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Multi-Layer DC/DC Converter for Fuel Cell-Based Air Independent Propulsion System

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ABSTRACT

One of the most important components of fuel cell power systems is the power conditioning subsystem. DC/DC converters play the leading role in the power conditioning subsystem and fuel cell hybridization with other electric power sources and storage. DC/DC converters control the load voltage and, in some cases, the fuel cell current, while current-controlled DC/DC converters control the loading level. Some advantages of designing converters in a multi-layer topology include reduced input current ripple and increased power density. Lower current-rating semiconductor devices can be used due to the current division among the layers and lower values of inductors and capacitors can be used due the lower input current and output voltage ripples, respectively. Furthermore, failure of one layer does not result in a complete system outage; the other layers can deliver a fraction of the nominal power. A fuel cell power system based on a 16 kW proton exchange membrane fuel cell stack and a multi-layer DC/DC boost converter is designed and implemented in this paper. The power system is intended for marine air-independent propulsion systems. The power system is modeled and analyzed using the MATLAB/Simulink software environment. The power system is implemented to verify the analysis and simulation results.

1. Introduction

Global warming is occurring as a result of greenhouse gas emissions. Aside from global warming, using fossil fuels has exacerbated environmental problems such as air pollution, ozone depletion, forest destruction, and acid precipitation. To mitigate these effects, many activities have evolved to reduce fossil fuel consumption by increasing environmentally friendly energy sources [1]. Renewable energy development appears to be unavoidable in order to meet current and future energy demands. However, electricity generation from wind or solar sources is intermittent and unpredictable. As a result, storage systems are required to supply enough energy when demand exceeds production. Among many types of clean energy sources, the fuel cell (FC) is one of the most efficient sources that can be used as an alternative energy source for electrically powered devices such as transportation, communication, and residential systems [2]. This is due to their high specific energy, high reliability, and zero-emission (if hydrogen is produced from renewable energy sources). Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), and Molten Carbonate Fuel Cells are the five existing Fuel Cell (FC) technologies (MCFC). When considering transportation applications, PEMFCs are the most applicable ones. Compared to other FC technologies, PEMFC has a high power density, low weight, and volume [3]. However, FCs have several

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drawbacks: 1) the response to power demand can be slow; 2) the output voltage can fluctuate with load variation; 3) cold start is difficult; and 4) FCs cannot absorb energy when compared to batteries or ultracapacitors (UCs). As a result, an auxiliary energy source, such as a battery or ultra-capacitors, is typically combined with the FC system to improve peak power capacity, dynamic characteristics, load voltage regulation, fuel economy, and load supply during cold start. FC hybrid power systems have three common structures: FC/ultra-capacitor, FC/battery, and FC/battery/ultra-capacitor. One of the main components of hybrid power systems is the DC/DC converter.

The FC/battery hybrid power system is investigated in [4]. In the proposed system, the proton exchange membrane FC (PEMFC) serves as the primary source in this system, connected to the load via a unidirectional boost converter; a lithium-ion battery serves as an auxiliary source, directly connected to the dc bus.

Fuel cells typically have a low voltage and high current capability, and their efficiency is proportional to the average current. Taking into account the auxiliary subsystems such as the oxygen excess ratio controller, air compressor, and water and cooling subsystems, overall system efficiency is in the range of 40-50%. As a result, designers must preserve efficiency when designing power systems; otherwise, the benefits of using fuel cell sources will be lost [5]. DC/DC converters adjust the FC voltage to meet the load voltage requirements. A DC-DC boost converter is required when the fuel cell voltage is lower than the load voltage. Several studies on DC/DC boost converters have been conducted to improve the power conditioning subsystem in power systems using renewable energy sources. A review on DC/DC converter architectures for power fuel cell applications is done in [3]. The input current ripple is one of the challenges of DC/DC boost converters in fuel cell power system applications. Using multi-layer boost converters is an effective way to reduce input current ripple [6]. A 16 kW PEM fuel cell/lead-acid battery power system with a multi-layer DC/DC boost converter is designed and analyzed in this paper. The power system is implemented and the design and analysis results are validated experimentally.

2. Fuel Cell Power System Design and Modelling

2.1. PEM Fuel Cell

The power system consists of a 16 kW PEM fuel cell as the primary source and a lead-acid battery bank as an auxiliary source. The fuel cell stack is modeled in the MATLAB/Simulink software environment. At the operating point, the stack voltage is approximately 55 V. Because the selected DC load nominal voltage is 110 V, the stack voltage level should be increased to 110 V and regulated at this voltage level. The power conditioning subsystem is in charge of this voltage regulation. As previously stated, the main component of this subsystem is the DC/DC converter.

2.2. Multi-layer DC/DC Converter

Given the system's power and voltage levels, a 55 V/110 V multi-layer boost DC/DC converter is designed and modeled in software. Figure 1 depicts the converter model. Figure 2 displays the model of the fuel cell power system.

3. Simulation Results

A pre-defined load profile is used to analyze and simulate the fuel cell power system model in the MATLAB/Simulink software. Figure 3 depicts the stack voltage-current and power-current profiles. Figure 4 displays the current profiles of the converter's input and output. Figure 5 depicts the input and output power profiles of the converter. The converter input current and input power are obviously the same as the fuel cell current and power.

4. Experimental Validation

To investigate the analysis and simulation results, a 16 kW fuel cell power system is used. As the power system load, a combination of electronic and ohmic loads is installed. Figure 6 depicts the measured voltage-current curve of a fuel cell stack. The voltage-current curve validates the simulated voltage-current curve presented in Figure 3. Figure 7 depicts the measured current profiles of the converter's input and output. It should be noted that the current change rate is controlled in the experimental tests for fuel cell safety purposes; thus, there is a slight difference between the dynamic changes of the currents during the load level increment and decrement. In addition, to prevent the battery bank from overcharging, the fuel cell operating point has been adjusted based on the load profile. Figure 8 depicts the measured input and output power profiles of the converter.

The experimental results validate the simulation results presented in Figures 3 to 5, despite the minor differences caused by implementation and utilization constraints.

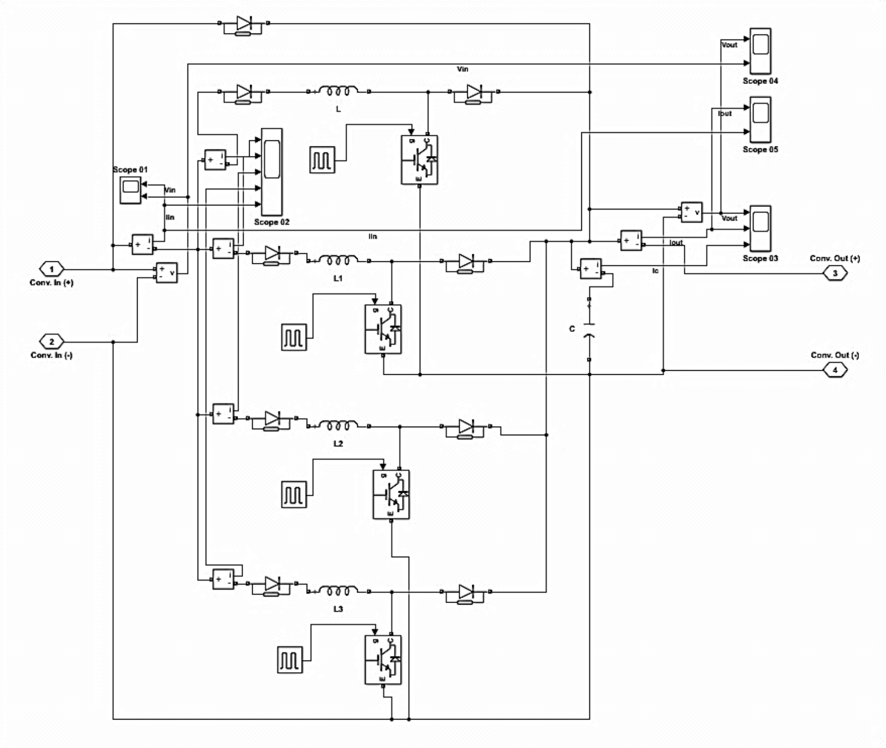

Figure 1: The DC/DC converter model

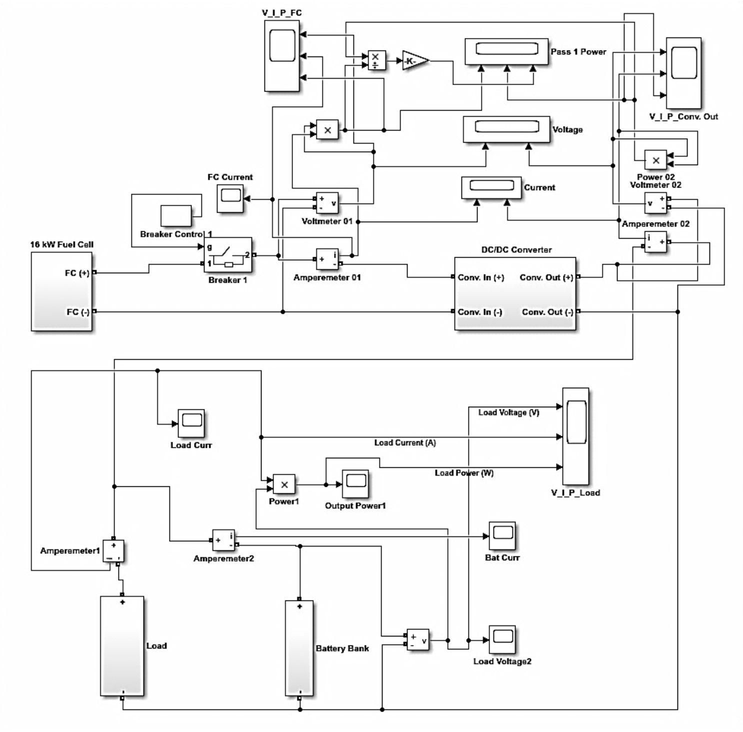

Figure 2: The fuel cell power system mode

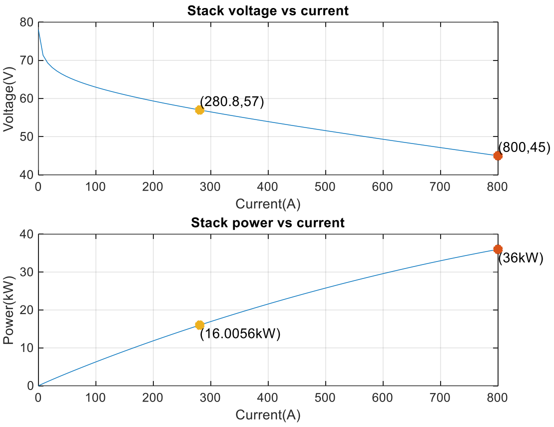

Figure 3:The fuel cell voltage-current and power-current profiles

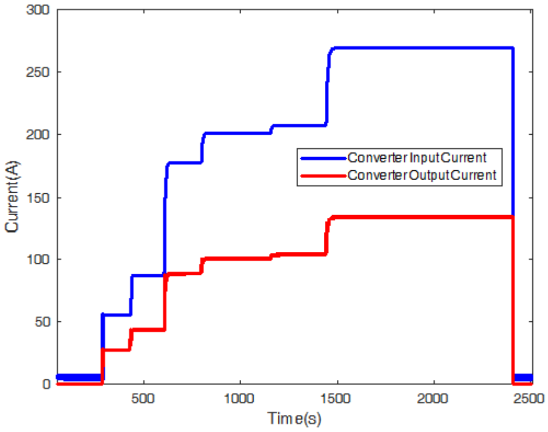

Figure 4:The converter input and output currents

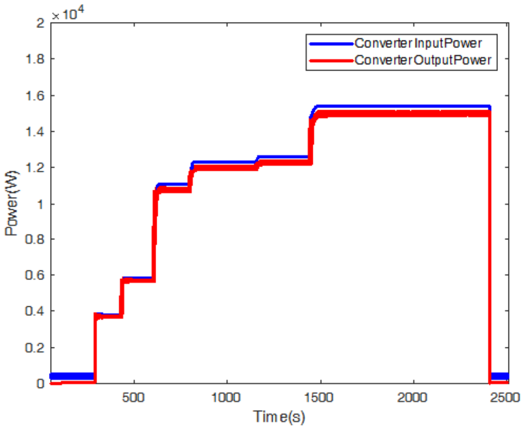

Figure 5:The converter input and output powers

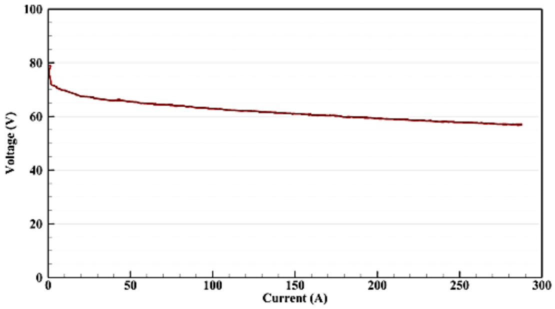

Figure 6:The fuel cell measured voltage-current profile

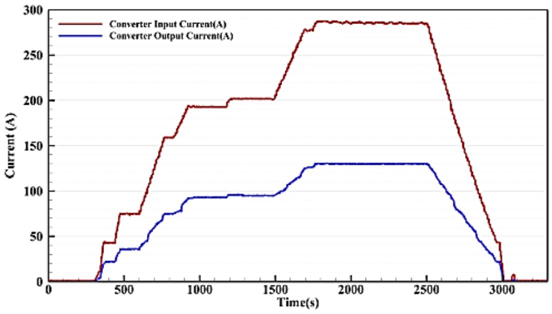

Figure 7:The converter measured input and output currents

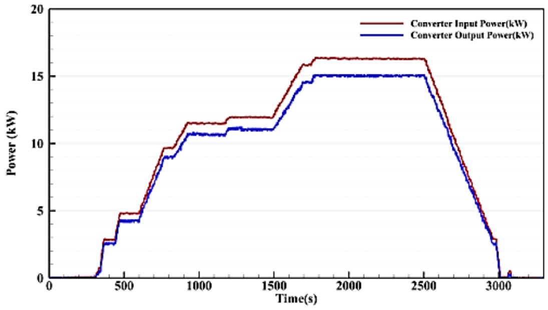

Figure 8:The converter measured input and output powers

5. Conclusions

A 16 kW PEM fuel cell power system based on a multi-layer DC/DC boost converter was designed, modeled, and analyzed in this paper. The power system has been designed for marine air-independent propulsion. The hybrid power system, which included a PEM fuel cell and a lead-acid battery bank, was designed to supply a 110 V 16 kW DC load. The fuel cell voltage was 55 V at the pre-defined operating point, and the 110 V load was supplied by a power conditioning subsystem that primarily consisted of the multi-layer converter. The power system was experimentally implemented and tested, and the analysis results were validated by the test results.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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