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Electrical Analysis of Proton Exchange Membrane Fuel Cells for Electrical Power Generation On-Board Commercial Airplanes

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Abstract- **Fuel cells have been considered for all types of trasnport including automobiles, buses, submarines, motorcycles and airplanes due to their high efficiency and their environmentally friendly nature. In most transportation applications, fuel cells are used to augment the existing electrical system and not as a stand-alone power source. The addition of a fuel cell to any type of transport, however, will have an influence on the dynamic behavior of the electrical system within the transport and may even cause instability in a previously stable system. This paper analyzes the consequences of integrating a Proton Exchange Membrane fuel cell to the existing electrical generation and distribution system of a Boeing 787-8 aircraft through modeling and simulation tools. Physical testing, although beneficial and critical, is expensive and time consuming. The modeling approach in the initial scoping stage provides an early indicator of the feasibility of fuel cell use on an airplane in addition to possible challenges that should be addressed with hardware testing. Simulation results are presented using MATLAB, Simulink, and SimPowerSystems environments.**

I. INTRODUCTION

Aviation is responsible for close to 13% of fossil fuels consumed by the transportation sector and for 2% of total global carbon dioxide (CO_2) emissions [1]. According to the International Civil Aviation Authority (ICAA), these numbers are expected to double by 2030 [1]. Because of this, the Committee on Aviation Environmental Protection (CAEP) has asked for more stringent emission standards on aircraft engines of all sizes.

Using fuel cells to replace or augment the electrical system of an aircraft may offer a solution to the issues described above. Fuel cells offer the potential for drastic reduction in CO_2 emissions. In addition, they offer exceptionally quiet operation, highly efficient use of the fuel energy (up to 90% when recovering waste heat), multi-fuel input options and for the larger values of stored energy, a higher energy storage density than batteries.

For a number of years, the manufacturers of commercial aircraft, most notably Boeing and Airbus, have realized that fuel cells may offer advantages for commercial aircraft operation. Apart from emissions reductions and thermal efficiency referenced above, they can constitute distributed power systems, enabling locating the power near the point of use (reducing wiring and increasing reliability) and also reducing the power draw from the engines, making it possible to decrease the aircraft engine size. A reduction in wiring and engine size may reduce the aircraft weight, an important benefit when it comes to aircraft design.

Recently the German Aerospace Center (DLR) has conducted successful flight tests of a fuel cell power system for hydraulic backup power [2], and a fuel cell-powered nose wheel drive motor [3]. In addition, Boeing has been examining the use of fuel cells for on-board electrical power generation for at least the past 10 years, including for distributed power systems [4-7]. A few years ago, Boeing sponsored a study which examined the use of a PEM fuel cell for a ram air turbine (RAT) emergency power backup system [8]. The results of that study indicated that the fuel cell could successfully replace a conventional RAT, but offered little performance advantages. Fuel cells have also been explored for auxiliary power units (APU) [9-12].

This paper analyzes the consequences (through modeling and simulation) of using a Proton Exchange Membrane (PEM) fuel cell as a stand-alone power system within the aircraft and to augment the existing electrical generation and distribution of an aircraft with the intent of increasing both stall margin and efficiency.

During descent and landing, the engines of an airplane are often throttled back to idle and are spinning slowly enough that if the power demand (either thrust or electrical generation) was to suddenly increase, the engine's compressor may cease to function properly, or stall, and the engine would shut down. The difference between the stall condition and the operating condition is referred to as the stall margin. It would be advantageous to remove some of the electrical burden on the engines during times of low engine power output. This would allow either a larger stall margin or a reduced engine size for the same stall margin.

In addition, in an airplane, the engine efficiency decreases with decreasing power. As the engine slows its thermal efficiency decreases, making the overall electrical energy generation less efficient.

An alternative source of power that is only used for peak electrical loads (a "Peaker") during descent and landing would provide dual benefit, increasing both stall margin and efficiency. Having a stand-alone system that meets the power demands of part of the aircraft (e.g. galley or In-Flight Entertainment) throughout the entire flight enevelope, would also increase stall margin and efficiency.

A MATLAB SimPowerSystems model consisting of a PEM fuel cell, DC-DC converter and the electrical generation and distribution system of an aircraft was developed and analyzed. A different MATLAB SimPowerSystems model was built to investigate the dynamic response of a stand-alone galley powered exclusively by a PEM fuel cell. The modeling approach in the initial scoping stage provides an early indicator of the feasibility of fuel cell use on an airplane in addition to possible challenges that should be addressed with hardware testing.

Additional impacts of incorporating a PEM fuel cell into an aircraft (e.g. weight, performance, fuel consumption, etc.) have been analyzed in [13] and are not discussed in this report.

II. BOEING 787-8 DISTRIBUTION SYSTEM

The Boeing 787 aircraft has two 250 kVA generators mounted on each propulsion engine, for a total of 1 MW of electrical generation capacity during normal flight. The auxiliary power unit (APU), used for ground power and in-flight emergency power, consists of two 225 kVA generators for an additional 550 kW of capacity [14].

The two engine generators produce power at 230 VAC, and because they are variable speed the frequency depends on engine operation and can vary from 380-800 Hz.

A schematic of the 787's electrical distribution system is shown in Fig. 1. The airplane employs four distinct distribution voltages and types used to serve different loads within the aircraft:

1. The 230 VAC system is used as the main bus and is fed by all generators, including the APU generators. The main bus feeds some of the larger loads within the aircraft (e.g. Wing Ice Protection, Cargo Heaters, etc.) as well as the three other buses.
2. The ±270 VDC is fed from the 230 VAC bus through an auto transformer rectifier unit (ATRU) and feeds large motors on the airplane such as the Environmental Control System (ECS) fans and compressors.
3. The 115 VAC system is fed from the 230 VAC system through an auto transformer unit (ATU) and is used for many of the airplane's large and small loads.
4. The 28 VDC system is fed from the 230 VAC bus through a transformer rectifier unit (TRU) and is also used for many of the airplane's large and small loads.

The complexity of the electrical system provides several options for fuel cell integration. Inverting the fuel cell's output would allow it to tie-into the existing 230 VAC bus and serve any of the airplane's electrical loads. Simple DC-DC conversion would allow the fuel cell to tie into either of the DC buses. In addition, several fuel cells could be distributed at the point of use, eliminating long wire lengths (and/or possibly eliminating the need for redundant buses), as described in a Boeing patent [5].

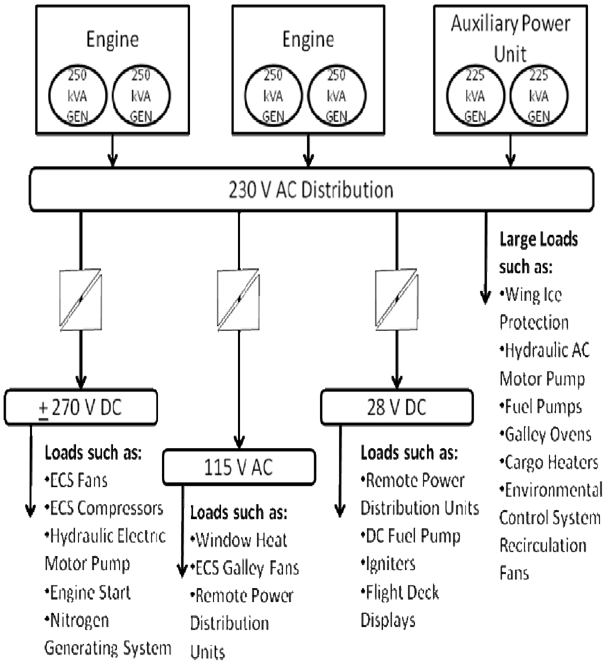

Fig. 1: Schematic of the Boeing 787 electrical system. The system is complex yet offers many options for a fuel cell to tie-in. Fig. modified from Nelson [14].

III. MODEL DESCRIPTION

An on-board Proton Exchange Membrane (PEM) fuel cell system was considered for the galley and In-Flight Entertainment (IFE) loads. An additional case where the fuel cell augments the power from the main engine and APU generators during times when the load demand is high was also analyzed as a Peaker concept. Initial analysis of the galley and IFE loads indicated that there may be advantages in designing the distribution system for 28 VDC, and therefore this is the voltage used in the simulation. However, the electrical transient and stability results would be nearly the same for other DC distribution voltages including +/- 270 VDC. The higher power requirements of the Peaker concept required higher voltages of either 230 VAC or ±270 VDC. Converting the native DC voltage of the fuel cell to AC imposes further weight/space penalties to accommodate the DC/AC inverter. Consequently, the Peaker concept was analyzed based on a ±270 VDC network which eliminated the need for a DC/AC inverter.

A. Proton Exchange Membrane Fuel Cell

A Proton Exchange Membrane (PEM) fuel cell stack model from the MATLAB/SimPowerSystems Toolbox library was used for the simulation. The MATLAB model implements a generic hydrogen fuel cell stack. Within the model there is the option of using the simplified or the detailed model. The detailed model allows parameters such as temperature, pressures, flow rates, fuel rates, etc. to vary. The simplified model was used for this project and represents the fuel cell stack during nominal conditions. Fig. 2 shows the equivalent circuit of a fuel cell stack that is the basis for the simplified PEM fuel cell stack model within MATLAB/ SimPowerSystems.

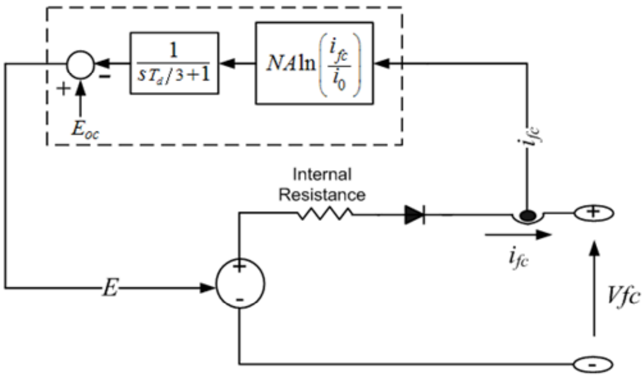

Fig. 2: Equivalent circuit of a fuel cell (from SimPowerSystems online product documentation).

In Fig. 2, T_d is the fuel cell response time (seconds), N is the number of cells, A is the Tafel curve slope, i_{fc} is the fuel cell current, E_{OC} is the open circuit voltage and i_0 is the exchange current. More information on the fuel cell stack model can be found in the SimPowerSystems documentation on the MathWorks website.

Examination of the two models' code and sample results revealed little difference when used for the purposes of the electrical simulation study. Therefore, the simplified model was chosen.

B. DC-DC Converter

The DC-DC converter is used to convert and stabilize the variable DC fuel cell output voltage to either 28 V DC for the Stand-Alone Galley Model or 270 V DC for the Peaker Model. The DC-DC buck-converter model used was replicated from one of the MATLAB/SimPowerSystems demos and is shown in Fig. 3. Slight modifications to the model were made to convert it from a current-regulated to a voltage-regulated converter. The duty cycle is controlled with a simple PI (Proportional-Integral) type controller. The schematic for the controller is shown in Fig. 4.

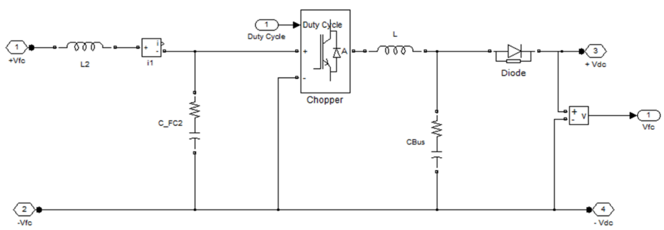

Fig. 3: DC-DC Converter Schematic

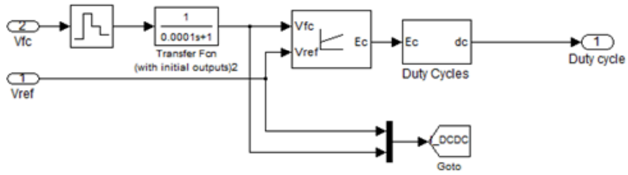

Figure 4: DC-DC Converter Controller

C. Stand-alone Galley

Due to the similarities between a stand-alone galley and a stand-alone IFE system, only the stand-alone galley was modeled and simulated. Results obtained for the stand-alone galley model are applicable to the stand-alone IFE system.

The stand-alone galley model consists of a 60 kW PEM fuel cell, a DC-DC buck converter and several galley loads. The DC-DC buck converter is used to step down the fuel cell voltage from about 625 V DC to 28 V DC.

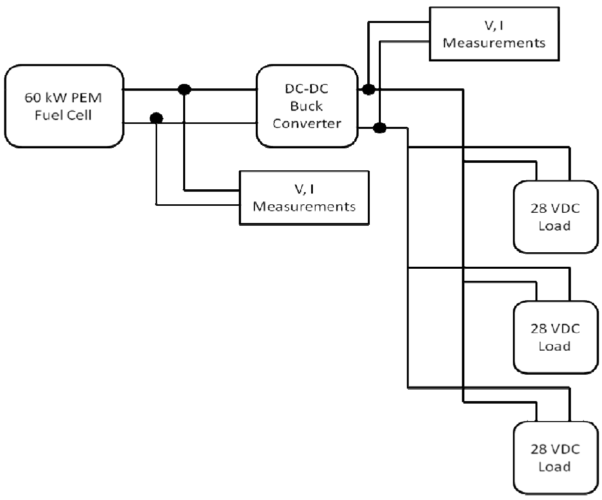

Fig. 5: Graphical representation of the stand-alone galley model

Table I lists the power consumption for each galley load modeled in the simulation. The loads were modeled as simple resistive loads and range between 1,600 and 4,240 Watts. Galley loads turn on throughout the simulation. The number of galley loads turning on at any one time was limited to two. Supervisory controls to enforce this rule can easily be implemented in the actual system and would ensure that the inrush currents resulting from turning additional loads simultaneously would be minimized. This kind of sequencing would also be transparent to the flight attendant. A graphical representation of the stand-alone galley model is shown in Fig. 5.

TABLE I:
Rated Power of Galley Loads

Load	Rated Power
Endura Water Boiler	4,240 Watts
Thermoelectric Refrigerator	1,620 Watts
DS3000 Steam Oven	3,800 Watts
Espresso/Cappuccino Maker	1,600 Watts
Endura Beverage Maker	2,760 Watts
DF3000 Convection Oven	3,800 Watts

D. Peaker Model Description

For the Peaker system a 75 kW fuel cell was. A DC-DC buck converter steps down the fuel cell voltage from 625 VDC to 270 VDC. The fuel cell is connected to the existing ±270 VDC electrical bus of the aircraft through the DC-DC buck converter. A generic aircraft electrical generation and distribution model from MATLAB SimPowerSystems was modified and used to model the generation and distribution system of the aircraft. The generation and distribution system of the aircraft includes a signal representing the mechanical input (engine speed) going into the generator, a Generator Control Unit (GCU) responsible for regulating voltage to 230 VAC (the main distribution voltage) and several other components (transformer, rectifier, etc.) representing the Auto Transformer Rectifier Unit (ATRU) that is responsible for rectifying the 230 VAC to ±270 VDC. It is important to note that the ATRU was modeled as a simple transformer-rectifier and it was not based on the specification of a real system. Therefore, the voltage sags may not be an accurate representation of a real system. Since the 75 kW fuel cell augments the aircraft generation, the engine generator size was reduced from a 250 kVA generator to a 200 kVA generator for the simulation. It is important to note however, that the fuel cell will meet the power demand only when the engine generator limits have been met

A graphical representation of the Peaker Model and how it is tied into the 270 VDC bus is shown in Fig. 6. Fuel cell parameters for the Peaker model are given in Table III.

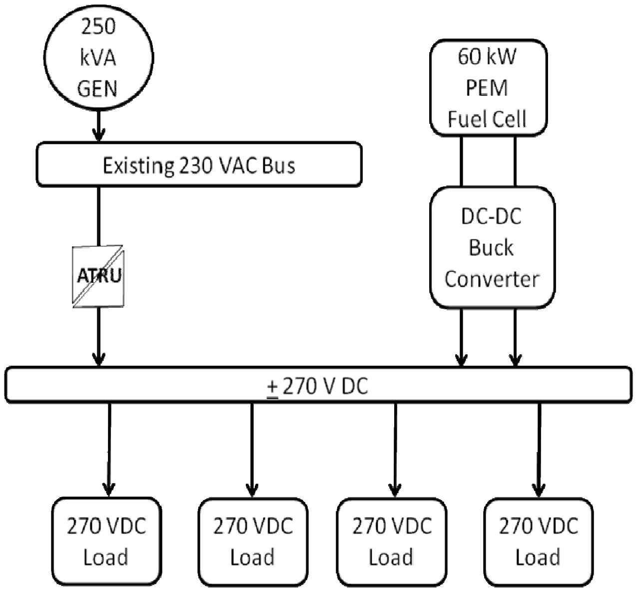

Fig. 6: Graphical representation of Peaker Model

IV. SIMULATION RESULTS

The electrical stability and transient characteristics of the on-board fuel cell system were analyzed using the models described above. MIL-STD-704F standards, often used by commercial airplane equipment suppliers and integrators (such as Boeing) in the design of their electrical system and components, were used to determine power quality (Refer to Fig. 7 and Fig. 10).

Table II:
Fuel Cell Parameters Used In Stand-Alone Galley Simulation

Parameter	Value
Voltage at 0 A	900 V
Voltage at 1 A	895 V
I_{nom} (A)	160
V_{nom} (V)	625
I_{end} (A)	230
V_{end} (V)	430
Fuel Cell Response Time	5 sec

A. Stand-Alone Galley Simulation Results

Fuel Cell parameters used for the stand-alone Galley simulation are given in Table II.

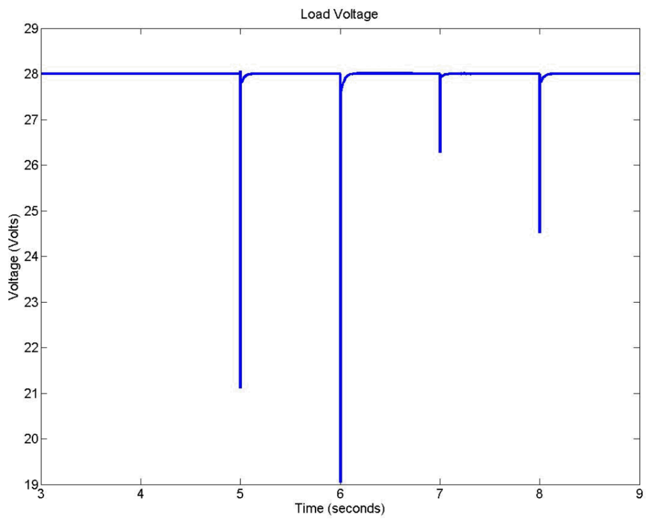

Fig. 8: Stand-alone galley system simulation: voltage as measured at the load.

Fig. 8 shows the load voltage during the simulation. The voltage transients at can be attributed to the increase in load power demand. MIL-STD-704F standards require that the load voltage be normally between 22 VDC and 29 VDC at all times. The load voltage is allowed to drop down to 18 VDC for a short period of time (< 0.1 seconds) and is allowed to go up to 50 VDC, also for a short period of time (< 0.0825 seconds). The voltage sags seen in Fig. 8 increase as the power demand increases. The lowest voltage sage seen (at t= 6 sec), corresponds to an increase in load of 8.48 kW. MIL-STD-704F standards are met throughout the simulation.

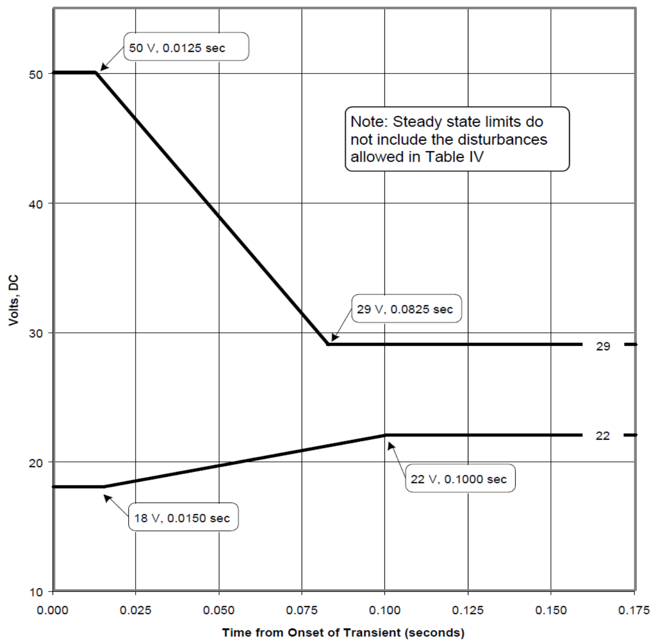

Fig. 7: Allowed voltage transient for 28 VDC systems. During transients, the system voltage must not go higher than the top solid line or lower than the bottom solid line. (Fig. 13 in MIL-STD-704F [15].)

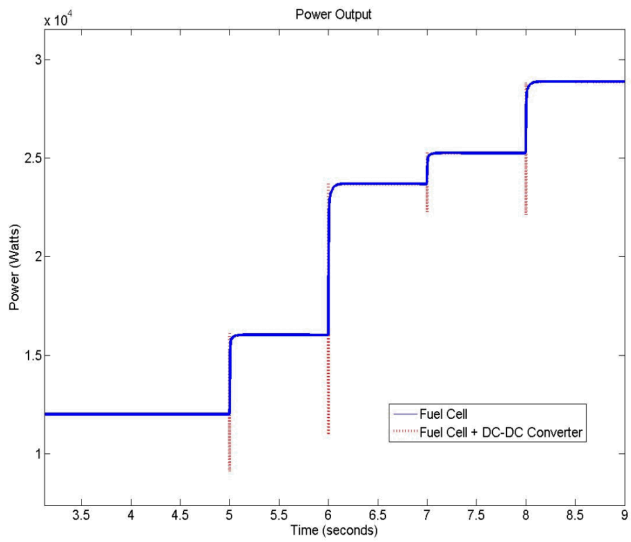

Fig. 9: Stand-alone galley system simulation: Power response from the fuel cell and the fuel cell + DC-DC converter

Fig. 9 shows the power response from the fuel cell as well as the power response seen at the output of the DC-DC converter.

B. *Peaker System Model Simulation Results*

The fuel cell parameters used for the Peaker simulation are given in Table III.

Fig. 11 shows the load voltage throughout the simulation. MIL-STD-704f standards for 270 VDC are shown in Fig. 10 and require that the load voltage be normally between 250 VDC and 280 VDC. The load voltage is allowed to drop down to 200 VDC for a short period of time (< 0.04 seconds) and is allowed to go up to 330 VDC, also for a short period of time (< 0.04 seconds). The voltage sags seen in Fig. 11 are attributed to the increase in load power demand. The voltage remains within the limits specified by MIL-STD-704F standards throughout the simulation. The voltage sags during the first part of the simulation are attributed to the generator response, while the voltage sags during the latter part of the simulation are attributed to the fuel cell response. The voltage sags seen when the fuel cell is responding to the increase in load power demand are far less significant than those seen when the generator responds to increase in load power demand. This is due largely due to the capacitors inherent in the DC-DC converters.

Table III:
Fuel Cell Parameters Used In Peaker Simulation

Parameter	Value
Voltage at 0 A	900 V
Voltage at 1 A	895 V
I_{nom} (A)	120
V_{nom} (V)	625
I_{end} (A)	326
V_{end} (V)	230
Fuel Cell Response Time	5 sec

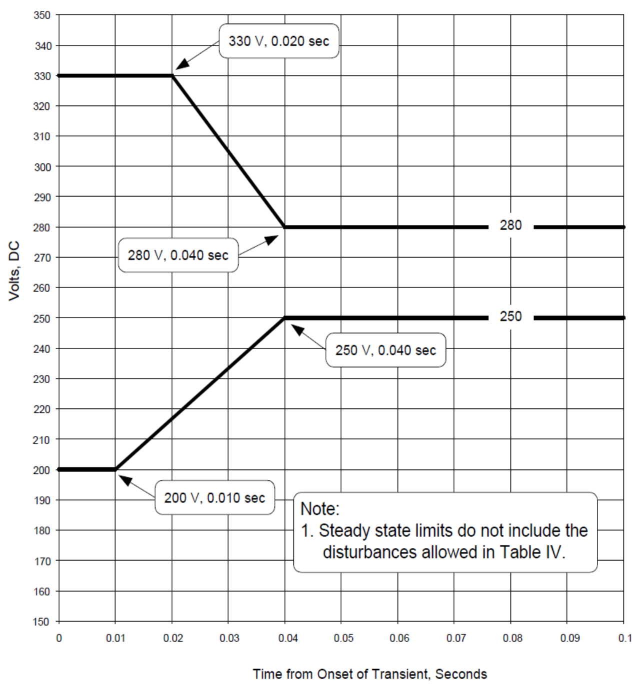

Fig. 10: Allowed voltage transient for 270 VDC systems. During transients, the system voltage must not go higher than the top solid line or lower than the bottom solid line. (Fig. 13 in MIL-STD-704F [15].)

Fig. 12 shows the power demand from the load (blue line, hidden behind black dashed line), the total power supplied (black dashed line), as well as the power outputs from the engine generator (pink line), fuel cell (green line), and DC-DC converter (red line). Initially the 200 KVA main-engine generator serves the base load of 150 kW. At 1, 1.5, and 2 seconds there are load increases of 15 kW, 15 kW, and

20 kW respectively, bringing the total load to 200 kW, which is all met by the engine generator. Beyond 4 seconds the generator can no longer handle an increase in load and the load is met by the fuel cell and the DC-DC converter, as evidenced by the jump in the green and red lines.

The fuel cell and DC-DC converter responds much faster than the generator. This is due to the capacitor within the DC-DC converter. The addition of the fuel cell system improves the overall performance of the airplane's electrical system.

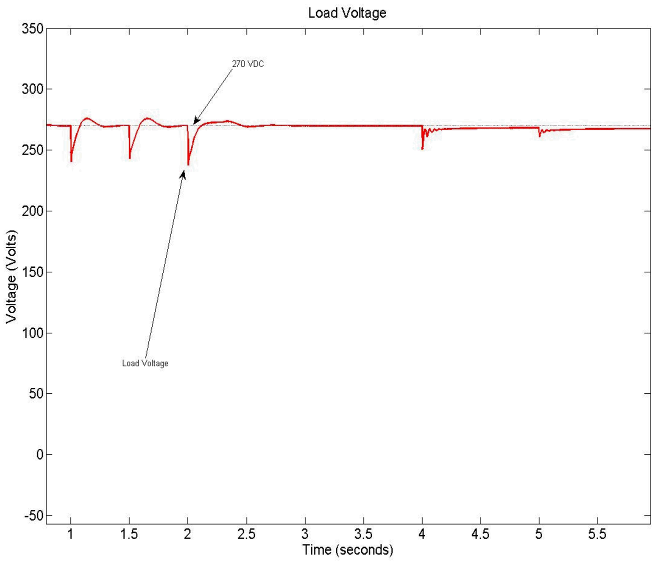

Fig. 11: Peaker system simulation: Voltage at the load. The system is stable and the transients are all within the MIL-STD-704F specifications.

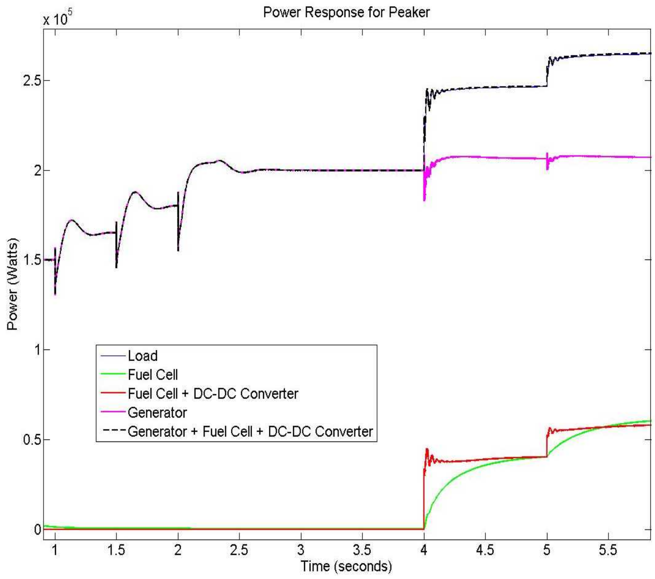

Fig. 12: Peaker system simulation: Power responses.

V. CONCLUSIONS

The fuel cell system can perform the required electrical functions for galley, IFE, and peaker power. It does not adversely affect system stability and meets the requirement for transients as put forth by MIL-STD-704F. Transient behavior is possibly better than the existing engine generator-based system, largely due to the capacitors inherent in the DC-DC converters.

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