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An auxiliary power unit for advanced aircraft electric power systems

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ABSTRACT

This article presents a comprehensive model and characterization of the Advanced Aircraft Electric Power Systems (AAEPS) with a hybrid Fuel Cell (FC)/battery Auxiliary Power Unit (APU). A model of fully controlled AAEPS for Boeing 767 is implemented in PSIM9 software environment. Also, a circuit model representation of the hybrid Proton Exchange Membrane (PEM) FC/battery APU is developed and integrated into the main power channel of a Variable Speed Constant Frequency (VSCF) aircraft electric power system at the main DC bus. The transient performance of the interconnected electric power system is studied under a large share of nonlinear loads. Moreover, the fuel cell based APU integrated model is extended to investigate the dynamic behavior of the AAEPS under various loading configurations. The entire system's stability is analyzed while different loading scenarios are taken into account. Several case studies are performed in order to measure the effectiveness and applicability of the proposed hybrid APU in an advanced aircraft operation. The time-domain analysis corresponding to each study is performed. Also, the obtained voltage and current data are validated using applicable aircraft electric power system's standards [20]. Finally, a bench model is developed for the hybrid APU to verify the simulation results from PSIM9 model.

1. Introduction

Much attention has been paid to modeling, control and characterization of More Electric Aircraft (MEA) power systems in recent years as it is becoming a viable alternative to the conventional aircrafts with mechanical energy systems. 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 some advantages of MEA over conventional aircrafts with more mechanical components [1–4]. In an advanced aircraft electric system comprised of integrated power electronics, different types of static/dynamic loads, harmonics filters and various kinds of switching components, the continuity of performance and security of operation is of major concern. Currently, electric energy provided to the aircraft system is mostly supplied by generators that are driven by the core of main propulsion engines. Electric generators, either driven by an aircraft's main propulsion engines or by a gas turbine auxiliary power unit supply the electric power needs of commercial aircrafts. Also, the maximum efficiency of delivered electric power by the main engines and their generators is 40% in flight, whereas on the ground with the engines off, and using the turbine-power APU, the efficiency barely approaches to 20%, of course with noise pollution and gaseous emissions (drawbacks) [5,6].

Moreover, due to growing demands in electric power capacity on the advanced aircraft, these generators would have to increase in size, which exceeds the limit of the core and available space in the aircraft system. Therefore, the current design would no longer meet the requirements of emerging MEA with large number of electric power facilities. One of the best alternative energy resources that could be considered as a reliable and more efficient replacement of the conventional heavy structures would be a hybrid battery/fuel cell APU system. As an energy resource, the low temperature (about 85 °C) proton exchange membrane fuel cells (PEMFC) provide a promising alternate solution to convert chemical energy into electricity [12–14]. Many resources have been recently invested around the world to push this technology forward, aiming to capitalize the high efficiency and low emission benefits [15] of hybridized PEMFC for applications ranging from stationary power plant to mobile auxiliary power units. In recent years, there have been extensive research studies reported on the applicability of fuel cell equipped APU for different applications, including: transportation systems, aerospace, vehicles, ships, etc. [6–11].

However, to the author's knowledge so far, no research has been reported on stability analysis and characterization of the hybrid battery/PEM-fuel cell APU system installed to the main DC

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channel of an AAEPS. The proposed hybrid energy system provides a great power density and high efficiency that are among the most attractive factors in aerospace applications. Furthermore, being environmentally friendly and providing a fast dynamic response as a backup unit for AAEPS are two other noteworthy characteristics of the developed battery/PEM-FC APU in any case of failure in the main generating system.

Recently many researches are done on the feasibility of using fuel cells in commercial aircrafts to generate energy, produce water, and inert gasses [30]. Fuel cell is a promising option for aircraft auxiliary power units because of increasing safety, reducing maintenance costs, and reducing noises [31]. Also, the use of lead-acid batteries is widespread due to their mature technology, high availability, and low cost [16]. These types of batteries are well recognized for having a relatively large specific power/weight ratio, so they have the ability of supplying high surge currents (due to sudden change in load power). This is mandatory for the purpose of having an uninterruptable backup system in the advanced aircraft with large initial power demand [17,18]. Furthermore, sealed lead-acid batteries are widely used in advanced aircraft systems because of their low maintenance, life cycle costs, and charging techniques [29]. In this study, we propose a hybrid PEM-FC and lead-acid battery system to achieve a clean and reliable source of energy for the aircraft continuous operation. The duty of the developed auxiliary unit is to provide electric power for the emergency loads distributed throughout the aircraft electric network, in case of failure in the main power system. This paper will focus primarily on the operation of a hybrid APU system that uses a battery in conjunction with a fuel cell, while different loading scenarios are considered as case studies. Moreover, the voltage and current signals measured across the battery, fuel cell, and other major nodes, as well as the loading profiles are used to analyze the system performance under various conditions.

This paper is organized as follows: Section 2 describes the Boeing 767 aircraft electric structure and system components. In Section 3, the circuit model representation of the developed hybrid APU system is presented and discussed. Section 4 describes the performance characteristics of the hybrid system interconnected to the main DC channel of the advanced aircraft electric network under study. Section 5 presents hardware implementation of the proposed APU system to address the dynamic behavior of the network when interacting with dynamic loads. Finally, conclusions are drawn in Section 6.

2. AAEPS model description

The schematic model illustrated in Fig. 1 is equivalent to a Boeing 767 aircraft electric network integrated with APU, as proposed by the author of [2,28]. The single channel model is comprised of several major components described with details in [27].

3. Hybrid battery/PEM-FC model development

The hybrid battery/fuel cell-based APU proposed for the advanced aircraft is known as a reliable source of energy for variety of advanced technology applications. Being environmentally friendly, and providing fast dynamical response are two noteworthy characteristics for the AEPS continuous operation. The APU system modeled in this chapter consists of several major components, including: (1) the Proton Exchange Membrane (PEM) fuel cells, (2) the lead-acid battery, (3) DC–DC boost converter connected to the PEMFC output terminals, (4) DC–DC buck-boost converter connected to the lead-acid battery package (5) bidirectional switch component used for providing the charging/discharging path between the PEMFC and battery, as well as between the APU unit and loads, (6) control units used for auto-regulation of both battery and fuel cell output profile, also controlling the bidirectional switch under different conditions of the system's operation. Fig. 2 represents a schematic view of the hybrid battery/PEMFC-equipped APU proposed for Boeing 767 aircraft system.

In the literature [4] the similar model is employed, and the performance of the APU system is characterized where the hybrid system is paralleled to the main AC bus via a 12-pulse voltage source inverter (VSI) at the voltage and frequency of 200 V-AC and 400 Hz, respectively. The proposed model demands for an extra 12-pulse inverter which raises the cost and weight of the design. Also, the voltage and frequency synchronization will be another technical challenge that the proposed method will encounter. In order to avoid the difficulties of implementation exist in the mentioned model, we propose an improved method in which the output of the APU system will be directly connected to the main DC channel of the aircraft electric network, using a power bidirectional switch along with an intelligent control system. Therefore, the proposed method will circumvent the necessity of applying extra switching 12-pulse inverter, as well as other hardware components for the AC voltage/frequency synchronization purpose. This approach turns out to be more effective and economically reasonable.

3.1. PEM-fuel cell equivalent circuit modeling

The PEM-FC is one of the most promising sources of energy, also considered as a "green" source of power, because they are environmentally friendly and have low emission of polluting gas, such as oxides of nitrogen and sulfur. In addition, they can provide energy with higher efficiency than conventional power plants, and are capable of operating with a very low level of industrial noises. A PEM fuel cell normally operates at air temperature for a quick start up performance, and its efficiency may reach up to 60% [6]. The output voltage and power rating of the PEM fuel cell can be designed to meet specific demands for different applications such as distributed generation power systems, electrical vehicles, as well as aerospace including AAEPS. For a low power fuel cell ($w \leq 1$-kW), the output voltage is in the range of 25–50 V, and the output voltage for above 30-kW power dissipation is estimated in the range of 200–400 V [6,8]. In order to characterize the dynamic performance of the aircraft electric system with a hybrid APU, a representative circuit model of the PEM-FC stack is required. Because of electro-chemical nature of the fuel cell stack along with the inherent complexity in the actual system, the representative circuit model would substantially facilitate the analysis of the fuel cell dynamics under various operating conditions.

This section presents the equivalent circuit model of the PEM-FC [19], which is used to predict the key dynamic behavior of the PEMFC stack integrated into the APU system under investigation. As illustrated in Fig. 2, the dynamic circuit model of the fuel cell includes the equivalent capacitances due to "double-layer charging effect", as well as the equivalent resistances of activation, concentration and ohmic voltage drop across the electrodes of FC stacks. Therefore, the second-order circuit model has been employed to derive the dynamic and steady-state behavior of the PEM fuel cell stack. The following expressions can be used to describe the dynamics of the PEMFC stack (Fig. 2) under different operating conditions for n cell with no load voltage $E_{\text{cell, nl}}$ connected in series, forming a stack, the FC's open circuit voltage $E_{\text{FC, nl}}$ can be calculated as

$$E_{\text{FC,nl}} = nE_{\text{cell,nl}} \tag{1}$$