Fuel cell hybrid system for shipboard applications

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Abstract- **This paper presents modeling and simulation study of a fuel cell power system for ships. The paper reviews the ship's current power system. A detailed discussion of the issues associated with integrating fuel cells to ships and power conditioning systems for fuel cells to overcome the limitations is also presented. A model of the fuel cell for transient analysis is built in PSCAD/EMTDC. An energy storage system to mitigate the fuel cell's slow dynamics is developed and described in the paper. Simulation results of the performance of this system are also presented.**

Keywords-fuel cells; hybrid; ships; battery

I. INTRODUCTION

The US Navy Office of Naval Research operates prototype naval ship at the Acoustic Research Detachment on Lake Pend Oreille, Idaho. The Ship has two sources of propulsion power, a 250 kW diesel generator and a 650 kW battery bank (12 strings).

The primary aim of the project is to supply propulsion power from a renewable, clean, efficient, and quiet power source. Fuel cells are known to be clean, efficient, and quiet power sources. Fuel cell systems lack moving parts, making them generally more reliable. Fuel cells emit zero or ultra low emissions. Fuel cells have high efficiency of energy conversion compared to combustion engines, low noise, low vibration, and low levels of undesirable exhaust. Fuel cells can produce power continuously as long as fuel and oxidant are supplied. Proton Exchange Membrane Fuel Cell (PEMFC) is the recommended fuel cell technology for the ship because it has quick switch-on, switch-off capability compared to other fuel cell technologies, low voltage degradation, long service life, favorable load and temperature cycles, and overload capability.

II. WHY FUEL CELLS ?

A fuel cell is an electromechanical device that produces electrical energy from the chemical energy of a fuel. When pure hydrogen is applied as fuel, it produces electricity and leaves water as a byproduct [1]. There are certain attributes of the fuel cell make it attractive for propulsion of AESD. A fuel cell is an environmentally friendly source of energy. Fuel cell systems are static and they lack moving parts making them generally more reliable. Fuel cells emit zero or ultra low emissions. They have high efficiency of energy conversion, low noise, low vibration, and low levels of undesirable exhaust. Fuel cells can produce power continuously, as long as fuel and oxidant are supplied [2]. They can generate electrical energy of about 10 times that of a lithium-ion-battery with the same cubic volume [3]. Fuel cells do not degrade over time, can operate in a wide range of temperatures (80 ^{0}C to 1600 ^{0}C), have no safety and disposal issues, and can provide high power densities over extended run times [4]. They have higher efficiency at partial load and little maintenance requirement [5].

III. DESIGN SPECIFICATIONS

The current configuration of AESD dictates the basic requirements for fuel cell integration. These requirements are summarized in Table 1.

TABLE 1
SPECIFICATIONS FOR FUEL CELL INTEGRATION

Parameters	Specifications
Output Voltage	714 ± 5% DC
Current	More than 75 A per string
Power	More than 50 kW per string
Energy	More than 129.60 MJ
Dimensions	570 ft^3 (Volume of battery racks)
Fuel Storage	Comply with NAVSEA and State of Idaho's requirements for waste streams
User Interface	Remote means to control and shutdown

V. TYPES OF FUEL CELLS

Based on the type of electrolyte used, fuel cells are classified into different types. There are five different kinds of fuel cells currently being used in industry. These are proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell, molten carbonate fuel cell, phosphoric acid fuel cell, and alkaline fuel cell.

The type of fuel cell for AESD is recommended based on certain criteria. First of all the selected fuel cell should fit in to the existing space inside the ship which is currently housing the propulsion batteries and diesel generator. In order to fit in the available space, the fuel cell must have a high energy density. The low operating temperature of the fuel cell is desirable because it helps to quickly start up the system, to control the waste stream and to operate in close proximity of the ship's personnel. The selected fuel cell must be capable of operating at shipboard environment and the type of fuel cell must be commercially available.

The aforementioned characteristics influence the type of fuel cell recommended for AESD application. Considering these factors, PEMFC is recommended as the best fuel cell for AESD application. PEMFC operates at low temperature which supports rapid start-up and shutdown. PEMFC will work even when it has not attained its full operating temperature. PEMFC is not adversely affected by thermal shock due to thermal ramping at the relatively low temperature [7].PEMFC does not exhibit corrosion issues because its electrolyte membrane is solid polymer. Other advantages of PEMFC include relatively long service life, low voltage degradation, favorable load and temperature cycles, higher energy density, and overload capability. PEMFC modules with output power of 30 to 40 kW were previously developed by Siemens AG and they have been successfully operated in the Class 212 submarines for the German and Italian navies [5]. The above-mentioned attributes of PEMFCs make them suitable for operation in the AESD.

VI. FUEL CELL INTEGRATION

There are some technical challenges in integrating fuel cells to the ships. When fuel cells are connected to a bus in parallel there is a higher possibility of circulating current to inject back to the fuel cell modules. It can reduce the efficiency and service life of the fuel cell modules, therefore the circulating current must be blocked from entering in to the fuel cell modules [9]. A diode or other protection must be inserted in series with the fuel cell modules to block any circulating current between fuel cells [10]. Inserting diodes adds additional losses to the system. Identical fuel cell modules are recommended for integration to AESD. For the purpose of simplifying the analysis fuel cell modules are assumed to have uniqueness in their characters, such as equal impedances, equal load sharing and equal response time. However, because of impedance mismatching, some modules supply more current to the bus than others. A robust control system must be built to monitor the parallel operation of the fuel cells. The power flow diagram for fuel cell integration is given in Fig. 1. A detailed discussion on fuel cell integration is described in [8].

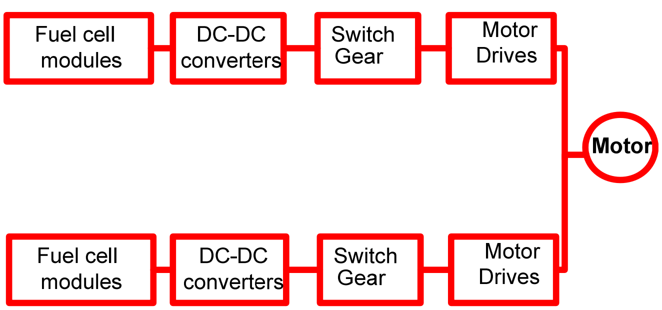

Fig. 1. Power flow diagram for fuel cell integration

VII. POWER ELECTRONICS INTERFACE

The output voltages of fuel cells may vary with age and current [1]. For AESD application, the regulation of the voltage is important. Therefore, the integration of fuel cells to AESD requires power electronic interface.

Fuel cells respond slowly to sudden load changes. Fast dynamic load demands causes significant voltage drop and might cause the fuel cell stack shutdown. Fuel cells have no overload capabilities, and cannot accept reverse current [1]. The current ripple caused by the dc-dc converters and inverters can reflect ripple back to the fuel cell stack [9]. Fuel cells are more vulnerable to low frequency ripple caused by the inverters because fuel cells cannot regulate the pressure level fast enough to react to the current variation. The efficiency of a fuel cell is reduced with output ripple current [1].

The power conditioning system should control the fuel cell output voltage, convert the fuel cell output to the appropriate type and magnitude, provide little to no harmonics, operate efficiently under all conditions and add little to the cost of the overall power system [1]. Due to the fuel cell's slow response, secondary energy sources can be used to maintain bus voltage during start-up and transients. Batteries and ultra capacitors are suitable choices for this secondary energy source. They can be interfaced to the system using bi-directional dc-dc converters [11]. The integration of secondary energy source to the fuel cell source is as given in Fig. 2.

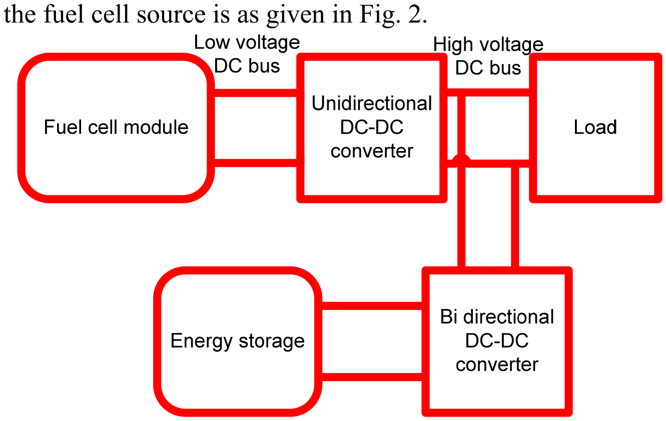

Fig.2. Integration of secondary energy source to the fuel cell

The application of bi directional dc-dc converter has the advantage of a faster, more stable response [1]. Any reverse current to the fuel cell can be blocked by a diode inserted in series with the fuel cell. Current ripple can be filtered by implementing a capacitor to absorb the ripple. The voltage of the fuel cell can be kept constant through the use of a dc-dc converter. Electrical isolation between the low voltage output of the fuel cell and high voltage dc output is required to protect the fuel cell.

A. DC-DC converters

The fuel cell dynamic response defines the control structure of the power conditioning system. The dc-dc converter to be designed must not react to load steps faster than the fuel cell. The dc-dc converter has to control and condition output power of the fuel cell and its electric characteristics have to match with that provided by the fuel cell and demanded by the load. In order to reduce the effects of current and voltage ripple on the fuel cell, the input current and voltage ripple of the dc-dc converter must be small [11]. To ensure the highly efficient and reliable operation of the fuel cell, the dc-dc converter has to apply a suitable strategy to adjust the output power of the fuel cell when it works under load current variations. The dc-dc converter must fit in to the requirements of high step-up conversion ratio, high stability of the output voltage during variations of the output current and input voltage, and high efficiency. Aforementioned requirements exclude all dc-dc converters without transformers and converters for which stable output cannot be produced for varying input voltages [2]. The recommended dc-dc converter topology for AESD is full-bridge. Full-bridge is highly efficient, stable, and it can provide isolation via a high-frequency transformer. The input and output current and voltage ripple of a full-bridge converter are small, and will ensure the safe operation of the fuel cell module and the transistors used for switching. The transistors' current and voltage stress are low in full-bridge topology. The schematic of the unidirectional full-bridge dc-dc converter is given in Fig.3. The unidirectional dc-dc converter has to regulate the variable and potentially low DC voltage of the fuel cell module to meet the voltage requirement of the high voltage dc bus. However, the unidirectional dc-dc converter must not react to load steps faster than the fuel cell. The switching scheme employed for the full bridge converter is phase-shifted Pulse Width Modulation (PWM).

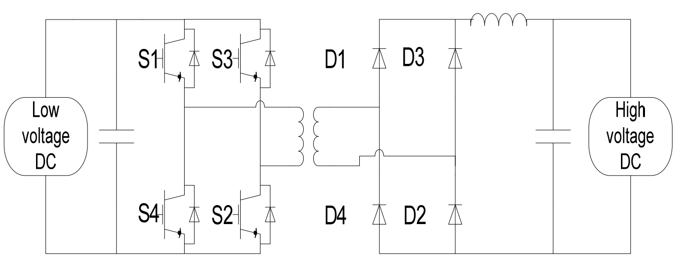

Fig. 3. Unidirectional dc-dc converter for AESD

B. Bi-directional DC-DC converter

Bi-directional dc-dc converter allows both directional power flows for energy storage discharge and recharge. Its response needs to be fast enough to compensate for the slow dynamics of the fuel cell during start-up or sudden load changes [12]. The secondary energy source (battery) is connected in parallel with the high voltage DC bus through a bi-directional dc-dc converter. During start up and load increases the bi-directional converter should let the battery assist the fuel cell by transferring energy to the high voltage DC bus . In this mode the bi-directional converter boosts the low voltage of battery to high voltage DC bus's voltage requirement. During load decrease, the bi-direction converter channels the excess energy from the high voltage DC bust to charge the batteries. In this mode, the bi-directional converter bucks down the high voltage DC to that of battery terminal voltage. An isolated full-bridge dc-dc converter topology is adopted for bi-directional converter in both boost and buck mode because full-bridge topology is best suited for very high power applications [*3*]. Bi-directional topology allows both directional power flows for battery discharge and recharge. The response of this converter should be fast enough to compensate for the fuel cell's slow response during start-up or sudden load changes. Full bridge bi-directional dc-dc converter is recommended for AESD operation. The schematic of the full-bridge bi-directional dc-dc converter is given in Fig.4.

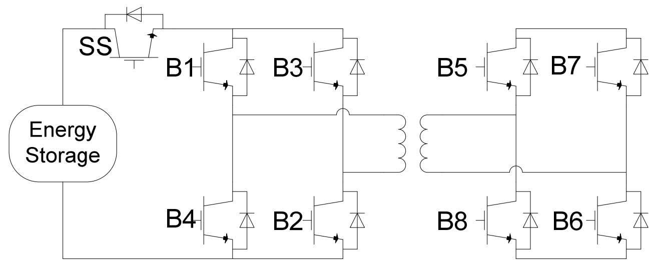

Fig. 4. Bi-directional dc-dc converter for AESD

XI. PEMFC DYNAMIC MODEL USING PSCAD

Fuel cell dynamics are based upon certain factors: hydration level of the membrane, response time of the compressor, the load step change, and temperature [14]. PEMFC's dynamic response is dominated the charge double layer effects in short time range (less than 1 sec) and by thermodynamic characteristics inside the fuel cell and by the fuel and oxidant flow delays in the long time range [15] The fuel cell losses are mainly divided into three categories: activation loss, concentration loss, and ohmic loss [16]. Fuel cells also exhibit a fast dynamic behavior known as the "charge double-layer" phenomenon, wherein this layer behaves as an electrical capacitor [16]. A block diagram for building an electric circuit model for PEMFC is given in Fig.5.

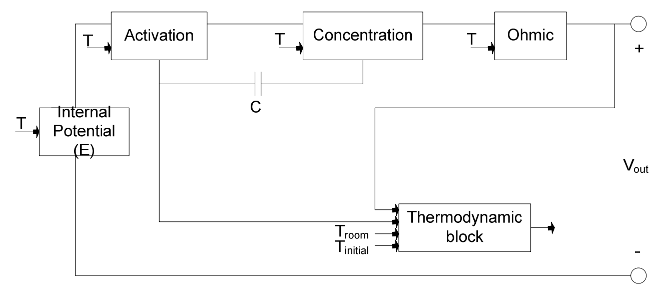

Fig. 5. Block diagram for building an electrical circuit model for PEMFC

The fuel cell internal potential is a function of load current and temperature. Activation losses result from the relatively slow speed of the reactions occurring within the cell. The ohmic loss results from the resistance of the polymer membrane to the transfer of protons and the resistance of the electrode and collector plate to the transfer of electrons. Concentration loss is due to gas concentration changes at the surface of the electrodes [16]. Fuel cells also exhibit a fast dynamic behavior known as the "charge double-layer" phenomenon. The "charge double-layer" stores electrical charge and thus energy. The collection of charges by the layer generates an electrical voltage that corresponds to the combination of activation polarization and concentration polarization. Whenever the current suddenly changes, it takes some time before the activation polarization and concentration polarization follow the change in the current [15]. The layers can store electrical energy and behave like an ultracapacitor [17]. The capacitance can be calculated through measurement of the dynamic response of a real fuel cell stack in a very short time range (millisecond) [14].

There are some analogies between the thermodynamic quantities and electrical quantities. These analogies enable us to develop an electrical circuit model for the thermodynamic block. The analogies between thermodynamic and electrical quantities are given in Table 2. The thermodynamic property inside the fuel cell is described in [17]. The power consumed by the activation, ohmic, concentration losses is regarded as a heat source which results in a temperature rise in the fuel cell.

TABLE 2
ANALOGIES BETWEEN THERMODYNAMIC AND ELECTRICAL QUANTITIES

Electrical potential: U(V)	Temperature: T(K)
Electrical current: I(A)	Heat flow rate: P_h (W)
Electrical resistance: R(Ω)	Thermal resistance: θ (K/W)
Electrical capacitance: C(F)	Heat capacity: C_h (J/K)
$R * I = U$	$\theta * P_h = T$
$I = C * \frac{du}{dt}$	$P_h = C_h * \frac{dT}{dt}$

A. PSCAD model structure of PEMFC

The previous section has introduced all the chemical, electrical and thermodynamic properties of PEMFC. All of the appropriate and significant PEMFC properties are modeled using electrical equivalent circuits. The full PSCAD model of PEMFC is a combination of the above mentioned individual blocks. The outer block of PSCAD modeling PEMFC is given in Fig. 6. The input parameters of the PEMFC block are load current (fed back from the external electric power circuit) (*I*), anode pressure (*Panode*), cathode pressure (*Pcathode*), room temperature (*Troom*), initial temperature (*Tinitial*). The output parameters of the PEMFC block are output voltage (*Vout*) and stack temperature (*Tout*).

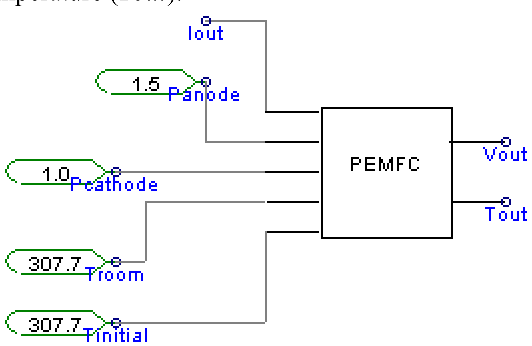

Fig. 5. Outer block of PSCAD modeling of PEMFC

The circuit model in PSCAD representing PEMFC is given in Fig. 7. Inner block combines the terminal voltage and thermodynamic block of PEMFC. This block also represents the number of cells in series in the stack. In this case there are 48 cells in series as seen near the bottom of Fig. 7. Output temperature is controlled through a saturation block. The lower limit of the saturation block is 273 and the upper limit of the saturation block is 373.

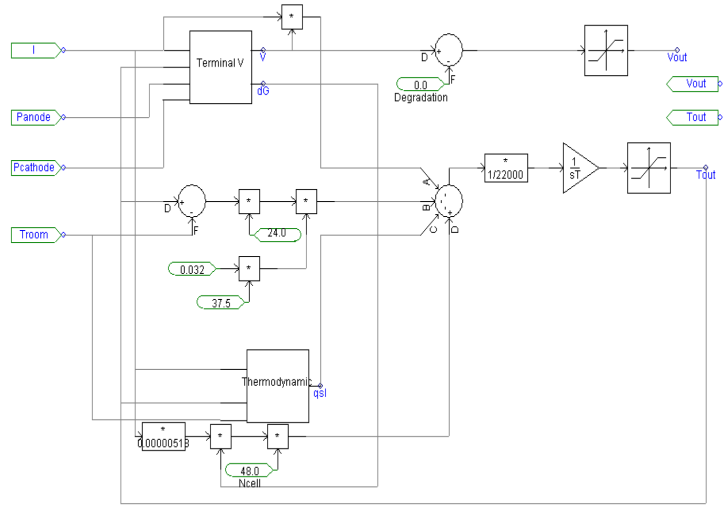

Fig. 5. Circuit model in PSCAD representing PEMFC

The terminal voltage block shown in the PSCAD model of Figure 5 is shown in Fig. 6. The figure consists of block models of activation, concentration and ohmic polarizations of PEMFC, internal voltage of PEMFC, and a delay block that imitates the charge double-layer effect of PEMFC [17].

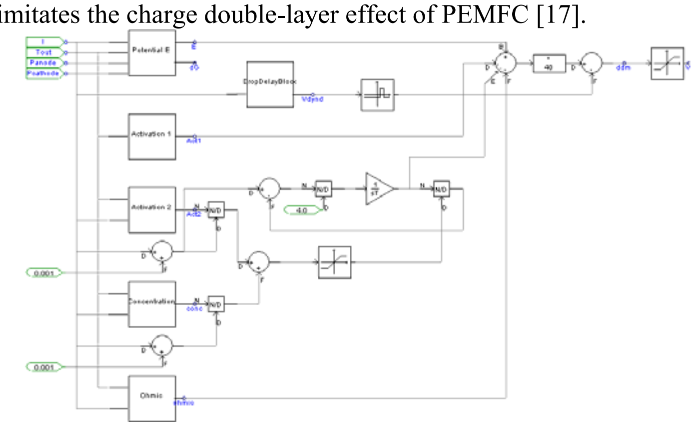
Fig. 6. Terminal voltage block of PEMFC in PSCAD

XII. ENERGY STORAGE FOR TRANSIENTS

Lead-acid batteries are recommended for energy storage since they are already used in AESD for propulsion, and can be implemented less costly compared to another battery models. During initial start up, fuel cell reaches steady state in 90 sec, and during a change in power demand, fuel cell reaches a new steady state in 60 sec [12]. For lead-acid batteries, 20 % change of nominal charge state is reasonable to avoid deep discharge and ensure long service life [12]. By considering the aforementioned conditions, the minimum battery storage required to support the fuel cell during all transients is 81.25 kWh. There are many lead-acid battery model proposals available. For simulation, simplified circuit model is used, and is given in Fig. 8 [17]. C_B is battery capacitance, R_P is self-discharge resistance of battery, R_2 is internal resistance, R_1 is over voltage resistance, and C_1 is over voltage capacitance [18].

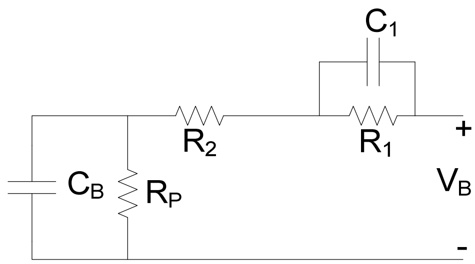

Fig. 8. Simplified circuit model for lead-acid batteries

XII. SIMULATION USING PSCAD

The system model consisting of the PEMFC equivalent circuit, the unidirectional dc-dc converter, lead-acid battery equivalent circuit, and the bi-directional dc-dc converter is simulated using PSCAD. The simulation diagram is given in Fig. 9. The system model also consists of protective diode and input/output filters. Both the unidirectional dc-dc converter and bi-directional dc-dc converter are modeled with RC snubber circuits to guard against voltage spikes. The turn's ratio of the transformer used for the simulation is 1:2.25. The proprietary motor drive is also modeled.

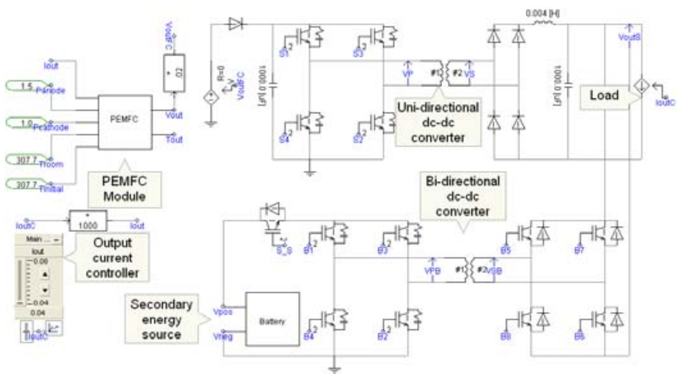

Fig. 9. PSCAD simulation diagram for power conditioning system and fuel cell module

The proprietary motor drive is also modeled. The control circuit is given in Fig. 10. A PI controller is used to regulate the duty cycle for the dc-dc converters.

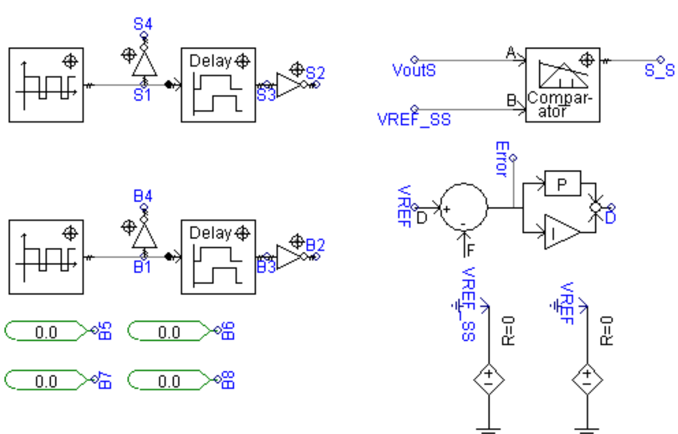

Fig. 10. PSCAD simulation diagram for PI controller and gate driving circuits

C. *Simulation results*

The simulation results for fuel cell response and dc-dc converter output were analyzed. The switching frequency was 10 kHz. The simulation run time was 6 sec, and the time step for the simulation was 5µs. The filters were designed for a 5% ripple. The Load current is varied from minimum to maximum in step increments. The responses of both the fuel cell stack and secondary energy storage are evaluated. The Load current profile of the dynamic test is given in Fig. 11.The Output voltages of fuel cell stack and high voltage dc bus are given in Fig. 12. As the load current increases, the output voltage of the fuel cell stack decreases due to polarization voltage drops. A PI controller was used to regulate the duty cycle of the converters. The reference voltage was 720 V, and it was compared with the voltage across the output capacitor. The duty cycle for the system is given in Fig. 13. For low load current, the controller employs a minimum duty cycle. As the load current increases duty cycle also increases and reaches its maximum value (.475) at maximum load current. Gating signals for the switch that connects secondary energy source to the high voltage dc bus are given in Fig. 14. During the start up secondary energy source is connected to the dc bus to assist the fuel cell to meet the change in load current. Once the fuel cell picks up the load secondary energy source is disconnected. At maximum load current secondary energy source is connected to the high voltage dc bus. The Temperature profile of the fuel cell stack is given in Fig. 15. During low load current temperature of PEMFC stack is low. As the load current increases, temperature also increases. This is due to the increase in chemical reaction takes place inside PEMFC.

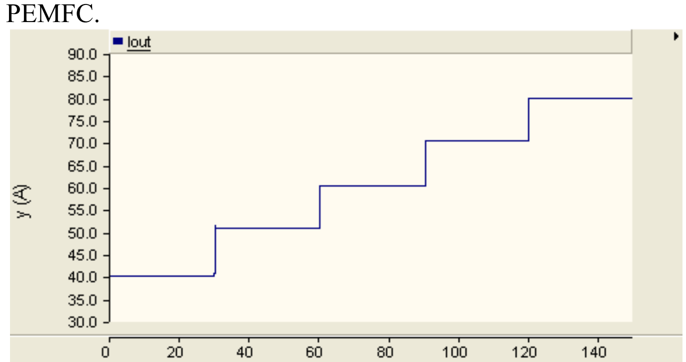

Fig.11. Load current

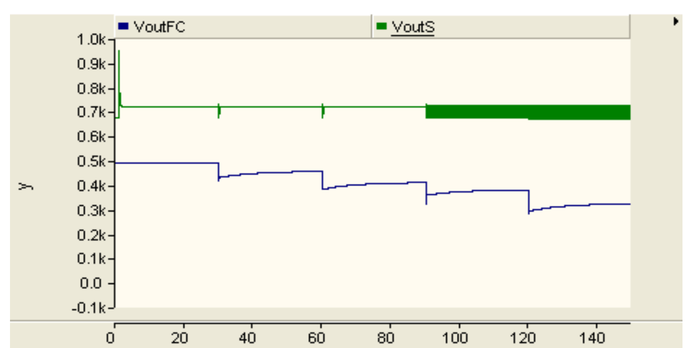

Fig. 12. Fuel cell module's output voltage and high voltage bus voltage

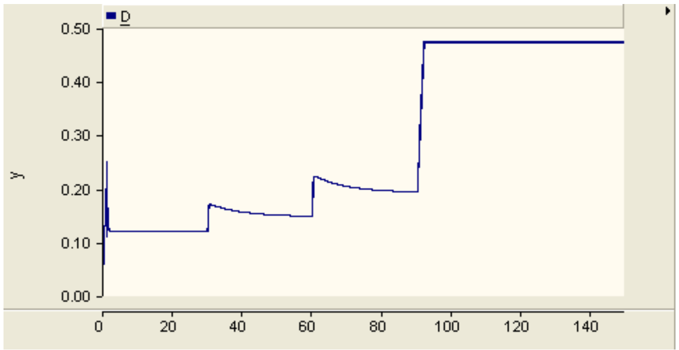

Fig. 13. Duty cycle variation of the system

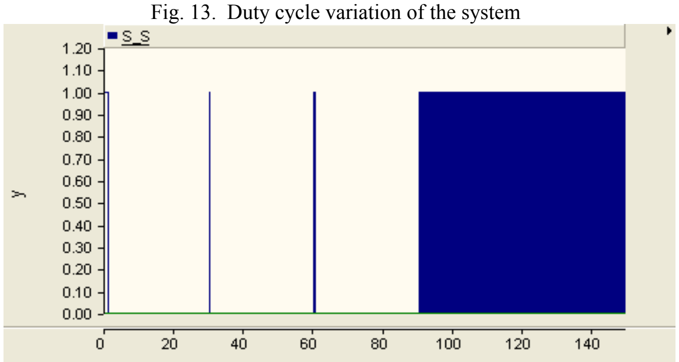

Fig. 14. Gating signal for secondary energy source switch

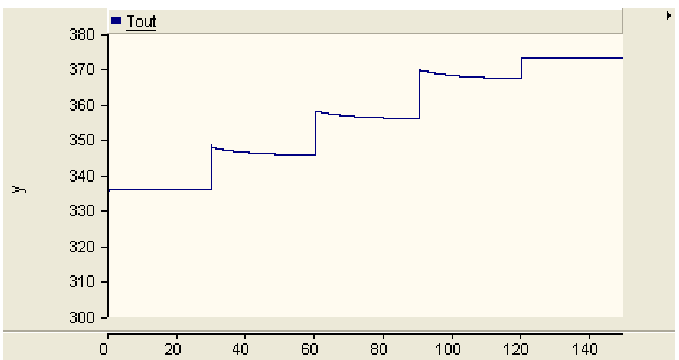

Fig. 15. Temperature of PEMFC stack

XII. Conclusions And Recommendations

Fuel cells are a promising technology for transportation. The integration of the fuel cell modules into the AESD requires a robust power conditioning system. This paper designed and simulated the power conditioning system to overcome the fuel cell modules' slow dynamic response to fast changes in load conditions. The PSCAD model of PEMFC was really helpful in examining the response of PEMFC under different loads. Simulations using PSCAD assisted in understanding the response of fuel cells to different load changes. A challenging task for this project was to find a way to interconnect the fuel cell and lead-acid batteries. They are connected through a bi-directional dc-dc converter. The bi-directional converter enables the batteries to assist fuel cell in startup conditions and large load variation conditions. It also enables the system to charge the batteries when the load decreases occurs. The proposed PEMFC system and powering electronics would provide increased efficiency over the current propulsion system of the AESD. It is clear that PEMFC modules can be integrated into the AESD with a power conditioning system. By replacing the current power system with fuel cell modules, the problems of transients caused by a diesel generator and the harmonic distortion caused by the battery charging system can be avoided. The recommended fuel cell power system is more reliable than the current power system. The integration of a fuel cell system onto the AESD would realize a two-fold fuel savings and significant reduction in emissions.

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