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DESIGN OF CURRENT SOURCE DC/DC CONVERTER FOR INTERFACING A 5 kW PEM FUEL CELL

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In domestic applications the low DC output voltage of a hydrogen fuel cell used as the main power supply or a backup power source has to be matched to the level and frequency of the AC voltage of utility grid. The interfacing power converter system usually consists of a DC/DC converter and an inverter. In this work, a DC/DC step-up converter stage is designed for interfacing a 5kW proton exchange membrane (PEM) fuel cell. The losses of DC/DC conversion are estimated and, basing on the relevant analysis, the most appropriate configuration of converter modules is selected for a DC/DC converter stage of increased efficiency. The authors present the results of experimental analysis and simulation for the selected configuration of four double inductor step-up push-pull converter modules.

Key words: *DC/DC converter, fuel-cell system, high-frequency power converters, double inductor step-up push-pull converter.*

Nomenclature

I_{FC} – fuel cell current,
V_p – primary voltage of the transformer,
f_s – switching frequency,
t_r – turn-on time of the transistor,
t_f – turn-off time of the transistor,
$I_{SW\,rms}$ – RMS drain current,
R_{on} – on-state resistance of the transistor switch,
R_p – resistance of the primary transformer winding,
R_s – resistance of the secondary transformer winding,
D – duty cycle,
I_{Lrms} – the inductor RMS current,
R_L – the inductor series resistance,
MLT – the inductor mean length turn,
R_{spec} – the specific resistance of the inductor wire,
V_D – the forward voltage drop on the diode,
B – flux density.

1. INTRODUCTION

A hydrogen fuel cell used as the main power supply or backup power source in domestic applications usually consists of a DC/DC converter and an inverter.

Due to a comparatively large input–output voltage difference, most often converters with a high frequency transformer are recognized as the optimal solution for the DC/DC stage [1–4]. Currently, many transformer isolated DC/DC converter topologies are known which are able to perform the voltage boosting necessary to match the inverter's DC-link voltage level: full-bridge, half-bridge, flyback, forward, basic push-pull topologies as well as a number of the derived topologies [5, 6]. These topologies can be classified into two groups – voltage source converters and current fed converters. In this work, a current-fed double inductor converter (DIC) push-pull topology (Fig. 1) was selected, since the losses in switches are considerably lower due to the low number of primary switches. This is an important advantage, since decreasing the primary switch losses considerably improves the converter's efficiency. Besides, the design of DIC transformer is simple (has no split windings).

The DIC topology is characterized by a low input current ripple, which is appropriate for interfacing the proton exchange membrane fuel cells [3, 4].

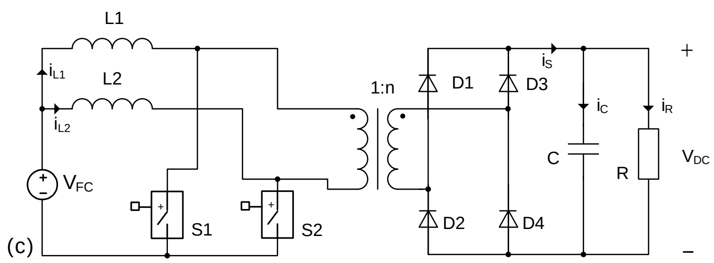

Fig. 1. Current-fed double inductor push-pull converter topology.

Since there is a relatively low voltage and high current at the primary side, both the inductors and the switches must be able to handle this high current, which even at low switch-on resistances will cause significant conduction losses in the components [7].

The mentioned losses can be reduced in two basic ways: by reducing the resistance of components or the current flowing through them. The latter can be achieved by connecting two or more identical converter modules in parallel. At such connection the input current load on the switches is halved, with the overall switch conduction losses halved as well, despite the doubled number of elements.

2. EVALUATION OF RELATIVE LOSSES FOR A DC/DC CONVERTER SYSTEM

The main parameters of a DC/DC converter stage are specified in Table 1. To increase the overall efficiency of DC/DC conversion the converter can be split into several modules connecting the inputs in parallel, and outputs – in series. Analysis presented in this chapter is used as a guide for choosing the number of converter modules with parallel input connection that would ensure the best efficiency of the overall DC/DC converter stage.

The equations used for efficiency evaluation of DIC topology (Table 2) are mostly a rough guide, since this classification is made based on a simplified circuit analysis.

Table 1

The parameters of DC/DC converter system

Parameter	Value
Input voltage	30–50 V
Input power	5000 W
Input current	100–167 A
Output voltage	400 V
Switching frequency	30 KHz
Desired input current ripple	2.5%
The transformer ratio	1:2

The power losses consist of conduction losses and switching losses. At higher switching frequencies which are used in DC–DC converters, the MOSFET power switch is the best choice in terms of cost and performance. In order to minimize the conduction losses, the selected MOSFET must have the lowest possible drain-to-source on-resistance. For power MOSFETs, the conduction and switching losses are calculated, while for the output diode rectifier the switching losses are very small as compared with the conduction losses and can be ignored. The voltage drop across the diode in a conducting state is primarily responsible for the losses in this diode.

Transformer losses consist of copper losses and iron losses. Estimation of copper loss in a high-frequency transformer requires considering skin and proximity effects in the winding window. Recent works (see, e.g. [8]) have shown that the power density per surface unit can be considered constant along the perimeter even in the case of an ETD type core. The skin and proximity effects allow deriving such an expression for copper losses in which the real parts of vector fluxes are summarized for each coil [9, 10].

Iron losses are generally described by the power balance equation, which requires only a minor number of parameters (usually given by the manufacturer).

Table 2

Equations used for efficiency evaluation of DIC topology

	DIC
P_{SW}, MOSFET	$2\left(\frac{I_{FC}}{2}\right)V_P f_S (t_r + t_f)$
P_C, MOSFET	$2 \cdot I_{SW\_rms}^2 \cdot R_{on}$
P_{COPPER}, transformer	$R_P (1-D)\left(\frac{I_{FC}}{2}\right)^2 + R_S (1-D)\left(\frac{I_{FC}}{2 \cdot n}\right)^2$
P_{CORE}, transformer	$K \cdot f_S^{m1} \cdot B^{m2} \cdot W_{tFe} \cdot 10^{-3}$
L inductor	$L = \frac{D \cdot V_{FC}}{2 \cdot \Delta I_{FC} \cdot f_S} = \frac{N^2}{\Re}$
$P_{\text{COPPER,}}$ inductor	$I_{Lrms}^2 \cdot R_L = I_{FC}^2 \cdot MLT \cdot N \cdot R_{spec}$
P_C, diode rectifier	$V_D \cdot I_{DC} \cdot \frac{(1-D)T/2}{T}$

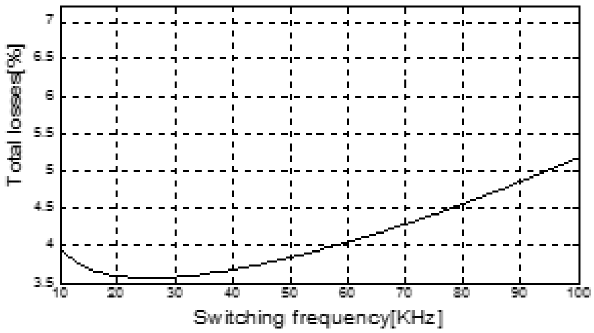

Fig. 2. Converter losses as a function of switching frequency.

Analysis of the DC/DC converter stage losses has been carried out for the module count (the number of modules from one to six). The losses of one DIC module can also be expressed as a function of switching frequency (Fig. 2). The curve in this figure shows that the minimum losses arise between 20 and 30 KHz. Thus, to minimize the required inductance the highest frequency from this range (30 kHz) was chosen.

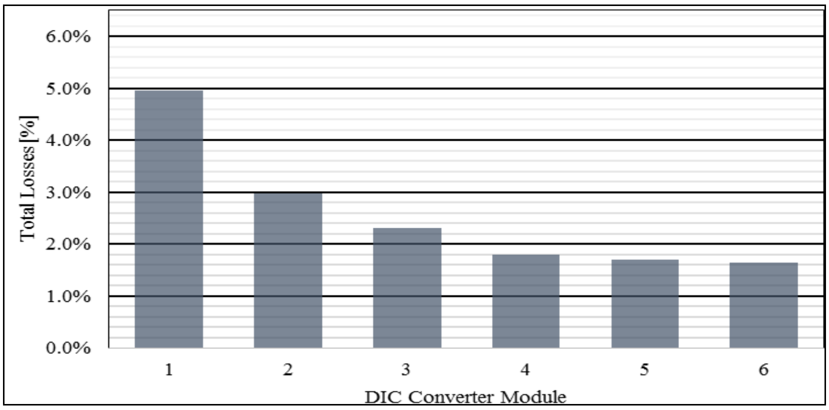

Fig. 3. Loss evaluation of DIC modules.

The results of loss analysis are summarized in Fig. 3. Based on them, it was decided to choose a configuration of the DC/DC converter stage containing four DIC modules with parallel-connected inputs. Using five or six modules would increase the overall converter's efficiency slightly more; however, from the price considerations a four-module DIC system is a more reasonable choice.

The advantages of such configuration are the following:

- reduced power handling of individual transformers, which results in smaller transformer size and simpler design;
- significantly reduced primary switch conduction losses due to lower switch currents;
- possibility to apply a multilevel inverter at the output of DC/DC stage, which results in decreased step-up transformer ratios and easier switching conditions (*dv/dt*).

3. DIC SYSTEM MODULATION

The DIC operation in a fuel cell can be described based on the PLECS simulation results. Since a steady operation point had to be examined, the fuel cell was modelled by a constant voltage source. The core losses of the inductances were neglected. The transformer was modelled as an ideal one, which introduces the leakage inductance in series. The block-circuit of a 5 kW four-module DIC system for the model is shown in Fig. 4. The respective four module inputs are connected in parallel, and the outputs – in series. The converter modules operate with a 30 kHz switching frequency. Scopes are connected for measuring the input current, the output voltage and current, the driving pulses and the load voltage.

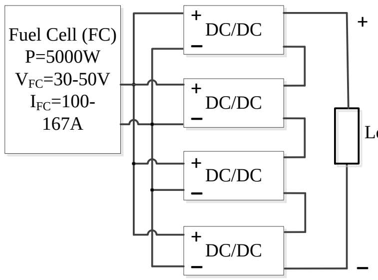

Fig. 4. Loss evaluation of DIC modules.

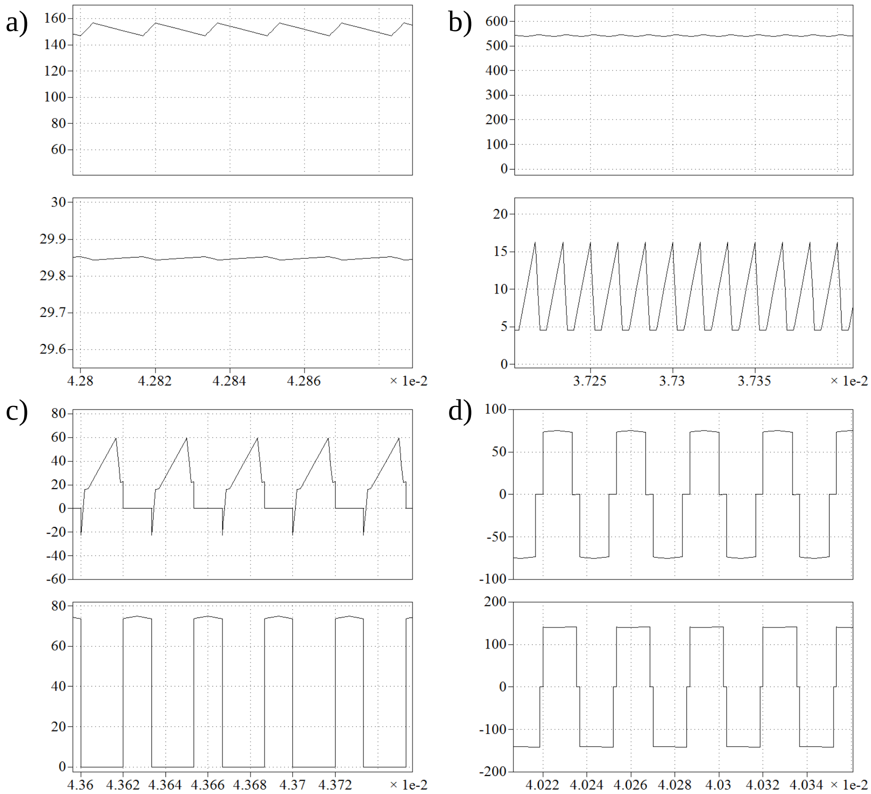

Fig. 5. The output voltage and current of fuel cell (*a*); the output voltage and current of DC/DC converter (*b*); the primary and secondary voltage of transformer of DC/DC converter (*c*); the voltage and current of the main switch of DC/DC converter (*d*).

Waveforms of the DIC system are presented in Fig. 5. As can be seen from the simulation, the converter operates normally, providing 540 V output voltage at the rated input and load conditions. The ripple of input current for the experimental prototype is below 5% of the mean value, which is within acceptable limits for the fuel cell.

4. EXPERIMENTAL

For the experimental testing four current-fed DIC modules were taken. To achieve an appropriate output voltage, the DIC inputs were connected in parallel and the outputs of DC/DC converters – in series. The experimental setup of the converter system is shown in Fig. 6. The testing was performed using a HyPM HD8 PEM [11] fuel cell module with the nominal power of 8 kW and a DC/DC converter connected to resistive load.

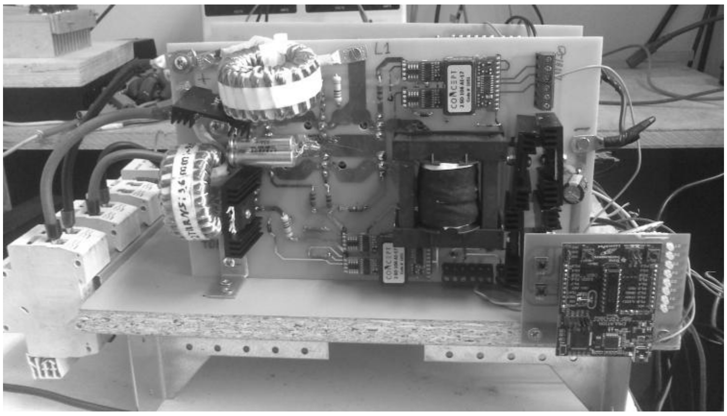

Fig. 6. The prototype of DIC.

The experimental setup of the control systems for DIC modules was built in a microcontroller. The available resources allowed for the use of a training kit (*Texas Instruments* ultra-low power MSP430G2452 microcontroller). As power supply a 3.3 V MCU was employed. The clock frequency was set to 8 MHz using an external quartz crystal. For programming, a JTAG interface programmer chip was taken, which allowed running the program code by command thus relieving the debugging process.

5. RESULTS AND DISCUSSION

The efficiency of the whole system was calculated based on the measurements of the input current/voltage and the load current/voltage. Generally, the experimental results (Fig. 7) have shown appropriate performance of the interfacing converter system with the input current ripple of the DC/DC stage being ±5 A (less than 5% of the average current value). The efficiency of the four current-fed DIC converter modules was relatively low at 10% of load, reaching 93% under the rated load conditions.

Figure 7*b* shows a successful reduction in the turn-off overvoltages across the primary power switches of the DC/DC stage. The main switches are operated under the ZVS conditions at turn-on and turn-off transients.

a) b)

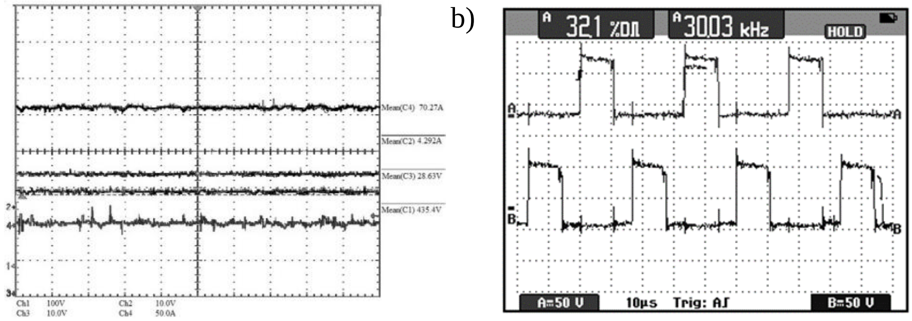

Fig. 7. Experimental waveforms of the DIC converter module. From the top: output voltage, input current, output current, input voltage output (*a*); voltage across the primary power transistors.

5. CONCLUSIONS

Based on the evaluation of relative losses, it has been decided to implement a configuration containing four DIC converter modules with the inputs connected in parallel and the outputs – in series for interfacing a 5 kW proton exchange membrane (PEM) fuel cell.

In the work it has been proved that the DIC performs well, with the efficiency of 93 %. The input current ripple of the experimental prototype is below ±5% of the average, which is within acceptable limits for a fuel cell of the type.

The elaborated prototype of a double inductor push-pull DC/DC converter can be used as a background for further work on the implementation of control hardware using a dedicated integrated circuit, since a current-fed converter involves new problems, e.g. the signal conditioning to realize the overlapping of gate signals. The dedicated PWM controllers are found to have such important advantages as the soft start-up and the built-in over-current protection.

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REFERENCES

1. *Fuel Cell Handbook* (6th ed-n, Nov. 2002). EGG Services Parsons Inc., Department of Energy (USA).
2. Gentile, G., Meo, S., & Esposito, F. (Sept. 2004). *Comparison among Different Topologies of DC–DC Converter for Fuel-Cell-Based Inverter System*. EPE-PEMC, Riga (Latvia).
3. Choi, W., Enjeti, P.N., Howze, J.W. & Joung, G. (2004). An experimental evaluation of the effects of ripple current generated by the power conditioning stage on a proton exchange membrane fuel cell stack. *J. Mater. Engin. Performance, 13,* 3257–264, New York.
4. De Caro, S., Testa, A., Triolo, D., Cacciato, M. & Consoli, A. (2005). Low Input Current Ripple Converters for Fuel Cell Power Units. *In: Proc. Hard Switching Converters and Control.* EPE (Germany).

5. Mohan, N., Undeland, T., & Robbins W.P. (2003). *Power Electronics. Converters, Applications and Design*. John Wiley & Sons.
6. Erickson, R.W., & Maksimovic, D. (2001). *Fundamentals of Power Electronics.* Chapman & Hall.
7. Andreičiks, A., Steiks, I., & Krievs, O. (June, 2011). Design of Efficient Current Fed DC/DC Converter for Fuel Cell Applications. ISIE2011. *20th Intern. Conf.,* pp. 206–210. Gdansk (Poland).
8. Ferreira, J.A. (Jan., 1994). Improved analytical modelling of conductive losses in magnetic components. *IEEE Transactions on Power Electronics*, *9*(1), 127–131. (Johannesburg, South Africa).
9. Steinmetz, C.P. (Feb. 1984). On the law of hysteresis. *Proc. of the IEEE*, *72*, 169–221.
10. Sedghisigarchi, K., & Feliachi, A. (2004). *Dynamic and Transient Analysis of Power Distribution Systems with Fuel Cells. Part I: Fuel-Cell Dynamic Model* (10^{th} ed-n). New York, vol. 2.
11. Hydrogenics Corporation 5985 McLaughlin Road Mississauga, Ontario (Canada) L5R 1B8, www.hydrogenics.com

PAAUGSTINOŠĀ STRĀVAS AVOTA LĪDZSPRIEGUMA PĀRVEIDOTĀJA IZSTRĀDE 5 kW ŪDEŅRAŽA DEGVIELAS ELEMENTAM

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K o p s a v i l k u m s

Ūdeņraža degvielas elementa invertoru sistēmas mājsaimniecības pielietojumiem parasti sastāv no līdzsprieguma paaugstināšanas un invertēšanas mezgliem. Šis raksts ir veltīts paaugstinošā līdzsprieguma pārveidotāja izstrādei 5 kW protonu apmaiņas membrānas degvielas elementam.

Rakstā izpētīts divu induktoru divtaktu strāvas avota paaugstinošais līdzsprieguma pārveidotājs, aplūkojot gan datormodelēšanas, gan eksperimentālos rezultātus.

Lai palielinātu DC/DC pārveidotāja efektivitāti var izmantot vairākus pārveidotāja moduļus, kam ieejas savienotas paralēli un izejās – virkne. Analīze Šajā raksta ir veikta analīze, balstoties uz kuras var izvēlieties skaitu pārveidotāj moduļu skaitu, kuri nodrošina vislabāko efektivitāti DC/DC pārveidotāja posmā.

Kopējais eksperimentāli noteiktais izstrādātās degvielas elementa pārveidotāju sistēmas fizikālā modeļa lietderības koeficients ir 93%.

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