A Fuel Cell Based Domestic Uninterruptible Power Supply

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Abstract- The design process for a fuel-cell-based inverter system for domestic use is discussed. The peculiar characteristics of the fuel cell stack energy source require the use of a battery for buffering. The fuel cell characteristics and the battery requirements for this application are discussed. A large number of different possible solutions are examined. The proposed solution uses an active filter and a battery to compensate for the slow dynamics of the fuel cell.

I. Introduction

This paper describes our participation in a student competition called Future Energy Challenge [1]. The competition is for the design of a fuel-cell-based split-phase inverter for domestic use. Fuel cells are emerging as a viable solution for remote generation, i.e., power generation in locations not reached by the power grid, backup generation and for distributed generation. As their use spreads, price is steadily decreasing, making them more and more attractive. The residential market (2 - 10kW range), which accounts for approximately 40% of the total electric power consumption in the United States, is a potential big market for fuel cell systems. In order to accelerate fuel cell penetration in this market, inexpensive, reliable power interface systems are needed. In particular the interface systems must account for the slow dynamics of fuel cells. The objectives of the competition are to design elegant, manufacturable systems that would reduce the costs of commercial interface systems by at least 50% to below $50 per kilowatt and, thereby, accelerate the deployment of distributed generation systems in homes and buildings. Another goal of the competition is to promote undergraduate education and foster practical learning through the development of innovative team-based engineering solutions to complex technical problems.

In the first section the system requirements are discussed. In the second section a brief overview of fuel cell operation is followed by a discussion of the characteristics of the fuel cell system used in the competition. In particular the slow dynamics of the fuel cell in comparison to the electrical system force the use of a battery for buffering. Once all the requirements are defined, the process of system topology selection is described and different possible topologies are discussed. Finally a topology is selected that includes an active filter in parallel with the input to compensate for the fuel cell slow dynamics. Some details of the implementation are described, in particular the active filter control strategy. Some simulation results are given.

II. System Requirements

The competition calls for a paper design at a 10kW power level and a prototype design at 1.5kW to demonstrate the feasibility and performance of the proposed solution. Table I shows the system specifications. Notice the aggressive specifications in terms of efficiency, THD, cost, size and weight. The output voltage is 120V/240V split single-phase voltage, which is common for residential utility in the United States. The specifications call for a standalone unit, not connected to the utility grid.

TABLE I
System Salient Specifications

Input source	Fuel cell, 42 - 72V (48V nominal)
Output power capability	10kW continuous for paper design, 1.5kW for prototype
Phase(s)	split single phase
Output voltage	120V / 240V nominal, 60Hz
Overall efficiency	>90% for resistive load
Total harmonic distortion	less than 5% when supplying a standard nonlinear test load
EMI	Able to meet FCC Class A (industrial)
Manufacturing cost	No more than $500 when scaled to a 10kW design in high volume production
Complete package size	A convenient shape with volume less than 50 L
Complete package weight	Weight less than 32kg for a 10kW unit, not including energy sources or batteries
Battery	Teams may elect to use a lead-acid battery set, with total nominal rating below 500Wh. If a battery is used, charge management must be provided

III. A Brief Overview of Fuel Cells

One of the challenges of the project is that the system must be compatible with the characteristics of the fuel cell power source. In order to understand the issues involved, some basic understanding of fuel cell operation may be useful.

For a simple introduction to fuel cells, refer to [2-3]. Fuel cells and batteries are electrochemical energy conversion devices that convert chemical energy directly to electrical energy. Due to this direct conversion, they have the potential for high conversion efficiency. Other energy conversion systems, such as internal combustion engines and conventional utility power plants, perform a similar transformation from chemical energy stored in the fossile fuels to electrical energy, but they do so through intermediate steps: they transform chemical energy into thermal energy, then thermal energy into mechanical energy and finally mechanical energy into electrical energy. Since they transform thermal energy into mechanical energy, they are subject to the Carnot Cycle efficiency limit

$$\eta_{max} = \frac{T_1 - T_2}{T_1}$$

where T_1 and T_2 are the high temperature and the low temperature of the Carnot Cycle in Kelvin respectively. Fuel cells on the other hand are not subject to the Carnot Cycle efficiency limit.

Different types of fuel cells are categorized according to the electrolyte used: Proton-Exchange-Membrane (PEM) (also called Polymer Electrolyte Membrane) fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells. Optimal operation of these fuel cell types happens at vastly different temperatures. For example, for molten carbonate and solid oxide fuel cells the operating temperature is 600 - 1000°C. In the following we will focus on PEM fuel cells, which operate at 60-100°C. The material properties of polymer electrolyte membranes have made present-day fuel cells possible. This membrane, when hydrated by absorbing water, becomes a good conductor of protons, but it does not conduct electrons. The fuel cell makes use of these unusual properties of the membrane. The PEM fuel cell produces electricity, water and heat using supplied hydrogen and the oxygen contained in air. A fuel cell consists of a thin polymer electrolyte membrane separating the anode from the cathode.

On the anode side hydrogen flows and on the cathode side oxygen (air) flows. The hydrogen gas with the help of a platinum catalyst separates into electrons and protons (hydrogen ions). This is the oxidation half reaction. The hydrogen ions pass through the membrane to the cathode side and, again with the help of a platinum catalyst, combine with oxygen and electrons, producing water. This is the reduction half reaction. The electrons, which cannot pass through the membrane, flow from the anode to the cathode through the external electrical circuit, delivering power to the electrical circuit in the process. This is how chemical power is transformed into electrical power in a fuel cell. The V-I characteristic of a single cell is shown in Fig. 1. The theoretical EMF of a cell at zero current and 80°C and 1 atm gas pressure is V_0 = 1.16V. As the current density increases, the actual voltage at the electrical terminals drops. The fuel cell efficiency is given by

$$\eta = \frac{V \cdot I}{V_0 \cdot I} = \frac{V}{V_0}$$

and is simply equal to the ratio of the terminal voltage to the theoretical EMF for the cell. The energy lost is transformed into heat. In the V-I characteristic three separate regions can be identified:

- Region of activation polarization. For very small currents the voltage drops rapidly as current increases.
- Region of ohmic polarization. In this region the voltage decreases linearly with current. Clearly a Thevenin equivalent circuit with a resistance equal to the slope of the curve is appropriate in this region. This is the normal operating region of a fuel cell.
- Region of transportation polarization. When current exceeds a certain value, the voltage collapses rapidly. This "knee" of the V-I characteristic represents the upper limit of safe operation for the cell. Given the significant losses, prolonged operation in this region may damage the fuel cell.

In conclusion, the voltage from one single cell is approximately 0.7V. As in batteries, cells are stacked in series to provide higher voltages. A large number of series cells leads to reduced reliability, since, if a single cell fails open, the entire stack stops functioning because the current flow is interrupted.

A fuel cell can be damaged by a reverse current flow. Therefore current backfeed into the fuel cell must be avoided.

A fuel cell system consists of a fuel cell stack plus a number of auxiliary systems needed for its operation, such as an air compressor to provide pressurized air flow through the cathode, a water-cooling system to remove heat from the stack, valves to control the hydrogen flow through the anode, humidifiers to add moisture to the gases, and so on. Notice that operation of the auxiliary systems involves power losses as well. In particular, the air compressor power consumption is significant.

Fuel cells need fuel to operate. While air is plentiful, a hydrogen source is needed. The simplest solution, a hydrogen tank, presents some problems: danger of explosion, large weight and volume of the tank, because hydrogen is not very compressible. Another solution is to produce the hydrogen as needed, for example by reforming methanol. Fuel cells with methanol reformers are being tested for hybrid car applications.

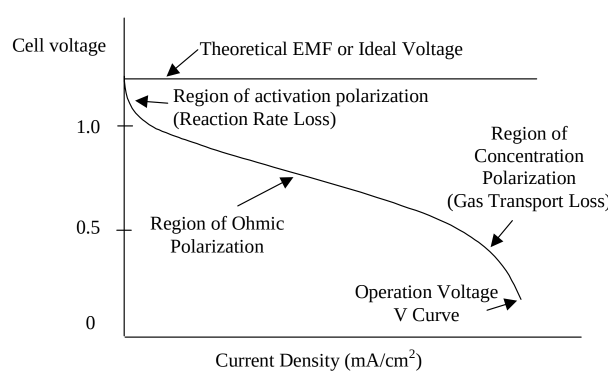

Figure 1. V-I characteristic of a cell.

Another choice to be made is whether to have an open system for the hydrogen or a closed system with a purge valve that opens periodically to remove exhaust gases. The first solution is wasteful because the hydrogen that has not reacted in the fuel cell is lost, while the second one causes a temporary pressure drop when the purge valve is opened, which in turn causes a temporary drop of the voltage generated by the fuel cell.

Fuel cell operation is a delicate balance of gas flows and chemical reaction rates. Sudden electrical load changes can cause problems. For example, a sudden increase in electrical load may cause the membrane to "flood". The water produced at the cathode is not removed fast enough and not enough oxygen is able to reach the cathode catalyst sites through the excess liquid water.

One important conclusion from the above is the following: for efficient fuel cell operation the fuel cell operating point should be adjusted as a function of electrical load. By doing this it is possible to: reduce the power losses in the air compressor at light loads, reduce losses of hydrogen in an open fuel cell system, and adjust the reformer rate of operation depending on hydrogen utilization. Since these adjustments involve mechanical systems, the response time of the fuel cell to varying electrical loads is slow. This slow dynamic response is one of the most significant challenges in the competition.

IV. FUEL CELL SOURCE CHARACTERISTICS

The fuel cell used for the competition is of the open system type, i.e., the hydrogen not reacting is lost. The static characteristic of the fuel cell stack for different values of hydrogen flow is shown in Fig. 2 [4]. Notice that when the hydrogen utilization approaches 100%, the fuel cell voltage reaches the knee point and collapses. Notice how the knee point moves to higher current levels when the hydrogen flow is higher. Once again, adjusting the hydrogen flow is a slow process; therefore the fuel cell can adjust only slowly to increased power demands.

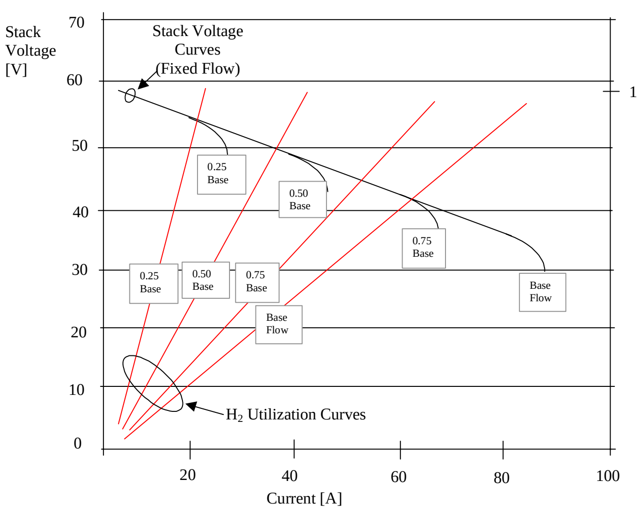

Figure 2. Static characteristics of the fuel cell stack for various levels of hydrogen flow.

The main fuel cell characteristics are shown in Table II. These characteristics refer to the fuel cell source used to test the 1.5kW prototype. Besides the rather large fuel cell voltage range, notice the slow dynamics of the fuel cell: at initial startup it takes 90s for the fuel cell to reach steady state; thereafter whenever there is a change in electric power demand it takes 60s for the fuel flow rates to adjust and for the fuel cell to reach a new steady state. As explained above, operation at knee of the fuel cell V-I characteristic is potentially harmful to the fuel cell. The fuel cell protection shuts down the fuel cell under these circumstances. On the other hand, if the power demand transient is slow (tens of seconds) the fuel flow controller of the fuel cell has time to adjust the fuel flow to accommodate the increased power demand. Notice that there is also a rather strict specification on low-frequency current ripple. The reason for this is that low frequency current ripple is undesirable, because the hydrogen flow has to be adjusted to peak current demand and this is wasteful. A simplified equivalent circuit of the fuel cell used for the competition is a Thevenin equivalent source with a Thevenin voltage of approximately 55V and a Thevenin resistance of 0.38W. The fuel cell controls adjust the fuel flow (and move the position of the knee in the V-I characteristic) with a single pole with a time constant of 20s. This is an approximate model but it represents the first-order behaviour of the fuel cell system.

The mismatch between fuel cell time constant and the typical electrical time constants of a domestic power system clearly points to the need of buffer energy storage in the interface system. The solution suggested for the competition is to use batteries for this purpose.

TABLE II
FUEL CELL CHARACTERISTICS

Fuel cell: voltage	48 V nominal (42 V to 72 V range)
Fuel cell: power	1.8 kW or less, continuous output
Fuel cell: transients	Initial Startup: 90 s to initial steady state. Electric power transients: 60 s to new steady state (from idle and above)
Current backfeed into fuel cell	not allowed
Low frequency current ripple	At 60 - 120Hz 10% maximum, lower ripple desirable
High frequency current ripple	Above 10kHz up to 60% ripple acceptable
Steady-state maximum current	55A
Inrush current	at startup up to 100A pulse lasting not more than 5ms

The competition also specified the interface signals between the inverter system and the fuel cell as in Table III. The fuel cell has a digital output indicating whether the fuel cell is operable or not. If the fuel cell trips, the inverter should shut down. The inverter has a digital output to the fuel cell indicating whether it is on or off. Then there are two analog signals to coordinate fuel cell available power with the power needed by the inverter system. The fuel cell sends to the inverter a signal indicating the available power. This is the maximum power that the inverter should extract from the fuel cell at a given time. The inverter sends to a fuel cell a power demand signal asking for the power it needs. The fuel cell controls adjust the available power to meet the demand. The adjustment process has a time constant of approximately 20s. If there is a mismatch, the battery should be used to provide the extra power needed by the inverter.

TABLE III
INTERFACE CONTROL SIGNALS

Fuel cell digital output signal	high=Fuel Cell Operable/Ready, low=Fuel Cell Trip/Not Ready
Inverter digital output signal	high=Inverter On, low=Inverter Off
Fuel cell analog output signal	0 to 5V linear scale indicating the maximum power available at a given moment
Inverter analog output signal	0 to 5V linear scale to request a power level from the fuel cell. Full scale is 1800W

V. ENERGY STORAGE REQUIREMENTS

The energy storage requirements of the system also provide some intriguing challenges. Once the system is operational, (after the 90 s start up) the energy storage has two specific tasks. Firstly energy storage must support increases or decreases in power demand until the fuel cell output can be adjusted to meet the new demand values. Let us assume that the fuel cell power output can be changed linearly with time. The problem specification states that the fuel cell takes 60 seconds to achieve the new demanded value.

For the 1.5 kW system, this implies an energy storage of 60s*0.5*1.5 kW = 45 kJ, and for the 10 kW system, 300 kJ. These are quite low numbers, converting to 12.5 Wh and ~85 Wh respectively, well below the battery limit specified for the low power prototype system of 500 Wh.

The second requirement is to support the fluctuating power demand within the 60-cycle period. The particular output specifications mean that at full load, instantaneous output power changes from 0 – 3 kW (or 0 to 20 kW) sinusoidally with a period of 8.33 ms. Supporting this variation requires a short term storage of 4J, or 26.5 J.

The rate at which power is required is a significant parameter used in choosing the correct technology for storage, and whilst electrostatic capacitors are a clear choice for the second requirement [5], the first is a little more obscure. No available technology is an ideal match, however lead acid technology does provide the closest match of specific power and specific energy, and also represents the most economical technology [6].

At the expected 35 Wh/kg for lead acid, only 350 g of battery is required, however for the power rating of typically 1 kW, using the common figure of 200W/kg, 5 kg is required, providing a total energy storage of 175 Wh. A conservative design would then use 5 kg of lead acid, allowing for the depth of discharge to be always less than 10%, resulting in very long life.

VI. CHOICE OF TOPOLOGY

The inverter system to be built is schematically represented in Fig. 3. In order to choose the system topology, we had to make a number of choices, represented by the decision tree shown in Fig. 4. The decision process is now discussed. Alternative solutions are also examined to highlight the trade-offs involved in the topology selection. Most of these solutions had been considered by the authors and were also suggested by other participants in the competition [7]. This high-level design process was very educational for the students involved in it.

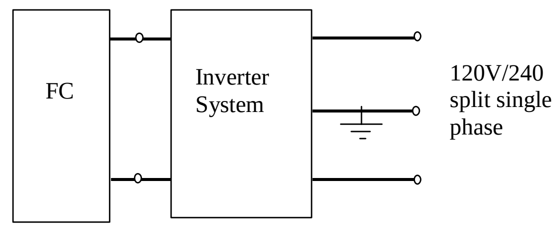

Figure 3. The inverter system.

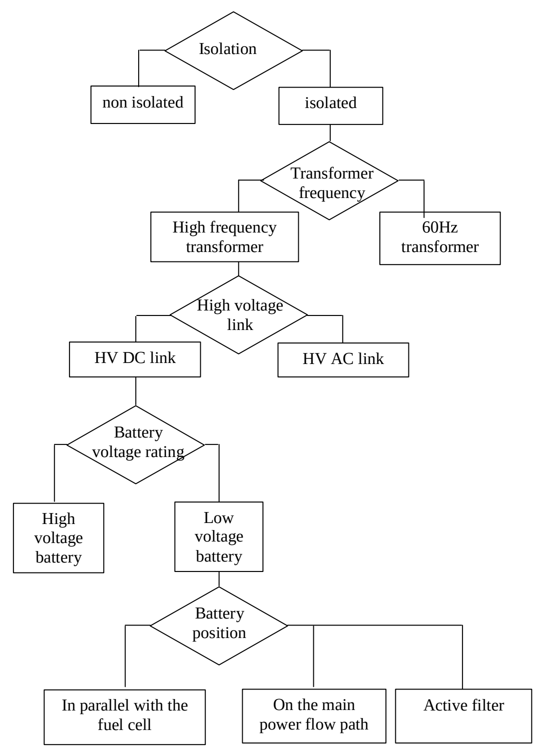

Figure 4. Decision tree for the design.

A few preliminary observations are appropriate at this point. The 48Vdc fuel cell voltage requires a system capable of boosting the voltage in order to obtain the 120V/240V split single phase at the output. The inverter design would have been easier with a higher fuel cell voltage, for example 400Vdc. On the other hand, high-voltage fuel cells are built by stacking a large number of unit cells and this adds to the cost and reduces fuel cell stack reliability. The competition organizers chose the fuel cell voltage based on a cost/performance tradeoff between the energy supply system and the output power processing.

A. Isolation

The competition rules do not require isolation between the fuel cell source and the output. Additionally, the fuel cell used for testing was floating, allowing a wider range of non-isolated solutions. Advantages of a non-isolated system are simplicity and cost savings. A disadvantage is that in practice isolation may be required for safety reasons. Another complication comes from the fact that a dual output is required, with the two outputs referred to a common point. Another disadvantage is that a significant voltage step-up is needed from 48V to at least $240\sqrt{2} = 340V$, which is required for the 120V/240V output. This means voltage amplification by a factor of seven. Achieving such a large voltage transformation without a transformer causes very high current and voltage stresses on the semiconductor devices used for the step-up converter. So a transformer may be desirable just to help achieve the voltage step-up.

Our team selected an isolated topology. However, two teams used non-isolated topologies. One of the topologies is shown in Fig. 5. A dc-dc non-isolated step-up stage uses a Cuk converter to create a high voltage DC intermediate voltage. This voltage is the input to a three-leg inverter, which generates the split single-phase output voltage. The three-leg inverter is needed to generate the three-wire output. The second topology is shown in Figure 6. The first stage is a step-up converter as in the previous case. In this case a split intermediate voltage is obtained by putting two high voltage batteries in series at the output of the boost converter. This allows using a dual half-bridge inverter to create the split single-phase output voltage. Some form of charge equalization may be needed for the two batteries. Another topology that we examined is the boost inverter [8]. It is an interesting topology, but we felt that the large voltage step-up needed for our application would have caused problems.

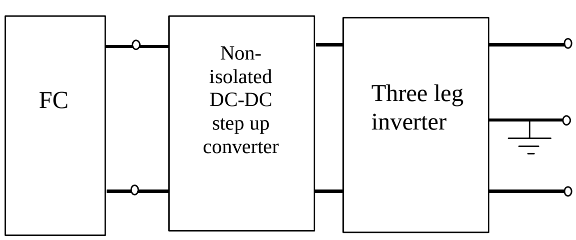

Figure 5. A non-isolated topology.

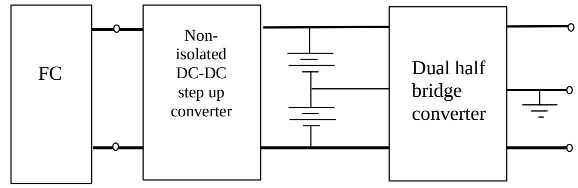

Figure 6. A second non-isolated topology.

B. Transformer Frequency

Having decided to use an isolated topology, the next design choice is whether to use a 60Hz transformer or a high-frequency transformer. The 60Hz transformer allows some very simple solutions. One of the teams examined the solution shown in Fig. 7. It consists of a full bridge converter driving a dual output 60 Hz step-up transformer. The output filter is on the high-voltage side. This solution appears simple and robust and provides boosting and inversion with a minimum number of components. The problem is that a 10kW 60 Hz transformer has a weight that exceeds the target system weight specified in Table I. For this reason the solution was not viable.

Therefore, the only option for the design is to use a high-frequency transformer.

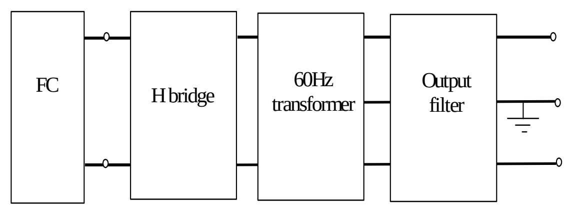

Figure 7. Topology with 60Hz transformer.

C. High Voltage Link: DC or AC?

The topology must generate a high-voltage AC output. Two basic functions are needed, voltage step-up and inversion. This can be achieved by having an intermediate high-voltage DC link or a high-voltage AC link. A different way to phrase this choice is whether the step-up transformer is part of a DC-DC step-up converter or part of the output inverter. Most of the schools opted for a high-voltage DC link and only two teams used an AC link solution. One of the schools adopted the solution shown in Fig. 8. The topology is a high frequency series resonant bridge converter operating under discrete pulse modulation. Since the resonant converter creates zero current switching conditions, SCRs can be used. A high frequency transformer is used to boost the voltage, creating the high voltage AC link. This is followed by a cycloconverter stage. This stage is a matrix converter that during the positive phase of the 60Hz waveform passes to the output only the positive pulses and blocks the negative pulses, and during the negative phase does the opposite. A 60Hz bandpass filter interfaces this stage with the grid at the output. It is interesting to notice that this topology uses exclusively SCRs, inexpensive and rugged devices. Another AC link solution is shown in Fig. 9. This solution has a boost converter at the input that acts as a buffer between the fuel cell and the battery. From the battery a full bridge creates an AC voltage, which is stepped up by the isolation transformer. A cycloconverter creates the 60Hz output voltage.

The DC link solution is shown in Fig. 10. The isolated DC-DC converter creates a split high voltage DC link, which is followed by a dual half-bridge inverter. Variations of this approach are possible. For the output stage full-bridge inverters may be used. For the input stage different isolated DC-DC converter topologies are possible, such as full bridge and push-pull. This is the solution that we selected. In particular, we adopted a DC-DC isolated phase-shifted full bridge topology, which is well suited both for the 1.5kW prototype and for the 10kW system. This converter generates a dual ±200V DC output voltage.

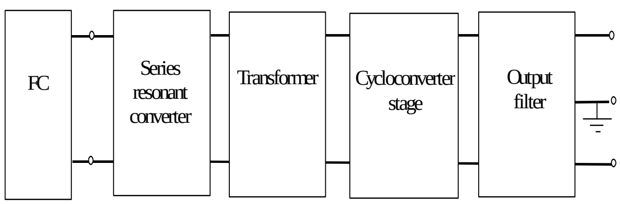

Figure 8. Topology with high-voltage AC link.

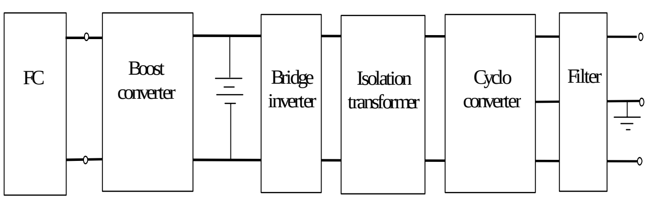

Figure 9. Another topology with high-voltage AC link.

D. Battery voltage rating

As explained in the section on fuel cells, their slow dynamics requires buffering in the interface system. Except for one team, which advocated the use of ultracapacitors in parallel with the fuel cell, all other teams used batteries for buffering. Except for the potential high cost of ultracapacitors, the solution has merit, because the fuel cell voltage droops significantly under load, allowing significant energy to be extracted from the ultracapacitors. Looking at battery solutions, a first choice is whether to use low voltage or high voltage batteries. The high-voltage option appears attractive: two high-voltage batteries may be placed in parallel with the two DC link capacitors of Fig. 10. In that case they would naturally provide buffering between the fuel cell and the output. From the control point of view, the output inverter stage can have fast dynamics to correct against load transients, whereas the isolated DC-DC converter stage can be operated so that the current taken from the fuel cell does not exceed the maximum available fuel cell current. The status of charge of the batteries determines the power request from the inverter system to the fuel cell, so that the fuel cell output slowly adjusts to load variations.

However, the use of 200V batteries presents serious charge equalization problems, see references [9-11]. Some type of active battery balancing scheme is necessary for system reliability. For this reason in our design a low voltage battery is chosen.

Further 175 Wh (the energy storage calculated in the Energy Storage Requirements section) over 400 volts results in cells of 0.5 Ah rating. These are very tiny cells in terms of currently available technology. A typical lead acid D cell, the smallest generally available, has a rating of 2.4 Ah.

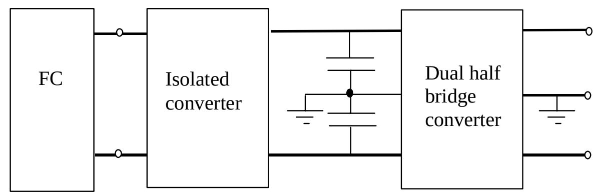

Figure 10. Topology with high-voltage DC link.

E. Low-voltage battery position

The final decision is the low-voltage battery position. One possibility is to place the battery directly in parallel with the fuel cell as in Fig. 11. Since current backfeed into the fuel cell must be avoided, a diode may be placed in series with the fuel cell. This solution presents some problems. First of all, the current taken from the fuel cell is not directly controlled, because the battery is connected directly to the fuel cell. Under dynamic conditions, an excessive current may be taken from the fuel cell, causing its protection to trip. A second problem is that the fuel cell voltage is not very constant. As explained above, the static characteristics of the fuel cell V-I characteristics have a slope that corresponds to an equivalent series resistance of about 0.38Ω. There is a serious mismatch between the effective resistance of the lead acid battery and the fuel cell, which operates over a very broad voltage band. The internal resistance of the battery determines its terminal voltage variation with current. Note that resulting from the above discussion, the battery can be considered to be always in its fully charged state, so its impedance is at its lowest, and its voltage is very stable. Further the discussion above on power and energy ratings leads to a choice of batteries with the lowest possible internal resistances. A typical lead acid D cell has a resistance of 5 milliohms. At the 48 V level, the D cell is very close the to the required size for the prototype.

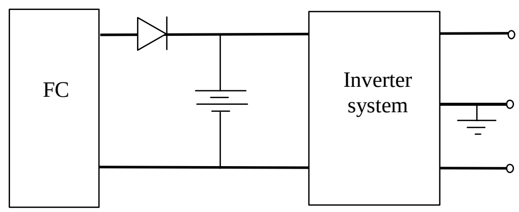

Figure 11. Battery placed in parallel with the fuel cell.

A second possibility is to place a buffer DC-DC converter between the fuel cell and the battery. The battery voltage then represents the input voltage for the following converter stage. An example of this solution is given in Fig. 9. The boost converter precisely controls the current taken from the fuel cell ensuring that the maximum allowable current is not exceeded.

A third possibility is to place the battery outside of the main power flow path and to interface it with the fuel cell through an active filter (a bidirectional DC-DC converter). This active filter has a dual function: when the output requires more power than the fuel cell can provide at that moment, the converter supplies the excess power taking it from the battery; otherwise, the active filter keeps the battery charged. This is the solution that we adopted. Advantages of this solution are that the current taken from the fuel cell is precisely controlled. Another advantage with respect to the solution of Fig. 9 is that we incur the additional losses of the active filter stage only when there is a load increase. Under steady state conditions the active filter is idle unless it is charging the battery. In a certain sense the battery and the active filter correct the slow dynamics problem of the fuel cell, so that the combination of these three elements becomes a power source with fast dynamics. This is shown in Fig. 12. What type of load is connected to the source is to a large extent irrelevant. Furthermore, an optimal battery voltage can now be chosen. From the discussion above of the technology, available sizes, the difficulty of equalizing large strings etc, it is clear that a low voltage, e.g. 24 V will be much more suitable. There is a large number of gel cell fully sealed lead acid batteries in the market at 12 V, 8 Ah, 2.5 kg which would be near ideal for this purpose. For the 10 kW system, this would become 24V at 50 Ah, again very common items.

VII. Discussion of Proposed Solution

A detailed block diagram of the proposed solution is shown in Fig. 13 (at the end of paper). There are three power converter stages:

1. Active filter (Bi-directional converter).
2. DC-DC Isolated Bridge converter.
3. Half Bridge Inverter.

Analog controllers are used for the three stages. A low-cost microprocessor is used as a supervisory controller coordinating protections and interfacing with the fuel cell control.

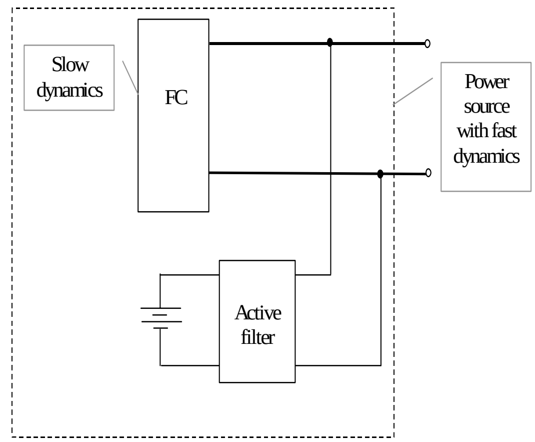

Figure 12. The fuel cell/active filter combination is equivalent to a source with fast dynamics.

These three subsystems are now briefly discussed.

A. Active filter

The active filter is a non-isolated bidirectional DC-DC converter. The choice of a 24V battery allows the use of a Buck converter. Given the low-voltage high-current application, MOSFETs are used as active devices. The converter uses a hysteretic current controller. The reference for the hysteretic controller is provided by the microprocessor as needed to perform the following tasks:

- Recharge the battery (the fuel cell provides the energy to charge the battery while at the same time supplying the load).
- Supply the load during transient conditions, when there is a mismatch between power available from the fuel cell and power requested by the load.

The microprocessor selects between two possible signals to send to the hysteretic controller:

- i_{ref1}. This is the current needed to recharge the battery. This signal is selected when there is no mismatch between fuel cell and load.
- i_{ref2}. This is the current needed to compensate for the mismatch between fuel cell and load. This signal is obtained by calculating the difference between available current and current effectively taken from the fuel cell. This error signal goes through a compensator to create i_{ref2}.

The microprocessor also sends to the fuel cell the power demand signal based on the power taken by the load and the state of charge of the battery.

An interesting possibility is to use the active filter to compensate for low frequency power ripple at the fuel cell. For example the 120Hz current ripple due to the single-phase inverters could be compensated. In our design the capacitors at the high voltage DC link were designed to absorb most of this ripple.

B. Full bridge isolated converter

This is a phase-shifted full bridge isolated converter with dual outputs. It generates the dual high voltage DC voltage needed by the inverter. A standard control chip is used. The controlled quantity is the output voltage.

C. Half-bridge inverters

The half-bridge inverters provide the split single-phase AC voltage at the output. They are controlled in sliding mode [12].

VIII. Simulation Results

The subsystems have been simulated and some results are given. Fig. 14 shows results of the simulation of the output inverter under sliding mode control. After an initial transient the output voltage is a good-quality sine wave. For the isolated DC-DC converter, Fig. 15 shows the transformer current. For the active filter Fig. 16 shows how the active filter current accurately follows the reference.

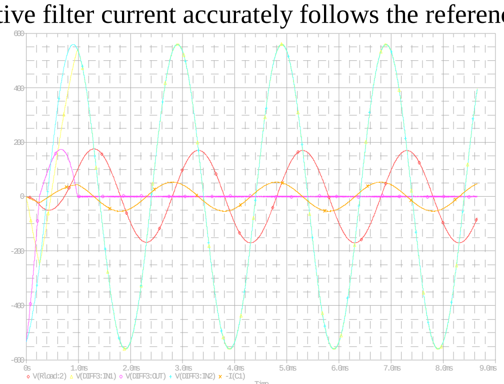

Figure 14: the blue line is the sliding mode surface, the yellow line is the actual control variable of the sliding mode, which are identical after an initial transient. The red line is the output voltage and the gold line is the output capacitor current (proportional to the derivative of the output voltage).

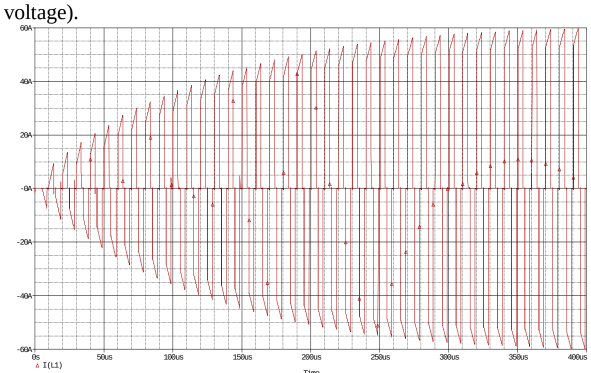

Figure 15. Current into the transformer primary.

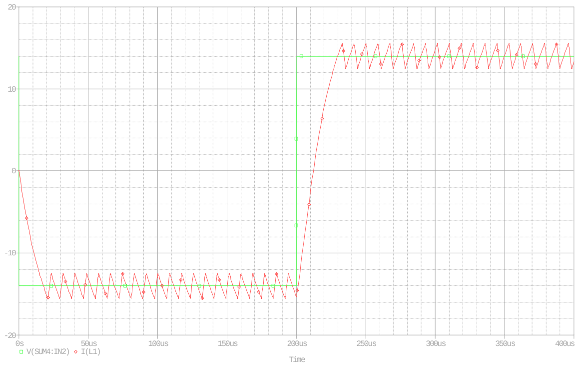

Figure 16: the reference current and the inductor current of the active filter.

IX. Conclusions

The design process for a fuel-cell-based inverter system has been discussed. The design was for an undergraduate student competition called Future Energy Challenge. A large number of possible solutions have been examined. The proposed solution uses an active filter and a battery to compensate for the slow dynamics of the fuel cell.

X. References

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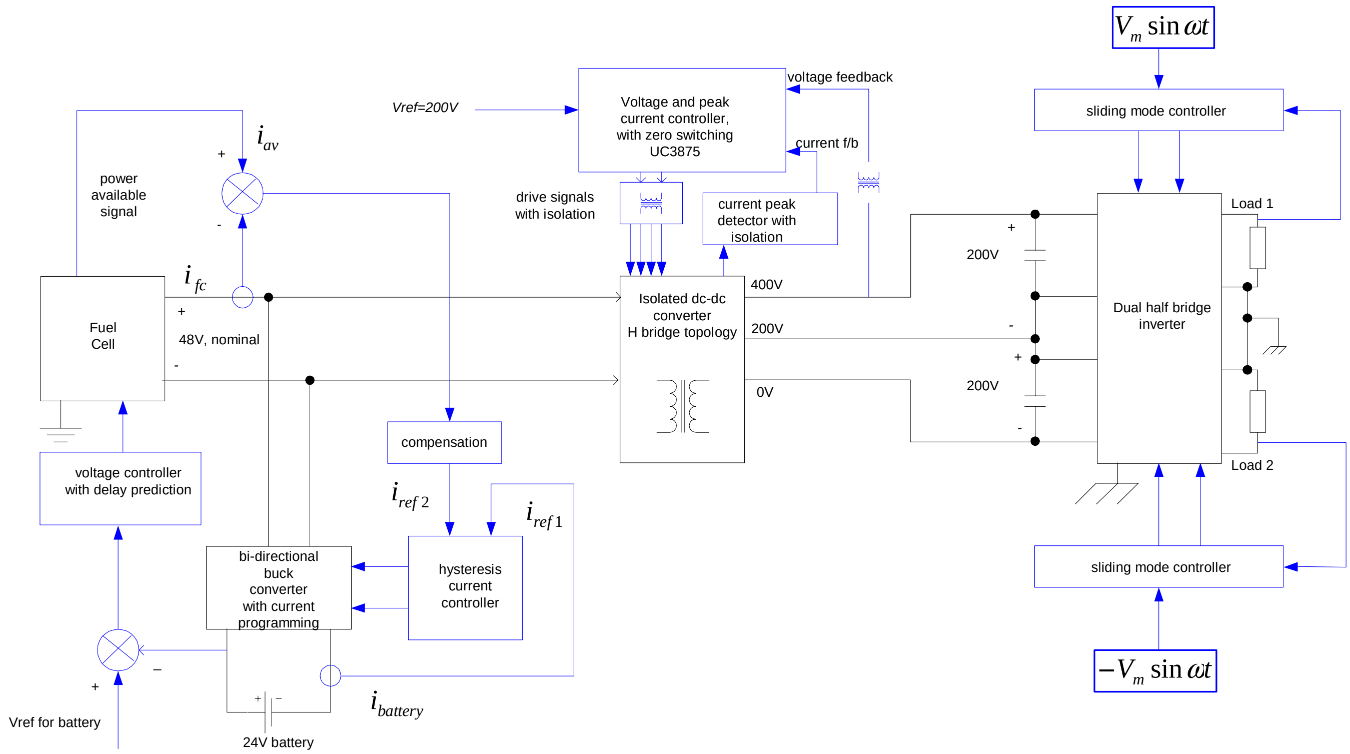

Figure 13. Detailed block diagram of the proposed inverter system.