

Control System for a PEM Fuel Cell Powered Heavy Duty Tactical Mobility Truck with Auxiliary Power Generation Capabilities

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ABSTRACT

The incorporation of hydrogen fuel cells into heavy duty tactical mobility vehicles can bring about great opportunities in reducing the pollutant emissions of this kind of platforms (GVW > 30,000 kg). Furthermore the transportation of fuel to operational areas has become a key aspect for any deployment therefore optimal use of this resource is of paramount importance. Finally, it is also quite common for such platforms to serve additional purposes, besides freight delivery, such as powering external equipment (i.e. field hospitals or mobile artillery pieces).

This work will describe the intelligent energy management system for a PEM Fuel Cell-Battery-Ultracapacitor Hybrid 8×8 heavy truck of the aforementioned weight class which also contemplates an internal electric/traction power generation unit. It will describe how the system optimizes the use of battery and hydrogen fuel energy while keeping system efficiency and performance at a maximum.

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INTRODUCTION

It is an undeniable fact that high fuel prices have come to stay. As an example, in the summer of 2008 the U.S. was hit with a petrol price increase that reached USD\$ 4.05 per U.S. gallon [1], that situation repeated itself in 2011 when, during the Arab Spring, the market price for said fuel had an average price of USD\$ 3.89 [1] where according to figures from the U.S. Energy Information Administration it remains. At the same time oil reserves in many countries have fallen or not kept up with the increasing demand from BRICS. In all this creates pressure on security cost related to the safe transport and exploitation of petroleum around world.

While a 2009 report from the RAND Corporation elaborates and concludes that the best way forward for armed forces is to place an emphasis on more efficient use of energy, it does so over the base assumption that each government has a deep pocket or a blank check with which to procure the ever more expensive fuel [2]. Sadly, the existing economic environment has proved this to be no longer the case, if it ever was. To prove the point, Nobel Laureate Joseph Stiglitz stated in a 2008 interview that the Iraq War had been the first American armed intervention since its own

revolutionary struggle where financing came primarily from abroad. This only aided into sinking the U.S. government into deeper debt with a USD\$ 12 billion-a-month bill [3].

To better understand how this motivated this work, let us focus on the context of expeditionary armed forces operations. In the Iraqi theatre each gallon of fuel dispensed has the extra price tag of aerial/terrestrial transportation and uniformed guard [4]. Estimating the real cost of the logistical operation this entails one has to resort to a methodology called Fully Burdened Cost of Fuel (FBCF), which takes into account the market price of energy plus the total ownership cost of all the security systems and assets involved in moving the energy from point of origin to end user. The author mentions sobering figures of USD \$ 44.00 for each gallon of fuel delivered to the American Department of Defence (DoD), although since the equation considers a logistical train, the furthest the end user is the more expensive the fuel (USD\$ 100.00 for a unit operating in Fallujah or as high as USD\$ 600.00 for out of reach units) [4].

In essence all the previously discussed facts pose two questions. What fuel alternative could be explored to ease the logistical, fiscal and security burdens on expeditionary

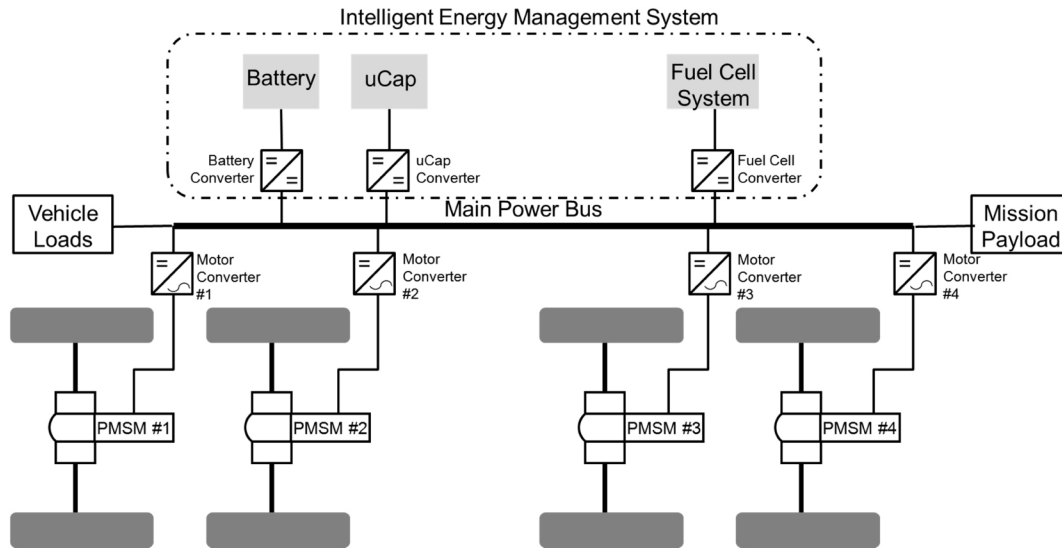


Figure 1. Vehicle power system diagram.

forces? How to best use this resource to achieve the individual objectives of day-to-day operating units?

In the first case, the American defence establishment (DoD, Army, etc.) have been looking into in-situ power generation that would reduce the number and frequency of fuel convoys together with optimizing the use of fossil fuels at forward locations therefore losing the tether on oil and avoiding exposure of assets to enemy attack. An example of this is the collaboration of the U.S. Army Corps of Engineers with the Energy & Environmental Research Center to develop an on-demand hydrogen supply system based on JP-8 reforming [5]. During this programme a hydrogen fuelling station and several technology utility demonstrators have been tested and found to match the performance of their diesel powered counterparts. Also third parties have begun on one side developing green portable power stations that could power electrical field loads between 0.4 to 10 kW using a mix of wind and solar power [6] while on the other working within the RENEWS and REDUCE projects have come up with micro solar power grids that can power multiple portable electronic devices reducing maintenance costs and logistical burden [7].

The context is now defined. Firstly, armed forces look to reduce both their dependency on ever more expensive fossil fuels and reduce the logistical burden which energy supply to forward locations entails. Secondly, fuel cell and hydrogen production technologies are at a stage where their use in forward locations and military vehicles can be more deeply explored. Finally, all this would be best served accompanied by power generation architectures and systems that can be portable, versatile and oriented towards optimizing the use of the most limited resource of all: Energy. With this in mind an intelligent energy management system has been coupled with a proposal for an 8×8 Heavy Duty Tactical Mobility Platform (Gross Vehicle Weight 31,000 kg.) that can provide power to

external loads. Such architecture should be able to attack the identified problem:

1. It could transport heavy freight loads.
2. By providing external power it can also reduce the logistical burden by serving a dual purpose.
3. The intelligent management system would ensure that energy is used in an optimum way towards fulfilling the unit's mission while maintaining all components involved operating in their optimum regions.
4. By using an electric drivetrain it would help reduce dependency on oil as electrical machines and fuel cells work with higher efficiency levels than internal combustion engines.

PROPOSED VEHICLE ARCHITECTURE

To comply with the demands of a tactical vehicle nature, the proposed system uses an 8×8 powertrain architecture capable of hauling a gross vehicle weight up to 31,000 kg. to an on-road speed of 100 kph and is able to climb a 60% slope. All the while having at its core the necessary hardware to supply both vehicle and mission critical electrical loads, whether the latter are on-board (part of the main vehicle electrical bus) or external (i.e. equipment supplied by external power outlets or Power Take Off coupled electrical generators). In order to achieve this, the architecture considers a single permanent magnet synchronous machine per axle for a total mechanical power rating of 300 kW fed by a double 150 kW fuel cell system working in parallel with ultracapacitor and battery banks. Figure 1 shows a diagram of the power distribution system.

The most common architecture found in high power platforms (> 100 kW) is that of a Fuel Cell-Battery-Ultracapacitor necessary because of the different reaction dynamics, energy density and power-to-weight ratio of each element. For example, Ultracapacitors have high reaction times, but are not as power dense as a battery. Batteries do not have so high cycle ratings as ultracapacitors and have longer reaction times, but can store energy recovered during braking or deceleration. Fuel cells are the slowest of the three, but can generate higher power levels per volume [8], [9], [10], [11].

At this stage in the development the system is still in the numerical modeling phase to be able to test the performance and operation of the Intelligent Energy Management System (IEMS). Therefore models of the main components have been crafted as described in the following sections.



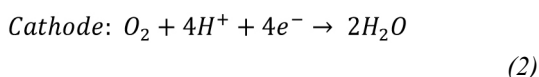
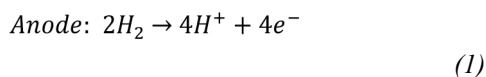
Figure 2. Typical Heavy Duty Mobility Platform

NUMERICAL MODEL

Fuel Cell Model

Proton Exchange Membrane Fuel Cells (PEMFC) are widely used nowadays for vehicle applications. This is in part due to their low operating temperature (50-100 °C [12]). Fuel cells are chemical reactors that create an electrical current from the reaction of hydrogen and oxygen inside a stack of polymer membranes [13].

Fuel Cell Voltage / Current Relationship.



Each cell is made up of a cathode, anode and membrane or electrolyte. High pressure hydrogen gas enters the cell through the anode manifold and tries to go through the electrolyte. The membrane allows only positive ions, or protons, to pass while blocking negatively charged electrons.

These electrons are collected and sent over an electric circuit creating a current which powers the load. Both protons and electrons reunite at the cathode where they react with oxygen in the pressurized atmospheric air to form water. The reaction at the anode is described by Equation 1, whilst the cathode process is described by Equation 2. The typical voltage of a Nafion 117 PEM fuel cell is 1.2 volts of direct current. To obtain higher voltages a string of such cells are connected together electrically and through manifold piping to create a stack. Figure 1 shows the polarization curve for one of the 150kW fuel cell modules contemplated, with governing losses indicated.

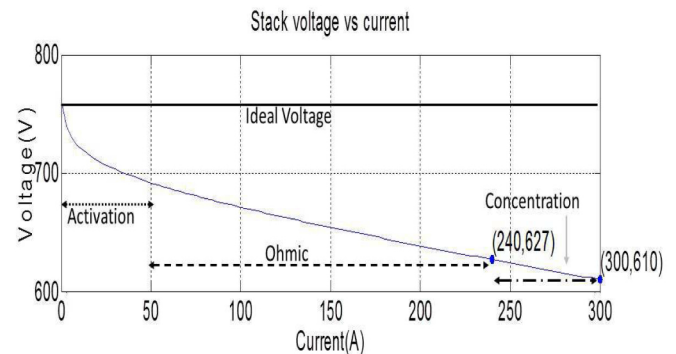


Figure 3. PEM Fuel Cell polarization curve.

The real power that can be drawn from a fuel cell is far from ideal. Natural losses are dominated by three kinds [13]:

- Activation losses, v_{act} : Caused by the transportation of electrons and the creation and destruction of chemical bonds on the opposing sides of the fuel cell. Because the reaction at the cathode is more complex and slower the local conditions on this side dominate when calculating these losses.

$$v_{act} = n_{cell} \frac{RT}{2\alpha F} \ln \left(\frac{I_{fc} + I_n}{I_o} \right) \quad [\text{V}] \quad (3)$$

- Ohmic losses, v_{ohm} : This resistance or loss arises from the polymer membrane's reluctance to allow the transfer of protons and from the resistance of the electrode and collector plates to transfer the freed electrons [14]

$$v_{ohm} = i_a R_{ohm} = i_a \left(\frac{t_m}{\sigma_m} \right) \quad [\text{V}] \quad (4)$$

This component comes to dominate the middle section of the polarization curve where electron flow has already been established. Its behaviour is nearly linear.

- Concentration losses, v_{conc} : Results from the shortage of reactants caused as they have been consumed by the reaction itself, hence its name. As there is no more material to subject to the reaction mechanism the voltage begins to drop rapidly due to the lack of available electrons to maintain the same

power level. It dominates the right-hand side of the polarization curve [14].

$$v_{conc} = i_a \left(c_2 \frac{i_a}{i_{max}} \right)^{c_3} \quad [V] \quad (5)$$

Fuel cell current density is defined by the stack current and the active area of the cell [10].

$$i_a = \frac{I_{st}}{A_{fc}} \quad [A/cm^2] \quad (6)$$

The ideal voltage of an individual cell is given by [15]

$$E_0 = \frac{-\Delta G}{nF} = \frac{237,340 [J/mol]}{2(96485) [C/mol]} = 1.23 \quad [V] \quad (7)$$

Taking into account the effect of temperature and reactant pressure Equation 7 is expanded [15] to obtain the open circuit voltage, E.

$$E = E_0 - \frac{RT}{nF} \ln \left(\frac{P_{H_2O} P_{O_2}^{0.5}}{P_{H_2O}} \right) \quad [V] \quad (8)$$

Finally the stack voltage, V_{st} , is given taking in account all the losses and the number of cells involved.

$$V_{st} = n_{cell} (E_0 - V_{act} - V_{ohm} - V_{conc}) \quad [V] \quad (9)$$

The only new term is n_{cell} , which is the number of fuel cells in the stack.

It is clear now that the voltage and current relationship has been established how a higher load current will negatively affect the stack output voltage level. This is a factor that needs to be considered in the design of the fuel cell power generation system. Higher currents will need more cells in the stack to keep up with the power demands of the whole architecture which can in turn be offset by a larger cell active area to in turn reduce the instantaneous current density which would also have an effect on the losses.

Battery Model

The architecture for Fuel Cell vehicles is best supported when additional means of energy storage are included in the power system. In this case a generic Li-Ion battery model has been included based the works of Tremblay *et al* [16], [17]. In a first instance the authors of the aforementioned works derived a generic model considering similar dynamics for charging and discharging, but then progressed to a more detailed equation where dynamics are different for each current flow regime. Unfortunately, the later version of the model considered parameters that are not readily available (i.e. polarization resistance), so in order to move forward a

hybrid model was created which uses polarization voltage, K, instead of resistance. Then, the open circuit battery voltage, E, is calculated as follows.

Discharge Model:

$$E = E_0 - K \frac{Q_{rated}}{Q_{rated} - \int_0^t i(t) dt} + A \exp \left(-B \int_0^t i(t) dt \right) [V] \quad (10)$$

Charge Model:

$$E = E_0 - K \frac{Q_{rated}}{0.1 Q_{rated} + \int_0^t i(t) dt} + A \exp \left(-B \int_0^t i(t) dt \right) [V] \quad (11)$$

Where E_0 is the open circuit voltage, in [V], K is the polarization voltage, in [V] A is the exponential voltage component, in [V], B is charge at the end of the exponential zone of the discharge curve, in [Ah], finally “i” is the battery current, in [A]. The 0.1 factor in the denominator of second term of the charge equation is there to model degrading over use. Overall the main assumptions of the model are that internal resistance is considered constant, there is no Peukert effect, there is no sensitivity to temperature and no self-discharge is considered.

To understand and calculate the values of the different terms in Equations 10 and 11, please consider Figure 4. This figure shows how battery voltage output drops as current draw accumulates until the rated value is reached.

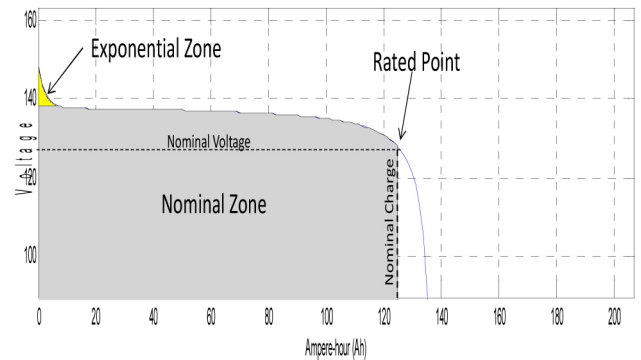


Figure 4. Typical Li-Ion battery discharge curve. Based on a 128 Vdc, 138 Ah battery pack.

All parameters for the model are deduced from discharge characteristics and assumed to be the same for charging. Based on the previous graph the following estimations have been made in order to calculate the different parameters of Equations 10 and 11.

$$\text{Nominal current} \quad I_{nom} = \frac{0.43}{1hr} Q_{rated} \quad [A] \quad (12)$$

$$\text{Nominal charge} \quad Q_{nom} = 0.904 Q_{rated} \quad [Ah] \quad (13)$$

Exponential zone charge

$$Q_{exp} = 0.0491 Q_{rated} \quad [\text{Ah}] \quad (14)$$

Fully charged voltage

$$E_{full} = 1.21 E_{nom} \quad [\text{V}] \quad (15)$$

Exponential zone voltage

$$E_{exp} = 1.08 E_{nom} \quad [\text{V}] \quad (16)$$

Voltage drop along exponential zone

$$A = E_{full} - E_{exp} \quad [\text{V}] \quad (17)$$

Charge at the end of the exponential zone

$$B = \frac{3}{Q_{exp}} \quad [\text{Ah}] \quad (18)$$

Polarisation Voltage, derived per assumptions from Equation 10.

$$K = \frac{(E_{full} - E_{nom} + A(\exp(-BQ_{nom}) - 1))(Q_{rated} - Q_{nom})}{Q_{nom}} [\text{V}] \quad (19)$$

Voltage Constant,

$$E_0 = E_{full} + K + Ri - A \quad [\text{V}] \quad (20)$$

Parameters Nominal voltage, V_{nom} , Internal resistance, R , and Rated capacity, Q_{rated} , are inputs from manufacturer data. The battery current “ i ” is calculated in the power bus section of the model later on. Figure 5 shows the circuit diagram for Equation 21.

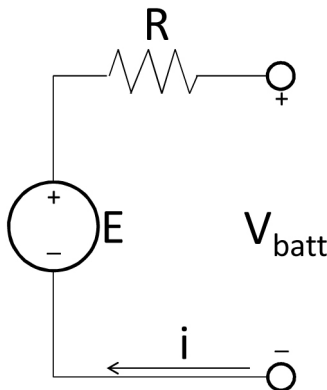


Figure 5. Battery model electrical circuit diagram

From the electrical circuit the equation for the total battery voltage, V_{batt} , can be derived.

$$V_{batt} = E + Ri \quad [\text{V}] \quad (21)$$

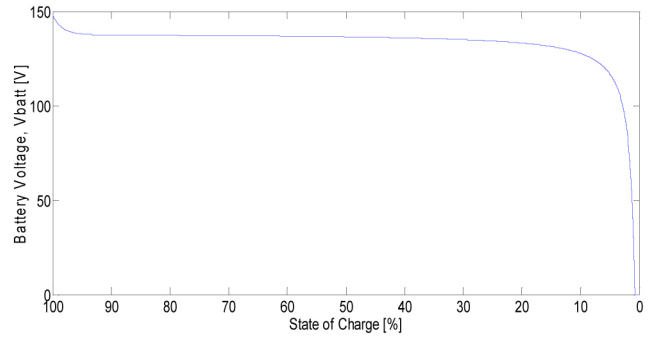


Figure 6. Discharge curve produced by battery model.

The above figure shows the performance of the battery model. This plot was produced by running the model with 128V and 138 Ah nominal parameters with an internal resistance of 9.27mΩ. The discharge current was 138 A.

Ultracapacitor Model

The final element of the power supply system is the ultracapacitor. This type of component provides a fast response not possible by the battery or fuel cell due to their chemical and gas flow dynamics. Ultracapacitors are well suited for fast transient responses and can cope much better than batteries in terms of charge cycling.

To better capture the behaviour their behaviour in this case the capacitor has been modelled as an RC series branch in order to account for its Equivalent Series Resistance (R_{ESR}). From first principles the following transfer function can be derived:

$$V_{cap}(s) = i(s) \frac{R_{ESR}}{C_{eq}s} \quad [\text{V}] \quad (22)$$

C_{eq} is the equivalent capacitance of the bank. In this architecture the bus bar voltage is 500 VDC and the chosen capacitors have a 125 VDC rating. Therefore an array of four capacitors connected in series is considered in order to match the bus' voltage.

The proposed control system needs to be able to calculate the State-Of-Charge (SOC) of the capacitor. Capacitor energy can be used, so from first principles it is computed as follows:

$$E_{cap} = \frac{1}{2} C_{eq} V_{cap}^2 \quad [\text{J}] \quad (23)$$

$$E_{cap.rated} = \frac{1}{2} C_{eq} V_{rated}^2 \quad [\text{J}] \quad (24)$$

$$SOC_{cap} = \frac{E_{cap}}{E_{cap.rated}} \times 100 \quad [\%] \quad (25)$$