EE 590F Special Topic Final Report

Simulating Fuel Cell to Residential Power Converters

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May 9, 2003

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1. Abstract

In this report Dymola/Modelica simulations of fuel cell energy converters are discussed. More specifically, a converter that satisfies the Future Energy Challenge (FEC) Topic (a) constraints and objectives is simulated. This report is intended to give a future Iowa State FEC team a head start on how to simulate this sort of converter. How the fuel cell, dc-dc push pull stage and inverter stages should be modeled are the primary focuses of discussion.

2. Introduction

a. Need for fuel cell converters

As the need for renewable energy grows the hurdles ahead are studied more carefully, and thus the problem areas have become more evident. One of these areas is the conversion of fuel cell energy into residential energy. The converters that perform this task are a considerable expense and several U.S. government agencies and departments (including the DOE) have realized this and put together an intercollegiate challenge called the Future Energy Challenge (FEC) that partially addresses this concern. [1]

b. FEC constraints

Although the design criteria for topic (a) of FEC are continually updated and changed every year, table 1 gives a general idea about the constraints of this challenge. Other constraints, not included below, are size/weight of the final product, communication specifications, lifetime, temperature ranges, cooling and safety, among others. For more detailed information visit the FEC web site.[2]

Design Item	*Minimum* **Target Requirement 10 kW System**
Manufacturing cost	Less than US$40/kW for the 10 kW design in high-volume production.
Output power capability – nominal Output power capability – overload	5 kW continuous, total (5 kW continuous @ displacement factor 0.7, leading or lagging, max. from each phase) 10 kW overload for 1 minute (half of input from fuel cell and half from battery[1] supply) @ d.f. 0.7 (lead or lag). 5 kW @ 0.7 d.f. max. from each phase.
Output voltage	120 V/240 V nominal (split-phase).
Output frequency	60 Hz ± 0.1 Hz.
Output voltage harmonic quality	THD < 5%
Input source	Fuel cell as defined
Maximum input current ripple	3% rms of rated current
Battery auxiliary power[1]	48 V dc nom. +10%-20%, with nominal rating of 500 Whr. .
Overall energy efficiency	>90%

Table 1: *Important constraints of the FEC Topic (a)*

c. Software constraints

The main purpose of using this software is to visually observe the pros and cons of the designs discussed and efficiently vary different parameters to draw appropriate conclusions. It should be noted, however, that some of the components used are ideal and thus yield "ideal" results instead of real. For example the transformers used in the DC-DC Push-pull Flyback stage, are ideal, and thus will yield results that in reality would burn the device. (For this specific issue refer to the UCF description of their Transformer operation under **2.2.1 Basic Circuit Operation of DC-DC stage**) [3]

d. Parts of converter

Since the standard fuel cell voltage has evolved to be 48 Volts nominal, the input voltage needs to be boosted before it can be inverted. Also since residential power requires clean sinusoidal AC Voltage appropriate inverter and filters are needed. Figure 1 shows the main stages of the converter discussed in this report.

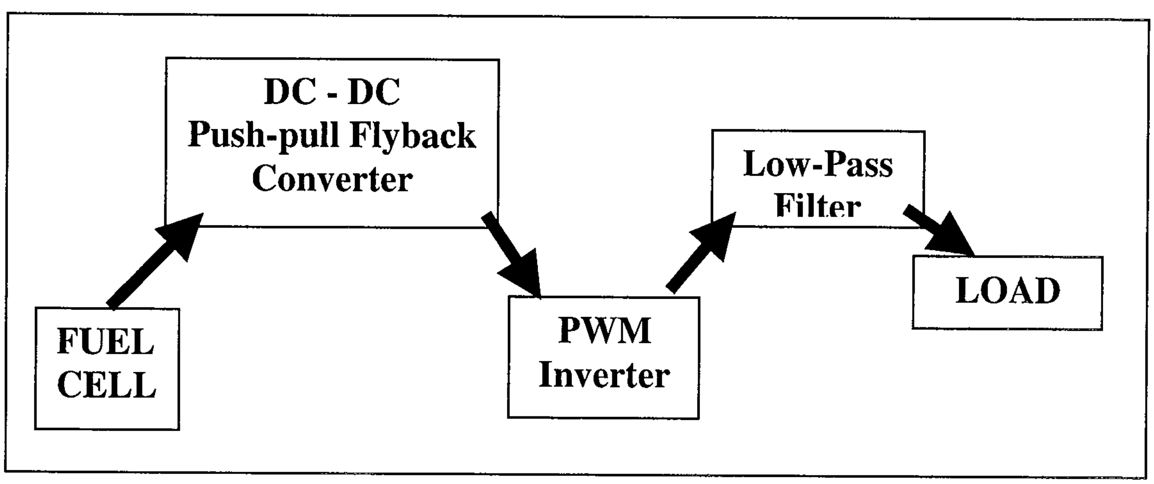

Figure 1: *Main stages of the converter*

3. Two FEC reports: TAMU and UCF

On the FEC web site there are final reports of the 2001 participants, in pdf format. [1] The simulations that were run, and are being described have used two FEC 2001 participants' final reports as benchmark papers: Texas A&M (TAMU) – winner of the 2001 Future Energy Challenge, and University of Central Florida (UCF). For the most part, their converter designs are very similar.

a. TAMU Report

This is by far the most extensive of the twelve reports on the FEC web site. As can be seen in figures 2, and 3, it has the same stages described earlier. For the TAMU final report visit:

http://www.energychallenge.org/2001Reports/TAMU.pdf (accessed May 8, 2003) [4]

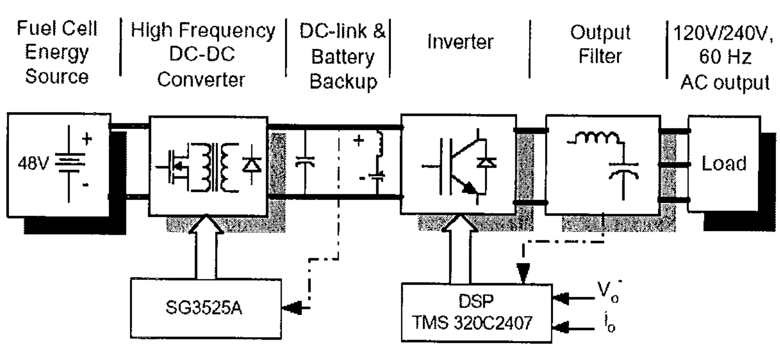

Figure 2: *Block Diagram of the TAMU Fuel Cell Inverter (from the TAMU Final Report)*

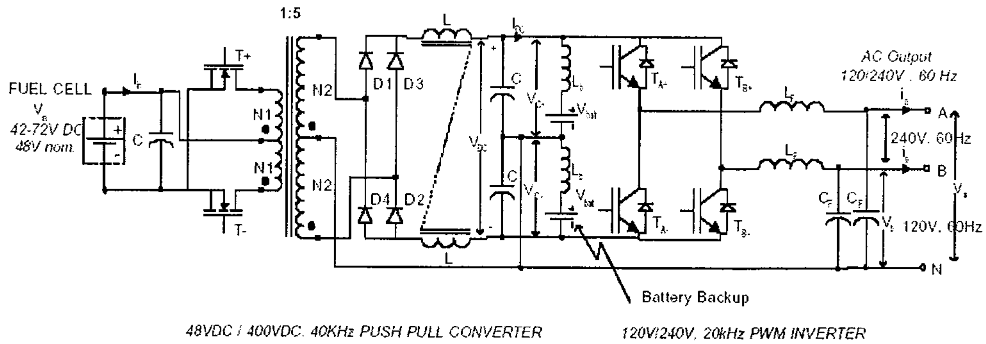

Figure 3: *Texas A&M FEC 2001 Converter Circuit (from the TAMU Final Report)*

b. UCF Report

The UCF design has slightly different parameter values, but the concept is pretty much identical. Figure 4, shows their circuit diagram.

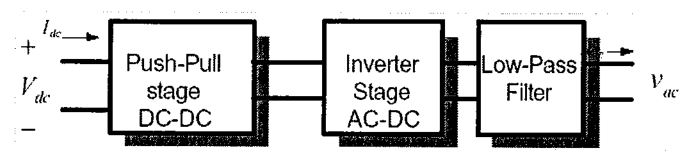

Fig 1(a): Block diagram representation of the proposed inverter system

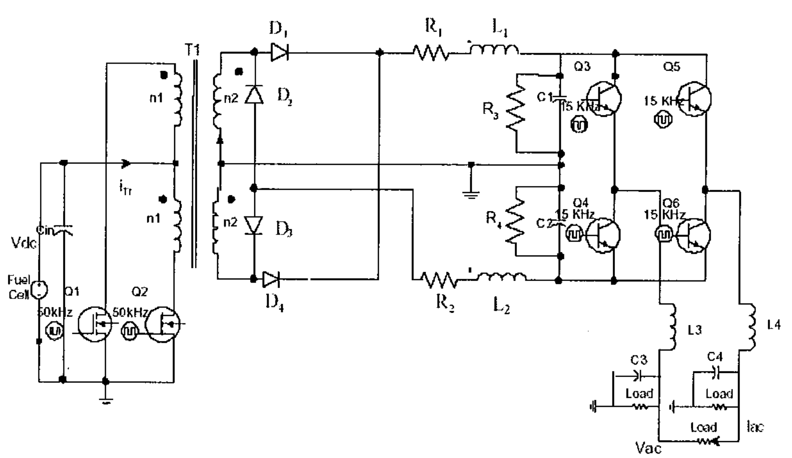

Figure 4: University of Central Florida converter circuit. (From the UCF Final Report)

4. Modeling

a. Stage by stage modeling

To understand what each of these stages does, it is helpful to isolate them and simulate them separately.

i.Modeling the fuel cell:

In the simulations run for this report the fuel cell has been modeled as a constant voltage source. This does not take into consideration: (a) the Voltage/Current density changes, and (b) the time it takes for those changes. An excellent reference to check out would be "Simulation of Fuel Cell Powered Drive Trains" (2000) by W.D. Steinmann, and P. Treffinger, which can be found at:

http://www.modelica.org/workshop2000/proceedings/Steinmann.pdf
(Visited May 4, 2003)[5]

In this paper they introduce a detailed fuel cell model (possibly more than needed for our purposes) that includes the individual fuel cell stages. Instead, a simpler model could be used by doing the following:

1. The fuel cell voltage will decay over time similar to the Voltage/Current density graph (their Figure 4) in this paper. To have a more realistic fuel cell model in Modelica this decay could be represented in a table format, using the input source "TableVoltage".

2. Every curve on that graph represents a different equation, so a better model would be to plug in data from each equation into a separate column. Using this table a relatively close model of the fuel cells can be achieved. (This is a purely mathematical model, which is a representation of the data to be obtained, instead of a model that accounts for the chemistry inside the fuel cell. Therefore it depends on the quality of the data found.)
3. Since the type of fuel cell used in the FEC, changes over the years, the according data needs to be found for the specific type of fuel cell used in the challenge.

Another paper is "Modeling of liquid Direct Methanol Fuel Cells", by Siebke, Meier, Eigenberger, and Fischer, which can be found online at:

http://pcvt12.icvt.uni-stuttgart.de/meier/siebkeetal_ecce01.pdf (Visited May 4, 2003)[6]

ii.DC - DC Push-pull Flyback Converter

The DC-DC Push-pull Flyback Converter stage boosts the voltage up to a desired level. In figure 5, this stage of the diagram layer of the Dymola/Modelica model is shown. On the far left is the fuel cell, with the red boxes around it.

The transformer is the hardest part to model. Since the Modelica transformer does not have a central point, two transformers are used. Phase shifted high frequency signals are used to create the desired output. Both TAMU and UCF have used a combination of MOSFET switches for this purpose.

Two high frequency square wave sources switch the current going through the transformer. There is a time offset to shift the phase, so that the output of the transformers will be boosted, phase shifted, square waves, as can be seen in figure 6. There are different ways these switches can be triggered. One of these, which should be looked into, is the resonant switching in which very high frequencies are used to reduce switching losses and increase overall efficiency. A paper to check out on this topic is “"Review of resonant techniques in power electronic systems" (1996) by A.J. Forsyth.[7] Other references are “Quasi-Resonant Multi-output DC/DC Converter with Push-pull topology” by Rossetto & others[8], and “Design Review: 140 W, Multiple Output high Density DC/DC Converter” by Laszlo Balogh[9]. The four diodes route the current through the inductor at the top-right side of figure 5, which then goes through the inverter, and comes back in through the inductor at the bottom-right of this figure.

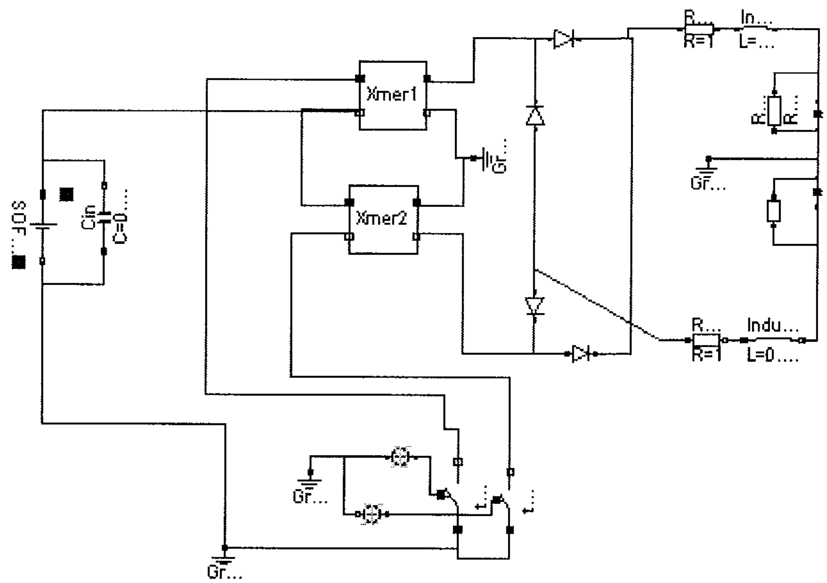

Figure 5: Modelica diagram of a DC-DC Push-pull stage.

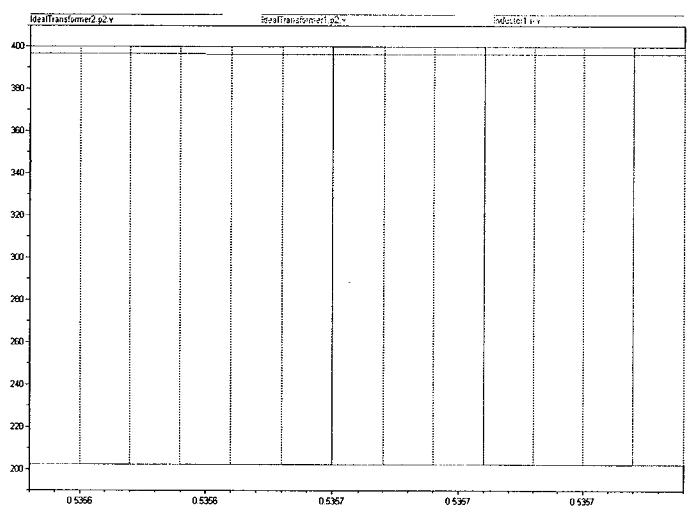

Figure 6: Transformer output from the DC-DC stage of converter simulation.

iii.PWM Inverter and Low-Pass Filter

For similar reasons, it is helpful to take a look at the inverter and filter stages of the circuit separate from the rest. In figure 7, the dc-dc stage is replaced with two constant voltage sources, to show the effects and results of the PWM, and filter stages.

The digital source provider in this case uses a Sine Voltage and a Trapezoidal Voltage to trigger the switches. Again, there are a number of different ways to design the source provider. The paper mentioned above for resonant converters by A.J. Forsyth also has a section on the switching transactions of inverters. Both TAMU, and UCF use IGBT switches here.

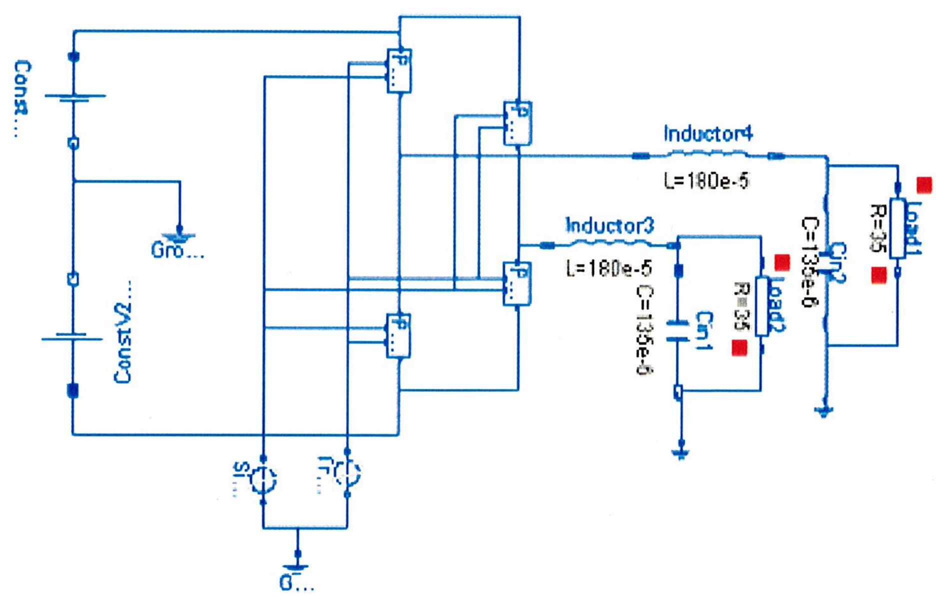

Figure 7: Inverter and filter stages of the design. (Split loads are the ones with red squares around them.)

With the filter and load specification shown in the diagram, if the DC-to-DC stage results in +/- 325 V, a 110V can be obtained, as seen in figure 8.

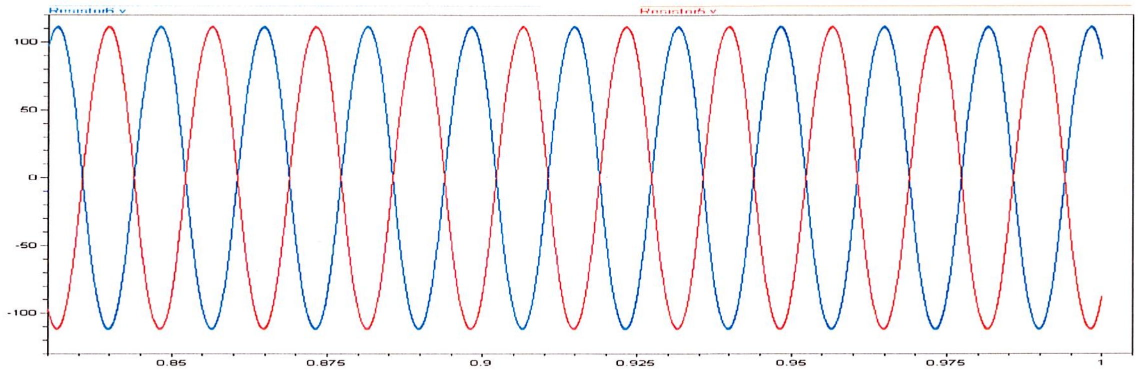

Figure 8: Blue line is the voltage across Load1; Red line is the voltage across Load 2.

iv.Load

Finally, the finished converter could be simulated under variable load conditions, instead of a constant one. Keep in mind that if the intention of the fuel cell is to supply the needs of a household, then energy consumption will differ over time, during the day.

b. Full model

Figure 9 shows the circuit diagram of a full model of the converter. Apart from the differences (DSP source types, frequencies, transformer model, device values etc.) mentioned above, this diagram displays the same converter as in TAMU and UCF. (See Full Page version in Appendix A, or in the enclosed disk)

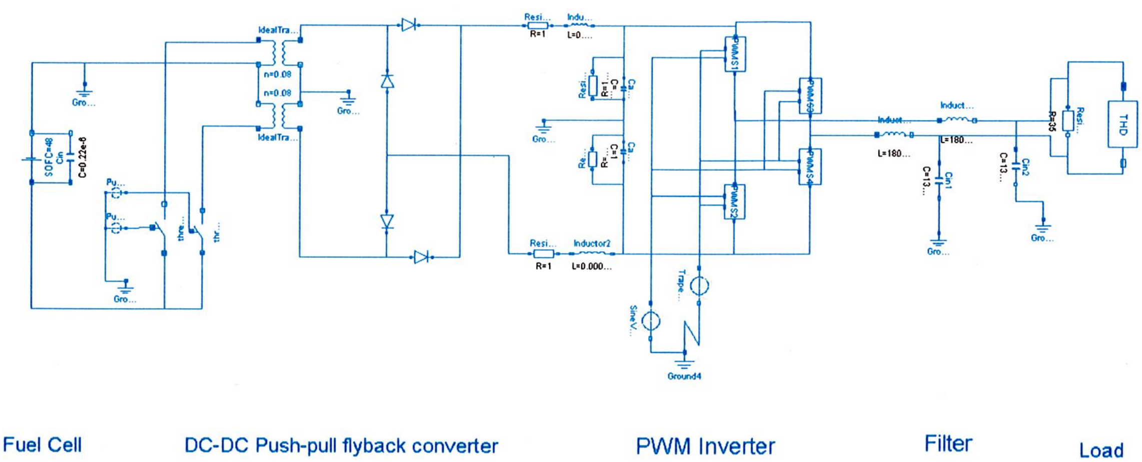

Figure 9: *Modified UCF model. (Kaya Tolon & Shashank Krishnamurthy)*

Important parameters (For all parameters, please check diagram in the included disk.)

Devices	Type Parameters	Value
SOFC (Fuel cell)	Voltage	48 V
C_{in}	Capacitance	0.22 e-6 F
Pulse Voltages (DC-DC stage)	Frequency	50 KHz
Inductors 1 & 2	Inductance	0.00018 H
Capacitors 1 & 2	Capacitance	2.2 mF
Trapezoid Voltage	Frequency	10 KHz
Sine Voltage	Frequency	60 Hz
Inductors 3 & 4	Inductance	1.8 mH
Capacitors 3 & 4	Capacitance	0.135 mF

Table 2: *Main parameters used in the modified UCF model.*

The higher the switching frequency is set at, the lower the Total Harmonic Distortion (THD) will become. Since in this model high frequencies are used, the THD is very low. The blue line on the graph in figure 3.3 shows the THD for the Load, which is 2.38%. This satisfies the output quality criterion.

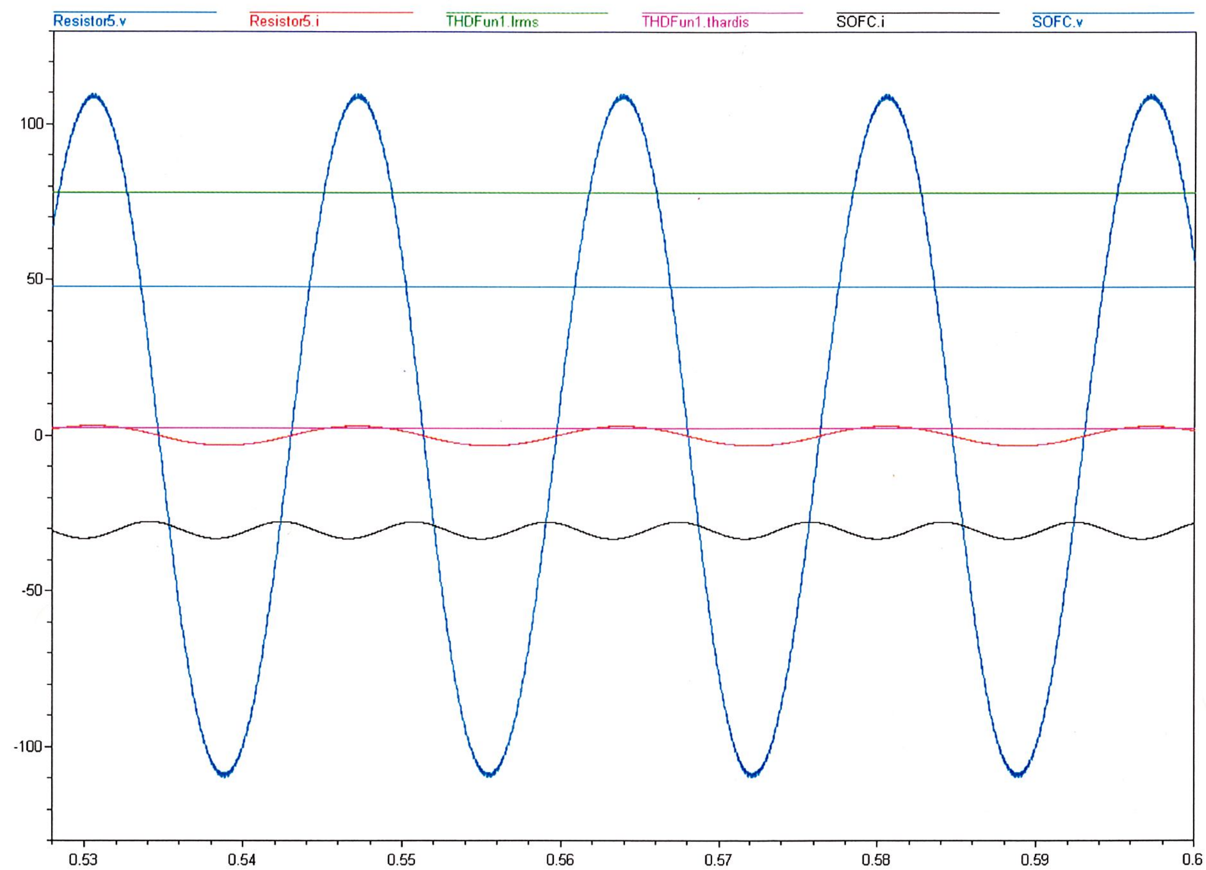

Figure 10: *Results for the simulation: the lines represent the following parameters: THD = 2.38% (pink),* V_{max} *= 110 (blue),* V_o *= 76V (green), Fuel Cell* V_{dc} *= 48V (blue), Fuel cell current (black).*

The efficiency of the inverter stage is close to 100%, since ideal components are being used. To obtain the overall efficiency of the converter the actual devices (with their according resistance/inductances) need to be used.

The choke inductors, capacitors, the DSP controls and the transformer, are the most expensive devices in this model. However more importantly the fact that there are many devices makes it fairly expensive. A simpler design having less total devices should be less expensive.

5. Conclusions

In this report, an approach to simulating a model complying with the Future Energy Challenge constraints has been discussed. Dymola/Modelica software has been used to simulate different models. One sample Modelica model has been enclosed in this report within a floppy disk, and a number of suggestions for improvement of this model have been given in section 4 "Modeling". Also references have been provided to supplement this report in giving a future Iowa State FEC team a head start.

Acknowledgements

I would like to thank Shashank Krishnamurthy for showing me the ropes in using Dymola/Modelica.

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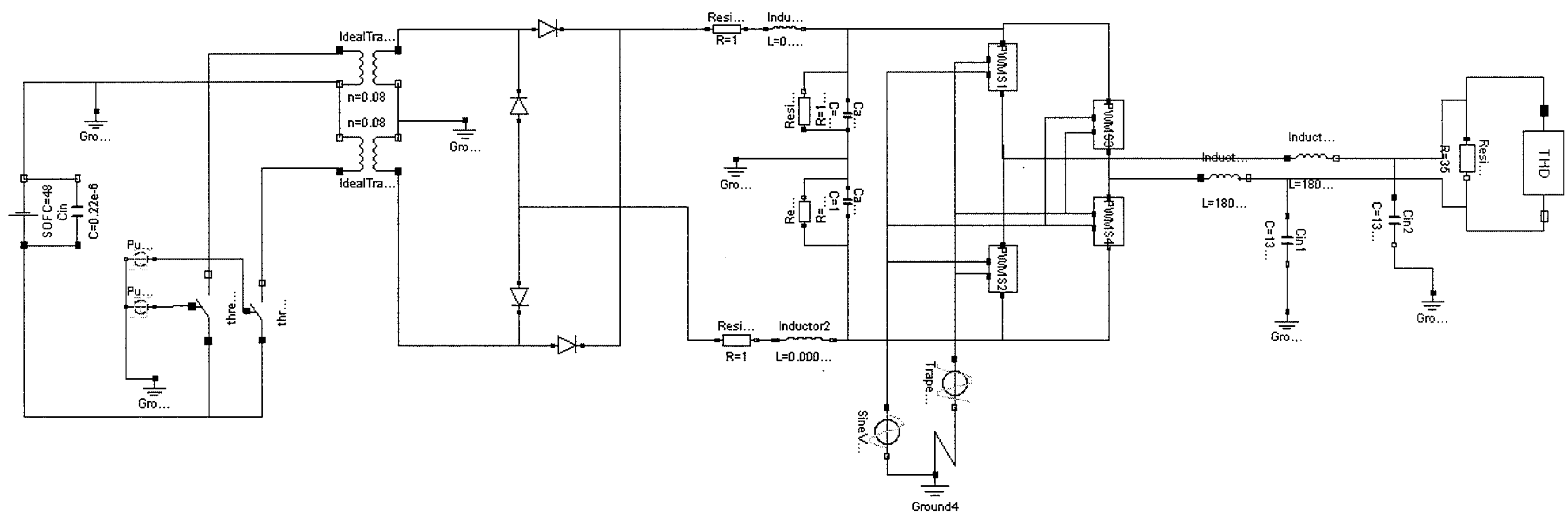
(Accessed May 9, 2003)

8 "QUASI-RESONANT MULTI-OUTPUT DC/DC CONVERTER WITH PUSH-PULL TOPOLOGY" L. Rossetto* G. Spiazzi** P. Tenti** F. Brasola L. Fontanella, and G. Patechi.

http://www.dei.unipd.it/~pel/Articoli/1994/Apec/Apec_94.pdf (Accessed May 9, 2003)

9 "Design Review: 140 W, Multiple Output high Density DC/DC Converter" by Laszlo Balogh
http://focus.ti.com/lit/misc/slup117/slup117.pdf (Accessed May 9, 2003)

Appendix A:



Fuel Cell | DC-DC Push-pull flyback converter | PWM Inverter | Filter | Load

Modified UCF model. (Kaya Tolon & Shashank Krishnamurthy)