Current-fed double inductor push-pull DC/DC converter with closed loop control system

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Abstract

In order to use hydrogen fuel cells in domestic applications either as main power supply or backup source, their low DC output voltage has to be matched to the level and frequency of the utility grid AC voltage. Such power converter systems usually consist of a DC-DC converter and a DC-AC inverter. A double inductor step-up push-pull converter with the output voltage and the input current control is investigated in this paper, presenting simulation and experimental results for passive and active overvoltage clamping. The prototype of the investigated converter is elaborated for 1200 W power to match the rated power of the proton exchange membrane (PEM) fuel cell located in hydrogen fuel cell research laboratory.

Keywords
Fuel cell system, high frequency power converters, ZVS converters

Introduction

The research of the hydrogen energy has gained a growing interest in the recent years. The hydrogen fuel cells are fully ecological, taking into account that heat and water are the only by-products, which are excreted into the environment [1]. In order to utilize the electrical energy, produced by fuel cells, characterized by slow dynamic response, low output voltage and large voltage variations, static power converters are researched widely.

The fuel cells used as main power supply or backup source in domestic application need to be connected to the grid. Such power converter systems usually consist of a DC-DC converter and a DC-AC converter. Because of comparatively high input and output voltage difference, most frequently as the optimal solution converters with high frequency transformer are acknowledged for the DC-DC stage [1]-[4]. There are many known transformer isolated dc-dc converter topologies, which could be suitable to perform the necessary voltage boost from the fuel cell voltage level to the inverter dc link voltage. Such converters are the full-bridge, half-bridge, the flyback, the forward and the push-pull basic topologies, as well as a number of their derived topologies [5], [6]. These can be divided into two groups – voltage source converters and current fed converters. In this paper a current fed topology is preferred, since it is characterized by low input current ripple, which is more appropriate for proton exchange membrane fuel cells modules [3],[4].

Considering the necessity of high voltage boosting function with low input current ripple, the most appropriate converters are current fed full-bridge and push-pull configurations. Since the converter efficiency can be considerably improved by reducing the count of the primary switches and implementing a transformer of a simple structure (without split windings), a double inductor push-pull converter (DIC) was selected and analyzed in this paper Fig. 1. The converter is elaborated for 1200 W power, since such is the rated power of the proton exchange membrane (PEM) fuel cell in hydrogen fuel cell research laboratory of Riga Technical University.

![Fig. 1. Current fed double inductor push-pull converter topology](image)

The hard switching converters have a drawback of voltage overshoots at turn-off due to the energy stored in the parasitic inductances. These voltage spikes are not only dangerous to the transistors but they substantially increase the switching losses.

There are two basic ways to protect the transistor switches from being damaged by the overvoltage. The first is using transistors with blocking voltage ratings that exceed these stresses. This, however, results in poor utilization of the transistors, since on state resistance of the MOSFET transistors increases dramatically with increased blocking voltage.

1 Control of the converter

To control the designed converter it will be compared two control types, the duty-cycle and the current control. In all switching converters, the output voltage is desired to be kept constant, in
despite of the disturbances in the converter element values, or inputs. For this, a control system is needed which can automatically adjust the duty cycle as necessary to keep constant the output voltage within an acceptable range, regardless of the load current or input changes. [5]

Two types of control for the DIC push-pull boost converter, the direct duty-cycle control and the current control. In the following will be briefly described both of them, enumerating some advantages and disadvantages for each. Basic scheme is depicted by Fig. 2.

![Fig. 2. Control of the converter](image)

1.1 Duty Cycle control

In duty-cycle control model the output voltage is measured and then compared to the reference voltage. The error signal is used as input in the compensator, which will compute from it the duty-cycle reference for the pulse-width modulator. Its principle is illustrated Fig. 3.

![Fig. 3. Direct duty-cycle control scheme](image)

1.2. Current control

In current control model the converter output is controlled by choice of the transistor peak current. The control signal is a current and a simple control network switches on and off the transistor such its peak current follows the control input.

In the literature [5] and [6] is stated that the current control, in the case of an isolated boost push-pull converter has some advantages against the duty-cycle control. First, it has simpler dynamics (removes one pole from the control-to-output transfer function). Second, it makes use of the current sensor information in normal operation mode – transistor failures due to excessive currents can be prevented by limiting the reference switch current. In the transformer can be induced a dc bias current by small voltage imbalances due to the small differences in boost inductors and/or switches.

The current control will alter the switch duty cycles in a way that these imbalances tend to disappear and the transformer volt-second balance to be maintained.

The disadvantage is that the current control has a susceptibility to noise in the reference and measured switch current signals. In general, a small amount of filtering is necessary for the measured current. The current control becomes unstable whenever the duty-cycle becomes larger than 0.5. This drawback can be overcome by adding an artificial ramp to the reference current signal.

Considering the above arguments, the current control seems to be more attractive for the present application.

1.3 The current controlled converter model

Evaluating the model of the current controller implies the calculation of the relation between the inductor current and the control signal Fig. 4. In our case there are two inductors and in the relation will be used the sum of these two inductor currents.

![Fig. 4. Current control scheme](image)

Is a known problem of the current control that it becomes unstable when the duty cycle passes by 0.5. The addition of an artificial ramp to the sensed signal can improve the stability of the controller, and for an adequate slope, it can be stable for all duty-cycles. However, in the present case the maximum duty-cycle is 0.5, thereby only a small slope is required, to improve the noise immunity of the system. This small slope will not influence the converter transfer functions and controller design.

The most important are that: it keeps the input current under a desired value and it realizes the current balance between positive and negative alternance in the high frequency transformer preventing the saturation of the transformer core.

The measured signals are the fuel cell voltage (VFC) and current (IFC) and the output voltage (VDC) Fig. 5. The fuel cell current (IFC) and output voltage (VDC) are used as feedback signals in control.

The protection is realized by using all the measured signals.

The voltages VDC and VFC are measured by means of resistive voltage dividers while the fuel cell current (input current) is measured with a current transducer (LEM).
Experimental set-up of the control board was fulfilled by the Field-Programmable-Gate-Array (FPGA). Flowchart of the FPGA’s program is illustrated in general by Fig. 6. It should be mentioned that the voltage-to-frequency integrated circuit was used at the FPGA’s input, as it generates related square-wave signal with defined frequency depending on the input voltage. The control system was tuned so that 100 kHz square-wave signal is at FPGA’s input related to the nominal output voltage of the DIC converter.

\[
C_{\text{clamp}} > T_m^2 (1 - D)^2 / \pi^2 \cdot L_{\text{lk}}.
\]  

To achieve ZVS for the main switch, it must be turned on after turn-off the auxiliary switch. This delay should be selected to be less than one quarter of the resonant period formed by \(L_{\text{lk}} \) and \(C_1\) capacitor \[4\]

\[
T_{M1-M1a} = \sqrt{L_{\text{lk}} \cdot C_1 \cdot \pi / 2},
\]  

where the value for \(C_1\) has been taken from the datasheet of the chosen switch. The maximum time delay between turning off the main switch and turning on the auxiliary, using the calculated minimum value for the clamping capacitor can be considered by

\[
T_{M1-M1a} = \sqrt{L_{\text{lk}} \cdot C_{\text{clamp}} \cdot \pi / 2}.
\]  

**3 Simulation of the DIC converter**

The simulation of the DIC converter was done using LTspice simulation tool. Since a steady operation point was to be examined, the FC was modelled by a constant voltage source. The core losses of the inductances were neglected. The transformer was modelled as an ideal transformer introducing the leakage inductance in series. The power MOSFET transistor switches (IXFN73N30) and active clamping MOSFET transistors (IRF740) were modelled using SPICE models provided by the manufacturers.

The operation conditions of the simulation are adjusted to the rated parameters of the converter.
Active load with a small filter capacitor of 10 µF was considered. The value of leakage inductance ($L_{lk} = 4.8$ µH) was obtained experimentally, by measuring the transformers mutual and self-inductances. It can also be noted, that the converter operates as desired, providing 400 V output voltage at rated input and load conditions and that the transistor voltage does not exceed the maximum allowed voltage of main power transistor 300 V and maximum allowed current 73 A.

The schematic of DIC converter with active clamping circuit in LTspice environment and simulation results for the active clamping topology are presented in Fig. 8. and Fig. 9. It can be noted that the shape of the auxiliary switch current is determined by the resonant circuit formed by the $L_{lk}$ and $C_{clamp}$.

![DIC Converter schematics with Active Clamping Circuit in LTSpice environment](image)

**Fig. 8. DIC Converter schematics with Active Clamping Circuit in LTSpice environment**

**4 Experimental results**

Experimental testing of active clamping DIC converter was carried out as well. The testing was performed using Ballard Nexa PEM fuel cell module with nominal power 1.2 kW and connecting the DIC converter to a resistive load. Measurements of the input current, input voltage and load voltage and current were done. Then the efficiency of the converter was calculated. The efficiency of the DIC converter with the active clamping circuit is around 93 % (Table 1.)

<table>
<thead>
<tr>
<th>Parameter (averal values)</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vin</td>
<td>26.7 V</td>
</tr>
<tr>
<td>Vout</td>
<td>336 V</td>
</tr>
<tr>
<td>Iin</td>
<td>28.73 A</td>
</tr>
<tr>
<td>Iout</td>
<td>2.12 A</td>
</tr>
<tr>
<td>Efficiency</td>
<td>93 %</td>
</tr>
</tbody>
</table>

Faster diodes (better turn-on and turn-off characteristics than integrated diodes in transistors) and 2.2 nF capacitors were added in parallel with active clamping transistors. In parallel with the power transistors, RC snubber circuits were implemented composed of 4.7 nF polyester film capacitors and 4.7 $\Omega$ 5 W resistors. Basing on equation (3) the capacitance of the clamping capacitor was 3.3 µF.

Experimental waveforms of the DIC converter with the active clamping circuit are shown in Fig. 10. It was possible to test converter at the full load as there was no primary switch overvoltage problems.

![Experimental waveforms of the DIC converter with the active clamping](image)

**Fig. 10. Experimental waveforms of the DIC converter with the active clamping – from the top: voltage across one active clamping transistor, voltage across one power transistor**

From the Fig. 11. it can be noticed that the load variation does not change the output voltage of the converter considerably. The following can be concluded, that the closed loop control system works as it changes the duty-cycle depending on the load and the output voltage remains constant.

![Graph showing load variation](image)
Fig. 11. Experimental waveforms of the DIC converter with the active clamping – from the top: output voltage, output current.

Conclusions

The power converter needed in order to use the hydrogen fuel cell as a main power supply or backup source in domestic applications, usually consists of a step-up DC/DC stage and a DC/AC inverter stage. As an efficient solution for the DC/DC stage – a double inductor push pull converter with active voltage clamping circuit is analyzed in this paper presenting simulation and experimental results.

It was acknowledged that the DIC converter with active clamping circuit performs well and the efficiency of the converter is 93%. The efficiency could be further increased basically in two ways: by decreasing the resistance of the converter’s primary circuit components or by reducing the primary current, which can be achieved by connecting two or more identical converters in parallel.

The ripple of the input current of the experimental prototype is below ± 5% of the mean value, which is within acceptable limits for the fuel cell.

The elaborated prototype of double inductor push-pull DC/DC converter with active clamping circuit can be used as a background for further work on clamp circuit optimization and the hardware implementation of the control, using a dedicated integrated circuit, for a current fed converter implies new problems, as the signal conditioning in order to realize the overlapping of the gate signals. However, using dedicated PWM controllers have important advantages as soft start-up and built-in over-current protection.

References