Doctoral school of energy and geotechnology
January 16–21, 2006. Kuressaare, Estonia

Design of power circuit of DC/DC step-up converter for a PEM fuel cell

Arturs Purvins, Oskars Krievs, Ingars Steiks, Leonids Ribickis
Riga Technical University
arturs.purvins@inbox.lv oskars@eef.rtu.lv ingars@eef.rtu.lv Leonids.Ribickis@rtu.lv

Abstract

A fuel cell is electrochemical energy conversion device, using hydrogen as a fuel for production of electrical energy. Fuel cells are compact, efficient and environmentally friendly. Fuel cell power systems are foreseen to have applications in various fields such as electric vehicles, and as distributed generation sources interfaced with electric utilities. Since fuel cells produce variable, low voltage dc, a power electronic interface is required to adapt the output to common ac loads or power grid. In this paper design of a DC/DC step-up converter for 1.2 kW Fuel cell is discussed.

Keywords

Fuel cell, step-up DC/DC converter,

Introduction

Fuel cells produce electricity by utilizing an electrochemical reaction to combine hydrogen ions with oxygen atoms. Hydrogen ions are obtained from hydrogen-containing fuels. Fuel cells use an external source of fuel and produce power continuously, as long as the fuel supply is maintained.

Fuel cell based power supply systems usually consist of fuel reformer, stack and power conditioning unit. Power conditioning unit includes DC-DC and DC-AC converters as well as filters. The stack generates voltage electrochemically using hydrogen from a reformer or hydrogen storage tank. The stack produces a variable, low voltage dc output requiring a power electronic interface to connect to any energy storage or ac loads.

The main goal of this paper is to chose and calculate the most convenient DC/DC step-up converter power topology for 1.2 kW Fuel cell stack, witch utilizing an ordinary voltage source inverter could drive standalone 230V AC loads or be synchronized with the power grid via main frequency transformer.

1 Fuel cell

1.1 Principles

Fuel Cell is a device that converts the chemical energy of a reaction directly into electrical energy. A fuel cell produces electricity, water, and heat using fuel and oxygen in the air. The Fuel Cell, compared to battery (energy storage device), is an energy conversion device that theoretically can produce electrical energy for as long as fuel and oxidant are supplied to the electrodes. Hydrogen has become the fuel of choice for most applications, because of its high reactivity, its ability to be produced from hydrocarbons, and its high energy density. Similarly, the most common oxidant is oxygen, which is readily and economically available from air for terrestrial applications, and again easily stored in a closed environment.[1]

The fundamental component of fuel cell consists of two electrodes, the anode and the cathode, separated by a polymer electrolyte membrane. Each of the electrodes is coated on one side with a thin platinum catalyst layer. The electrodes, catalyst and membrane together form the membrane electrode assembly. A single fuel cell consists of a membrane electrode assembly and two flow field plates Fig. 1. [2]

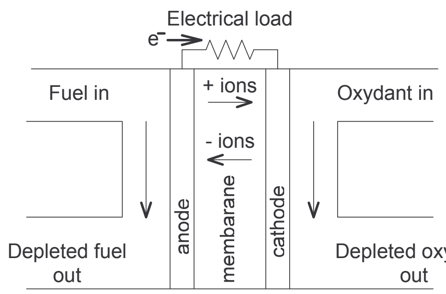

Fig. 1. Simple fuel cell schematic

Gases (hydrogen and air) are supplied to the electrodes on either side of the membrane through channels formed in the flow field plates. Hydrogen flows through the channels to the anode where the platinum catalyst promotes its separation into protons and electrons. The free electrons are conducted in the form of usable electric current through an external circuit, while the protons migrate through the membrane electrolyte to the cathode. At the cathode, oxygen from the air, electrons from the external circuit and protons combine to form pure water and heat [1].

Individual fuel cells are combined into a fuel cell stack to provide the required electrical power. A single fuel cell produces about 1 volt at open circuit and about 0.6 volts at full load. Cells are stacked together in series to provide the required output voltage. In turn, the output current of a fuel cell is proportional to its active area. Consequently, the fuel cell stack geometry can be tailored to provide the desired output voltage, current and power characteristics [3].

PEM fuel cell stacks produce unregulated DC power from hydrogen and air. Water and heat are the only by-products of the reaction. The PEM fuel cell stack incorporated into the system has been developed with a number of important attributes for the portable power market. First, the fuel cell stack operates at low pressure, minimizing parasitic losses, reducing noise, and enhancing system reliability. Second, the fuel cell stack architecture does not require external fuel humidification. Furthermore, this fuel cell stack is air-cooled, which further simplifies the overall system design.

In this case the fuel cell stack has been sized to provide 1.2 kW of net output power. The output voltage varies with power, ranging from about 43 V at system idle to about 26 V at full load. During system operation, the fuel cell stack voltage is monitored for diagnostic, control and safety purposes. In addition, a cell voltage system monitors the performance of individual cell pairs and detects the presence of a poor cell. The unit will shut down if a cell failure or a potentially unsafe condition is detected in the fuel cell stack.

1.2 Characteristics

Fig. 2. illustrates polarization characteristics of the fuel cell stack system. Net output power ranges from zero to 1.2 kW. Net output current ranges from zero to 46 amps across the operating range of the power plant. Output voltage varies with operating load according to the polarization characteristics of the fuel cell stack. Normal idle voltages of the fuel cell stack system are approximately 43 VDC. At rated power, the fuel cell stack system output voltage ranges from 26 VDC to 29 VDC.

Referenced polarization characteristic curve of fuel cell power module compared to curve of experimental data agrees in general (Fig. 2.). However there are some discrepancies in experimental data.

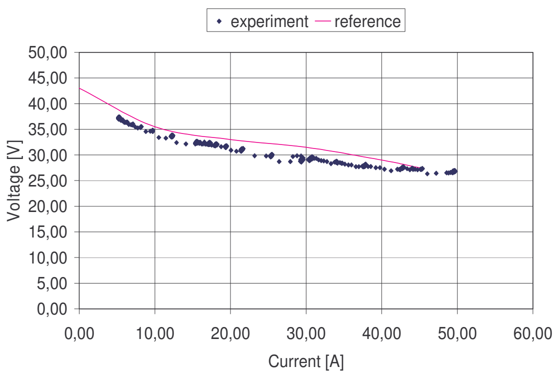

Fig. 2. Polarization curve (reference and experimental data)

Experimental transient response characteristics of the fuel cell power module are shown in Fig. 3. The graph illustrates the system's response to step changes in load. The fuel cell stack immediately (about 0.6 seconds interval) provides current to support a load step change.

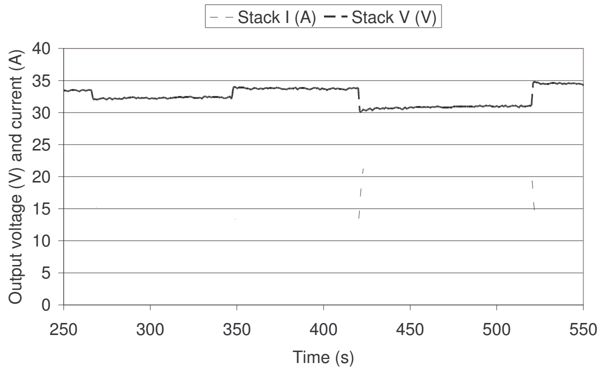

Fig. 3. Transient response curve (experimental data)

A similar transient interval occurs after a load step from 22 A to 12 A. Output voltage gradually recovers and stabilises to 34 volts over a 0.5 seconds interval.

2 Choice of DC/DC converter topology

In this chapter several different step-up (output supply voltage is greater than input source voltage) voltage converters are described: boost converter, half bridge and full bridge push-pull topologies.

To choose an appropriate DC/DC converter it is necessary to know the required input and output parameters. Input of converter is defined by power output of the fuel cell stack:

Rated power 1200 W,

DC voltage range 22…50 V.

Rated converter output power is assumed 1500 W and output DC voltage – 400V, as required for normal 230V AC voltage source inverter operation.

Switching voltage regulators are commonly used for both step-up and step-down applications, and differ from linear regulators by implementation of the pulse-width modulation (PWM). Switching regulators control the output voltage by using a switch with a constant frequency and variable duty-cycle. Switching frequencies are generally from few kHz to a few hundred kHz. It is possible to control the output voltage by varying the duty-cycle, depending on the load state and input source voltage. The clear advantage of switching regulators is efficiency, as minimal power is dissipated in the power path (switches) when the output supply voltage is sufficient for the load state. The disadvantage of switching regulators is complexity, as several external passive components are required on board. Output voltage ripple is another disadvantage, which is generally handled with bypass capacitance near the supply and at the load.

Boost, or step-up, converters produce an average output voltage higher than the input source voltage. Figure 4. shows the boost topology. When the switch is on, the diode is reverse-biased, hence isolating the load from the input source voltage and charging up the inductor current. When the switch is off, the output load receives energy from the inductor and the input supply voltage. The inductor current begins to discharge, inducing a negative voltage drop across the inductor. Because one port of the inductor is driven by the input supply voltage, the other port will have a higher voltage level, thus the boost or step-up feature. As with the buck converter, the capacitor acts as a low-pass filter, reducing output voltage ripple as a result of the fluctuating current through the inductor. [4]

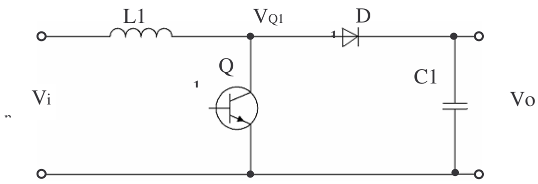

Fig. 4. Boost converter

The voltage step-up ratio Vo/Vin is limited only with breakdown voltage on power switch element Q1. In our cease, if transistor is in OFF state between collector and emitter is 400V DC. Average collector current is close to maximal:

$$I_{c.\max} \approx \frac{P_o}{U_{in.\min}} = \frac{1500}{22} = 68A \quad (1)$$

because of the big duty cycle.

$$\frac{T}{t_{off}} = \frac{V_o}{V_{in}} = \frac{400}{22} \approx 18 \quad (2)$$

That means, transistor OFF time is 1/18 from period and respectively ON time 17/18 from period.

The boost converters have no electrical isolation between the input and output circuits, it is the main reason to choose converter with transformer in power circuit, where the output is completely isolated from the input and PWM (Pulse Width Modulation) of power switching elements provides constant output voltage at variable input voltage. A full bridge push-pull converter is shown in Fig. 5.

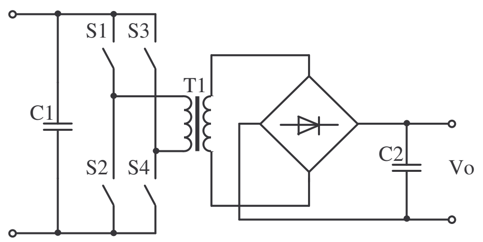

Fig. 5 Full-bridge push-pull converter

In Fig. 6 half-bridge converter is shown. The main advantage of this circuit is that it contains less switching elements allowing to decrease the power losses in converter. In this cease it is significant because of the big current in the primary winding of transformer. Conduction losses in one switch (the effective switching current $I_{sw.rms}$ is calculated in chapter 3.1)

$$P_{cond} = I^2_{sw.rms} * R_{DS(on)} = 48{,}21^2 * 17 * 10^{-3} = 39{,}5\ W, \quad (3)$$

where $R_{DS(ON)}$ = 17 mΩ [6].

The switching losses depend on the switching frequency f_s and the conduction times of the switch [6]:

$$P_{sw} = \frac{1}{2} I_{sw.rms} V_{in.\max} (t_{on} + t_{off}) f_s =$$

$$= \frac{1}{2} * 48{,}21 * 50(55 + 44)10^{-9} * 60 * 10^3 = 7{,}16\ W \quad (4)$$

For this reason it is better to use half-bridge scheme shown in Fig. 6. It is more useful to choose the topology with four diodes in the output part, because of only one secondary transformer winding and relatively insignificant losses in rectifier.

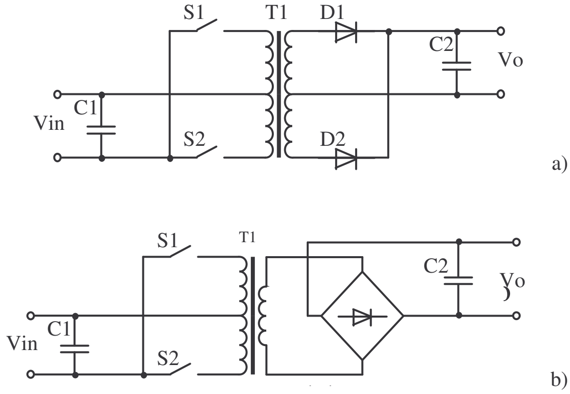

Fig. 6 Half-bridge push-pull converter

a) with two secondary windings, b) with one secondary windings

Switching frequency in this application must be higher than 20kHz, because of the decrease in mass and dimensions of the transformer, increase in it's efficiency and, last not least, it is the limit of audibility of human.

With the proliferation of choices between MOSFETs and IGBTs, it is becoming increasingly difficult for today's designer to select the best device for an application. Nevertheless, MOSFETs are preferred at high frequencies within device breakdown voltage range below 250V [5], because of slightly smaller on-state voltage drop and better switching performance.

3 Calculation of DC/DC Half-bridge push-pull converter

DC/DC converter power scheme (fig. 6b) calculation data:

Rated output power Po = 1500 W

Input DC voltage range 22…50 V

Transformer frequency is selected f = 60 kHz.

The Duty cycle of this converter may theoretically increase to 100%. In practice this is not possible because the serial connected power switches S1 and S2 (Fig. 5), have to be switched with a time difference to avoid a short circuit of the input supply. In calculations duty cycle maximum is assumed D_{max} = 95 %.

The converter has two operating modes depending on whether the output current falls to zero or not. Because of lower peak current of rectifier and switch and lower output voltage ripple continuous mode is chosen, where current ripple on L1 must be lower than double output current value $\Delta I_{L1} < 2Io$.

3.1 Choosing the power switches

The main parameters for choosing the power switches are the peak voltage that the switch must block, the effective current that will flow through them and the switching frequency.

The maximum voltage on transformer in OFF state can reach maximum input voltage $V_{in.max} = 50V$;

The maximum effective switch current by duty cycle 100%

$$I_{sw.rms} = \frac{I_{in.\max}}{\sqrt{2}} = \frac{68,18}{\sqrt{2}} \approx 48,21A, \quad (5)$$

where maximum input current

$$I_{in.\max} = \frac{P_{in}}{U_{in.\min}} = \frac{1500}{22} = 68,18A \cdot \quad (6)$$

This calculation was done without power loses in converter, where Pin = Pout = 1500W.

Taking in account the above requirements for the switch, it has been chosen the International Rectifier IRFZ44N [6]

3.2 Choise of rectifier diodes

Maximal output effective diode current calculated by duty cycle 100%

$$I_{d.rms} = \frac{I_{o.\max}}{\sqrt{2}} = \frac{3,75}{\sqrt{2}} = 2,65A \quad (7)$$

where maximum output current

$$I_{o.\max} = \frac{P_o}{U_o} = \frac{1500}{400} = 3,75A \quad (8)$$

Blocking diode voltage must be higher then Vo = 400V. Was chosen fast switching YENYO FS3J [7]

3.3 Calculation the output filter

Output filter consists from coil and inductivity with task to make better output power of converter.

Inequality of coil inductivity for continuous mode

$$L \geq \left(\frac{1}{2f}\right)\left(V_0 - V_{in.\max}\right)\left(\frac{V_{in.\max}}{V_0}\right)\left(\frac{1}{\Delta I_L}\right) =$$

$$= \left(\frac{1}{2*60*10^3}\right)\left(400-50\right)\left(\frac{50}{400}\right)\left(\frac{1}{7,5}\right) = 48,61\ \mu H \quad (9)$$

Where

$\Delta I_L = 2I_{o.max} = 2*3.75 = 7.5$ A. (10)

Allowable output voltage pulsation is conjectured $\Delta Vo = 5V$, so, capacitance of output filter

$$C \geq \frac{\Delta I_L}{4\Delta V_0 2f} = \frac{7,5}{4*5*2*60*10^3} = 3,13\ \mu F \quad (11)$$

3.4 Calculation of the transformer

Transformer coefficient

$$K = \frac{V_0}{\eta 0,95\left(V_{in.\min} - V_{DS}\right)} = \frac{400}{0,98*0,95\left(22-1\right)} \approx 21 \quad (12)$$

Where VDS ≈ 1V is drain-to-source voltage when transistor is ON [6]. Voltage drop on diodes rectifier in this calculation aren't notable because of relatively big output voltage. Transformer efficiency $\eta = 0,98$ [9].

How large a core is needed to handle a certain amount of power? This is a question often asked, but unfortunately there is no simple answer.

As core material was chosen ferrite with flux density B = 0,2T (2kG)

$$W_a A_c = \frac{k' P_o 10^8}{Bf} = \frac{0,00528*1500*10^8}{2000*60*10^3} = 6,6cm^4 \quad (13)$$

Where Wa – window area in cm^2:

Core window for toroids

Bobbin window for other cores

Ac – effective magnetic area of the core in cm^2

k' – coefficient for square wave operation:

k' = 0,00633 for toroids

k' = 0,00528 for pot cores

k' = 0,00528 for E-U-I cores

B – flux density in gauss [8]

Magnetic area core is conjectured $Ac = 2,5cm^2$. Transformer core was selected from catalogue.

Calculation of number of primary Np and secondary Ns turns around the inductor's core.

$$N_p = \frac{\left(V_{in.\min} - V_{DS}\right)10^4}{K_f fBA_c} = \frac{(22-1)*10^4}{4*60*10^3*0,2*2,5} = 2 \quad (14)$$

Where Kf – proportionality constant describing the energy in the wave form:

Kf=4.44 for sinusoids,

Kf=4.0 for square waves

B – flux density in tesla

Number of secondary windings

$$N_s = N_p K = 2*21 = 42. \quad (15)$$

Calculation of wire cross-section (without isolation) of primary Wcs.p and secondary Wcs.s turns by wire current flow density $J = 3A/mm^2$

$$W_{cs.p} = \frac{I_{sw.rms}}{j} = \frac{48,21}{3} = 16,07\ mm^2 \quad (16)$$

$$W_{cs.s} = \frac{I_{o.\max}}{j} = \frac{3,75}{3} = 1,25\ mm^2 \quad (17)$$

Wire area needed (only for copper) for transformer (fig. 6b) with two primaries and one secondary windings

$$A_w = 2W_{cs.p}N_p + W_{cs.s}N_s =$$

$$= 2*16,07*2 + 1,25*42 = 116,8mm^2 = 1,17cm^2 \quad (18)$$

Available window area for wire

$$W_a = \frac{W_a A_c}{A_c} = \frac{6,6}{2,5} = 2,64 cm^2 . \quad (19)$$

Formulas 18 and 19 show that there are enough places for transformer windings.

4 Modelling of DC/DC converter

4.1 Simulation programms

Usually each electrical engineering simulation program has some advantages and disadvantages. Sometimes simulation programs implementing real component models (e.g. SPICE models) confront convergence problems when calculating relatively simple electrical schematics.

In this case PSim® simulation program of Powersim® Inc. PSim® was used, because there was almost no problem with preliminary DC/DC converter simulation with virtual components. For more precise and realistic simulation real component models must be used.

4.2 DC/DC converter simulation

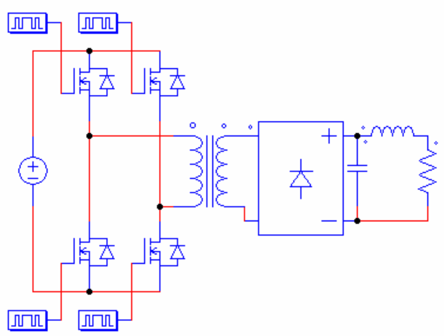

Fig. 7. Full-bridge transformer-isolated DC/DC model

Simulations were run to verify the operation of the circuits at the maximal duty cycle. Switching frequency of MOSFET is 60 kHz. An output filter (capacitor and inductance) value is as calculated previously.

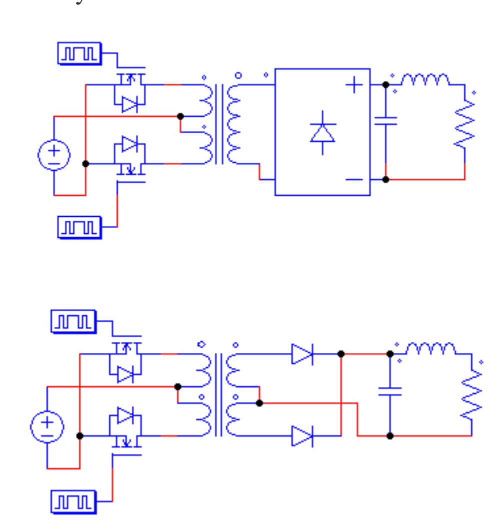

Fig. 8. Model of half-bridge push-pull converter with a) 1 sec. winding b) 2 sec. windings

Figure 9 shows the output voltage of the half-bridge push-pull converter with the calculated converter parameters at full load. The simulation results comply with the calculations.

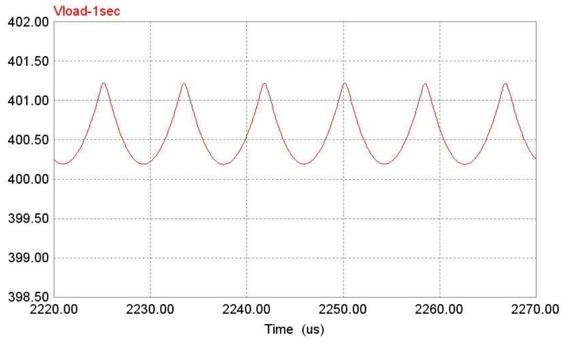

Fig. 9. Output voltage of the half-bridge push-pull converter

Conclusions

Several different step-up DC/DC converters have been compared in this paper in order to select an appropriate converter for a 1.2kW Fuel Cell power module. As the most suitable topology the half-bridge push-pull converter was chosen. The main advantages of this topology were electrical isolation between the input and output circuits and lower loses in switches in the input part of converter. This is an important advantage since the largest losses in the converter appear in the switches. Thereby reducing them, considerably improves the converter efficiency. Switching frequency of the converter was chosen 60kHz, allowing to create a compact and noiseless converter with reasonable switching losses.

References

[1] EGG Services Parsons Inc., *Fuel cell handbook (6th edition),* United States Department of Energy, November 2002.

[2] Troy A. Nergaard, „Modeling and Control of a Single-Phase, 10 kW Fuel Cell Inverter", Virginia Polytechnic Institute, 2002.

[3] D.Burger, E. Dougan, J. Oberle, S. Periyathamby, "DC/DC Converter", April 2004..

[4] Power Supply Regulation. http://www.altera.com/support/devices/power/regulators/pow-regulators.html, October 2005.

[5] IGBT or MOSFET: Choose Wisely. www.irf.com/technical-info/whitepaper/choosewisely.pdf, October 2005.

[6] Catalog. http://www.chipcatalog.com/search.php?q=IRFZ44N, October 2005.

[7] Catalog. http://php.ec88.com.tw/yenyo_new/product-e.php?mod=7&product=3, October 2005.

[8] Transformer Core Selection. http://www.mag-inc.com/pdf/2004_Design_Information.pdf, October 2005.

[9] Акимов Н. Н. Ващуков Е. Р. Пропенко В. А. и др. Резисторы, конденсаторы, трансформаторы, дроссели, коммутационные устройства. РЭА справочник. – Минск, Беларусь, 1994. – 586с.

[10] PSim® Proffesional Version 6.0.9, Powersim®.