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A novel Generalized State-Space Averaging (GSSA) model for advanced aircraft electric power systems

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ABSTRACT

The growing complexity of Advanced Aircraft Electric Power Systems (AAEPS) has made conventional state-space averaging models inadequate for systems analysis and characterization. This paper presents a novel Generalized State-Space Averaging (GSSA) model for the system analysis, control and characterization of AAEPS. The primary objective of this paper is to introduce a mathematically elegant and computationally simple model to copy the AAEPS behavior at the critical nodes of the electric grid. Also, to reduce some or all of the drawbacks (complexity, cost, simulation time..., etc) associated with sensor-based monitoring and computer aided design software simulations popularly used for AAEPS characterization. It is shown in this paper that the GSSA approach overcomes the limitations of the conventional state-space averaging method, which fails to predict the behavior of AC signals in a circuit analysis. Unlike conventional averaging method, the GSSA model presented in this paper includes both DC and AC components. This would capture the key dynamic and steady-state characteristics of the aircraft electric systems. The developed model is then examined for the aircraft system's visualization and accuracy of computation under different loading scenarios. Through several case studies, the applicability and effectiveness of the GSSA method is verified by comparing to the actual real-time simulation model obtained from Powersim 9 (PSIM9) software environment. The simulations results represent voltage, current and load power at the major nodes of the AAEPS. It has been demonstrated that the obtained results from GSSA model in Matlab® closely agree with those of obtained in an actual AAEPS implemented in PSIM9 software.

1. Introduction

MORE Electric Aircraft (MEA) has been proposed by many authors during the past decades and is becoming a viable alternative to the commercial aircraft with mechanical power systems. It has been found that aircraft with more electric systems reduce fuel consumption and improve reliability as a result of fault-tolerant electric power distribution and elimination/reduction of the hydraulic systems [1,12]. Also, reduced design complexity, lower flight test hours, less tooling, shorter checkout time and elimination/reduction of the hydraulic system (which has a deleterious impact on the environment) are considered to be other benefits of the AAEPS [12,16]. In an advanced aircraft electric system comprised of multi-converters, several types of loads, harmonics filters and other kinds of switching components, the continuity of performance and security of operation is of prime concern [39]. The system is in the normal condition if there are no overloads, no overvoltages, no undervoltages, and the specific standards are met by system's profiles. The control center should maintain the AAEPS normal operation by continuously monitoring the electric network at critical nodes [12,13,39]. This data should be updated automatically in time domain in order to catch any chaos or rapid change caused by loads demand. There is, consequently, a need to monitor system activity. However, measuring all the necessary signals may be impossible or may not be economically feasible. To address these issues, the proposed GSSA technique can be recognized as a powerful tool for advanced aircraft systems analysis [2,38,39]. Time domain analysis of an advanced aircraft with complex electric components demands substantial number of facilities and test hours. Hence, using GSSA method would facilitate the data acquisition of the entire aircraft electric system components under investigation, leading to a considerable reduction in computer processing requirements and hours. Use of GSSA method was originally introduced by the author of [3] and has subsequently been applied

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Nomenclature

r_g	synchronous generator's leakage resistance
l_g	synchronous generator's leakage inductance
V_g	synchronous generator's phase voltage
r_{ac}	AC side's line resistance
r_f	AC side's filter resistance
L_f	AC side's filter inductance
C_f	AC side's filter capacitance
V_m	peak value of the AC voltage
L_{ac}	AC side's line inductance
r_{dc}	DC side's line resistance
L_{dc}	main DC link's inductance
C_{dc}	main DC link's filter capacitance
V_{dc}	voltage at the main DC bus
I_{dc}	current at the main DC bus
V_{cv}	DC/DC buck converter's constant voltage
I_{cv}	DC/DC buck converter's inductor current
I_g	synchronous generator's phase current
k	order of Fourier coefficient

Greek symbols

ω	angular frequency
δ	phase angle
Δ	difference
π	Pi ($\pi \approx 3.14$)
μ	commutation angle
α	commutation angle start point

Acronyms

GSSA	Generalized State-Space Averaging
AAEPS	Advanced Aircraft Electric Power Systems
MEA	More Electric Aircraft
SSA	State-Space Averaging
TRU	Transformer Rectifier Unit
VSCF	Variable Speed Constant Frequency
IDT	Identification and Diagnostic Toolbox
SG	Synchronous Generator
TVL	Time Varying Load
VSI	Voltage Source Inverter
BPF	Band Pass Filter
LPF	Low Pass Filter
APU	Auxiliary Power Unit
DQ0	Direct–Quadrature–Zero
PI	Proportional Integral

Subscripts

f	filter
g	Generator
BC	Buck converter
CV	Constant voltage
CC	Constant current
CP	Constant power
avg	Average
act	Actual

to describe the dynamic behaviors of multi-level DC/DC converters in [4,5]. The main restrictions of using State-Space Averaging (SSA) with small variations condition for state variables have been compensated using the large-signal model, proposed by this approach [10,11]. The advantages of GSSA method over state-space averaging estimation used for switching-based circuits with small ripples have been discussed in [3,6]. The authors of [6,7] have utilized GSSA method to develop models of quasi-resonant converter systems. In [8,9] the applicability of this method has been demonstrated to describe the discontinuous conducting mode in various types of Switching Power Converters (SPC) and the dynamic behaviors of Neutral Point Diode Clamped (NPDC) converters, respectively. The authors of [24] developed a fast dynamic phasor model for analysis of the rectifier unit in an AAEPS. Also, in literature [25] the applicability of averaging technique in modeling and simulation of switch mode shunt converters coupled with power systems (e.g., STATCOM, AF,. . ., etc) have been investigated.

This paper will report a new approach for modeling, control and system analysis of advanced aircraft electric network. Unlike real-time system monitoring which is complex, time-consuming and higher cost, the proposed GSSA model is simple, time effective and highly accurate. The main contributions of this paper are: (i) a generalized averaging model to represent the starting-up, normal steady-state operation, and aircraft electric power systems dynamics due to rapid changes in the power demand. The simulation results show that the averaged model can copy the aircraft real-time behavior well, (ii) despite conventional averaging models, the GSSA model in this paper is implemented based on DC and AC components using an accurate mathematical operation. This will provide a reliable scheme for voltage ripple monitoring at the major nodes for a safe operation (iii) the GSSA model has been developed for each power electronics block as a stand-alone system, giving enough flexibility to that particular block to be integrated into any other similar network (with slight modifications).

As mentioned above, the proposed method aims to provide a reliable technique for advanced aircraft system analysis while reducing complexity, costs and test hours. Although, the proposed model offers a reliable technique for aircraft systems analysis, a bench model hardware characterization is missing from this report and may be targeted for the future research.

2. VSCF AAEPS structure and electric components

The schematic model depicted in Fig. 1 is equivalent to a Boeing 767 electric power system, as proposed by the author of [12]. The single channel model (as shown below) is comprised of several components, including:

2.1. 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, although the frequency varies in the range of 400 Hz to 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 appropriately modifying the field excitation current of the SG.

2.2. Rectifier unit

Connected to the 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.