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On modeling and control of advanced aircraft electric power systems: System stability and bifurcation analysis

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ABSTRACT

This paper presents a comprehensive dynamic bifurcation model and stability study of advanced aircraft electric power system (AAEPS). The proposed bifurcation model is utilized to investigate the aircraft electric power system stability under various system configurations and loading conditions. Further investigations are performed to verify the sustainability and robustness of the aircraft electric power system and subsystems to time-dependent changes occurring in the system dynamics due to variations in control loop parameters and changes in the loading conditions and power demand. Moreover, stability analysis for changes in operating frequency of the aircraft electric power system's AC channel is reported. It has been demonstrated that equilibrium points corresponding to the differential equations of the aircraft electric power systems undergo different bifurcation behaviors when the system's operating parameters are subjected to variations. Finally, several case-study models are developed and implemented and the corresponding two-dimensional bifurcation diagrams were obtained with results verified using available experimental measurements. The AAEPS stability study and bifurcation analysis can assist engineers in identifying preferred regions of operation and safe margin design based on the variation of the system's loading and parameters.

Introduction

There have been extensive research efforts on modeling and characterization of the More Electric Aircraft Power Systems (MEAPS) in recent years. Electric energy has been proposed by many authors over the past decades, and it is becoming a viable alternative to the commercial aircraft with conventional mechanical energy systems. Reduced design complexity, lower flight test hours, less tooling, shorter checkout time and elimination/reduction of the hydraulic systems, which have deleterious impact on the environment, are some advantages of more electric aircraft over conventional aircraft with more mechanical equipment [1–9]. Due to the fact that the electric power systems of aircraft are inherently nonlinear, maintaining a range of stable operation is of prime concern. In order to address this complication, many nonlinear system analysis techniques have been developed to aid in the comprehension of system stability issues. One method that has come to prominence in recent years for the stability analysis of power systems is bifurcation theory [10–16,37].

Broad studies have been conducted on bifurcation theory as it is known to be a powerful tool for analysis of ac transmission systems [17–23]. All the conducted researches have led to the conclusion that voltage instabilities can be prevented by controlling power system bifurcation. Although much effort has been put forth in analyzing ac transmission systems, little work has been published regarding the analysis of HVDC systems using bifurcation theory [17,24]. Also, great researches have been carried out on control and stabilization of power electronic devices for renewable energy applications [38,39]. Among the mentioned literatures, stability assessment of the AC system in a typical more electric aircraft using small signal analysis is addressed in [36]. Based on our knowledge so far, no research has been reported on the stability analysis of the aircraft electric system using bifurcation theorem. It has been emphasized that increasing in power demands, environmental concerns and economic factors are causing power systems to operate very near their stability limits [19,25] Increasing demand on generation systems is due to rapid growth of dynamic loading. System instability commonly occurs when a load increase causes the generation system to exceed its capacity limits. Advanced aircraft electric systems contain of many switching power converters and dynamic loads. The authors of [26–31]

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demonstrate the relevance of bifurcation theory to the application of switching power converters. The linear nature of the circuit topology employed for power converters is complicated by the dynamic behavior of the circuit switching. Each of the preceding factors gives merit to the necessity of system stability analysis for the advanced aircraft electric power systems (AAEPS).

In a mathematical point of view, complex conjugate pairs of eigenvalues moving from the LHP to the RHP or vice versa across the imaginary axis characterize Hopf bifurcations are indicative of chaotic motions and oscillatory behavior in power systems [19,22,23]. The presence of Hopf bifurcations in the MEAPS is determined herein, and their effect on the stability of the system is scrutinized. Ascertainment of the existence of this type of bifurcation is achieved via multi-parameter variations correlated with control parameter changes, alterations in loading conditions and fluctuations in the operating frequency of the SG, which results from vacillations in the generator's engine speed.

In this article, we have analyzed the dynamic consequences of Hopf Bifurcations leading to oscillatory instabilities. Also, the sustainability and robustness of the system and subsystem under various conditions of operation has been investigated. The effects of parameter variations associated with changes in load configuration (e.g., step change and continual change in load power), variation in control parameters (e.g., PI control parameters) and variations in operational frequency due to SG engine speed transition are addressed via several case studies. The forecasting of stability margins for bifurcation parameters is obtained from real-time simulations in PSIM9 environment and further supported by analytical discussion.

This paper is organized as follows: In the second section the AAEPS model is briefly described. The third section presents the mathematical model of the aircraft electric power system. The fourth section presents the bifurcation analysis and dynamic behavior of the AAEPS. The main conclusions of the study are presented in the last section.

Advanced aircraft electric power system model

The analysis reported in this paper is based on the single-channel model of the Variable Speed Constant Frequency (VSCF) AAEPS, shown schematically in Fig. 1. The depicted model is equivalent to the Boeing 767 aircraft electric power system as proposed by [6,7,9].

The complex system shown in Fig. 1 is composed of several components as follow

Generating system

The generating system is comprised of starter/generators, a voltage control unit and a feedback control system from the dc-link. In the VSCF Synchronous Generator (SG), the rated operating frequency is 400 Hz, though the frequency may vary in the range of 400–800 Hz to compensate for engine speed changes. A feedback proportional–integral (PI) control strategy regulates the voltage of the 270 V-DC bus by properly regulating the field excitation current of the SG using PWM switching technique.

Rectifier unit

Connected to the synchronous generator is a transformer rectifier unit (TRU) with a passive 12-pulse rectifier unit. This configuration ensures the cancellation of low-order harmonics. Moreover, to implement the 30° phase shift required to obtain 12-pulse operation, a Y/Y/D transformer is employed.

DC/AC loads

Various types of controlled DC and AC dynamic loads are distributed throughout the aircraft electric network. Depending on the operation conditions (e.g., normal operation or emergency situations), the loading configurations may change on different time scale, hence providing a time-varying pattern of power demand. The load modeling is a critical issue in aircraft electric power system analysis, since the stability properties of the network is strongly dependent on power demands set by loading configuration. A major portion of the loads (AC/DC) in the aircraft system under study has dynamic profile. The DC non-linear loads are classified as constant power (CP), constant current (CC), and constant voltage (CV) loads. Also, passive loads exist in an AAEPS at different power ratings widely distributed throughout AC main bus. In this paper, lumped circuit elements of series RL, as a representation of AC passive loads are modeled with a minimum load power factor of 0.85 lagging [6,7,9] connected to the ac network. Also, a three-phase induction machine (IM) as a representation of AC dynamic load is connected to the constant frequency (CF) main AC bus for a separate case study.

Power inverter

A voltage source inverter (VSI) is also connected to the 270 V-DC bus, consisting of two 6-pulse switching bridge inverters. In order to maintain a constant 115 V/200 V, 400 Hz at the main ac bus, a feedback PI controller is utilized to regulate the modulation index of the SPWM inverter. Also, a Y/Y/D transformer applies the necessary 30° phase shift to combine the signals from each output phase of the 6-pulse inverters. The combination of the signals produces the required 115 V/200 V RMS, 400 Hz line voltage at the main AC bus.

Mathematical model of the aircraft electric power system

This section exemplifies the dynamics of the physical system with parameter dependent differential–algebraic equations describing the reduced-order aircraft electric system performance at the major node of integrated power electronic system using Generalized State-Space Averaging (GSSA) approach. In our previous effort [32] it was demonstrated that by applying averaging technique to modeling and simulation of the aircraft system under investigation, the key dynamic features of the system can be obtained. Although, the simplified differential equations are utilized to compute the stability region of the system dynamics via eigenvalues extracted from corresponding state matrices, the stability analysis is also supported with bifurcation diagrams captured from real-time simulations in PSIM9 environment in next sections. The movement of complex conjugate pairs of eigenvalues from the LHP to the RHP or vice versa across the imaginary axis characterizes Hopf bifurcations as an indicative of chaotic motions and oscillatory behavior in the aircraft electric power systems [22,23]. Since, the stability and bifurcation behaviors through numerical calculations are not sufficient to prove existence for stability or bifurcation in the system, the real-time system analysis was also carried out in the PSIM9 software environment. The consistency between mathematical calculations and the real-time simulations was examined by giving a model example in this section.

Synchronous generator system

Fig. 2 shows a circuit representation of electric system network corresponding to SG with excitation current control method. As