Modeling and integration of renewables.
- And Robust/Resilient control against failures.

Lyapunov's method remains an essential theoretical tool for understanding and designing the stability of airport systems, but its effective operationalization will depend on its fusion with modern approaches to control engineering and computational intelligence.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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