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High-efficiency DC/DC converter for low-voltage applications

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Abstract. The paper focuses on a DC/DC converter that is used to adapt a varying output voltage from a solar panel to demands of an electrolyzer unit or battery charging purposes. The converter covers an input voltage span from 9 V to 24 V and has an output voltage of 12 V at a maximum current of 50 A. A modular topology of the converter is described along with a microcontroller control strategy. Finally, the efficiency increase of the synchronous interleaved buck-boost converter in various operating modes and load changes is experimentally evaluated and compared to the 2-transistor buck-boost converter.

Keywords: synchronous buck-boost converter, switched-mode power supply, electrolyzer, hydrogen production, efficiency

DC/DC pretvornik z visokim izkoristkom za nizkonapetostne aplikacije

Povzetek. V članku je predstavljen DC/DC pretvornik, namenjen vmesni močnostni stopnji med spremenljivim napetostnim izhodom sončnih panelov in porabnikom - elektrolizno enoto. Pretvornik zagotavlja konstantno izhodno napetost kljub spremenljivi izhodni napetosti sončnih panelov, ki je posledica spremenljivega sončnega obsevanja. Predstavljena zgradba in krmiljenje pretvornika naprej omogočata tudi polnjenje baterijskih celic s konstantnim električnim tokom. Poleg opisa pretvornika in regulacije izhodnih veličin so v članku podani tudi izmerjeni rezultati izkoristkov predstavljenih topologij pretvornika.

Ključne besede: sinhroni pretvornik navzdol-navzgor, stikalni pretvornik, elektrolizna enota, proizvodnja vodika, izkoristek

1 Introduction

Among various approaches to electricity generation that are environmentally friendly, photovoltaic (PV) modules are becoming more and more popular. Due to their low production costs, high efficiency and long lifetime, the number of installed PV modules is growing rapidly with the annual growth rate of more than 30% [1]. Consequently, there is a great demand for systems that enable electricity transformation and – if possible – also energy storage. The latter is of significant importance due to a non-constant available solar radiation. A traditional approach here is to implement a system with a stack of batteries that are charged with a surplus energy from the PV panel and are being used when electricity demands are higher than the available energy from the PV panel. At a first sight, such a solution is not problematic, however several issues regarding the batteries have to be addressed. Among them, the battery power management and consequently the number of charging/discharging cycles of the battery are crucial. Another aspect that is becoming more and more relevant is connected with the treatment of used batteries. A possible way to overcome the battery-related problems is to implement an electrochemical device – an electrolyzer producing hydrogen from water by means of electricity. With this approach, the surplus of electricity that can not be used immediately (or can not be stored in batteries) is used to convert chemically-bonded energy of water into hydrogen gas. This can then be used in another electrochemical device – fuel cell, when there is a demand for electricity. Since the efficiency of these electrochemical transformations is relatively low [2] compared to efficiencies of electricity transformation (modern transformers, inverters, converters, etc.), a special attention is required. Namely, the electrochemical transformation, and therefore in this case the hydrogen production, is only justified when the electricity for its operation is obtained either from renewable sources and there is a surplus of available electricity at that point or from conventionally obtained electricity in a “low tariff” period.

A principal block diagram of a system that enables the storage of surplus electricity in a form of hydrogen is shown in Figure 1. Normally, a direct path of electricity from renewable sources is set through a DC/DC converter, followed by a DC/AC inverter which can be finally synchronized and connected to a public electrical network or be used as a stand-alone AC system. Alternatively, the electricity is used to supply the electrolyzer for hydrogen production. In both cases, the output of renewable sources has to be adapted for further use. In this paper, a DC/DC converter that is designed to cover an input voltage span from 9 V to 24

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V and delivers 12 V of output voltage is described in detail.

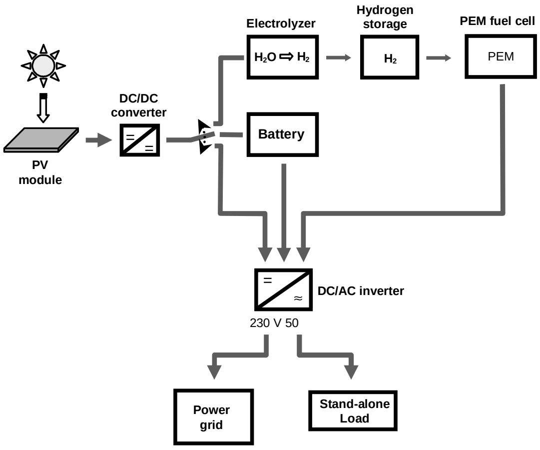

Figure 1. Electricity conversion with hydrogen generation option

2 DC/DC converter

The proposed scheme for hydrogen production is based on a DC/DC converter that can operate in a step-up (boost) mode when the input voltage is lower than the output or in a step-down (buck) mode, when the input voltage is higher than the required output. Normally, for this operation, a buck-boost topology of converter is selected (Figure 2). One can observe that there are four semiconductor devices implemented in the diagram – two transistors and two diodes. Since the voltage drop on these elements can represent a significant part of the output voltage, MOSFET transistors with low $R_{DS\text{-}ON}$ are required. To minimize the voltage drop and consequently losses, two diodes can be replaced with transistors, as seen in Figure 3, to utilize the active conducting of transistors [3]. Such topology is known as synchronous non-inverting buck-boost converter.

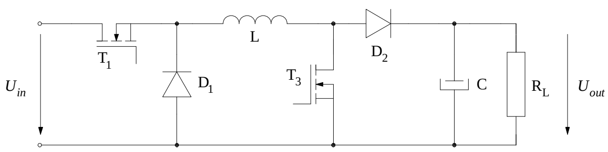

Figure 2. 2-transistor buck-boost converter

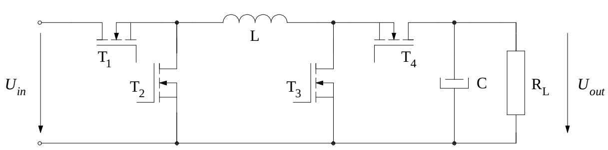

Figure 3. 4-transistor buck-boost converter

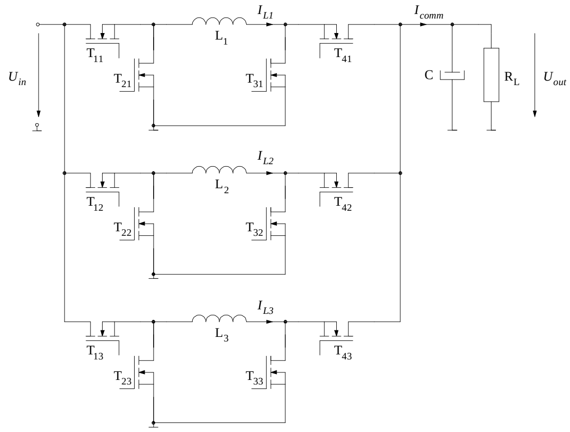

Figure 4. Proposed modular topology

In order to increase the power capability, three identical modules are connected in parallel (Figure 4). In this way, transistors with lower current rating can be used, since the output current is shared equally among the modules. Interconnection of multiple (N) converters operates with identical switching frequency f_s, but with phase shifting of

$$\alpha = \frac{360°}{N} \quad (1)$$

between them (Figure 5). The benefit of such interleave power conversion technique is the ripple cancellation effect [4]. As seen in Figure 5, the frequency of the common current ripple is three times the frequency of the single module current ripple.

$$\Delta i_{out} \ \alpha \ \frac{1}{f_s} \quad (2)$$

Due to the inverse proportion of the inductor current ripple Δi_{out} and switching frequency f_s (2), the modular topology of the synchronous buck-boost converter offers lower common current ripple. In an interleaved multiphase converter, the value of the common current ripple is also a function of a duty cycle D. The current ripple cancellation factor K_Δ is introduced, which is defined as the ratio of the magnitudes of common current ripple Δi_{out} and inductor current ripple Δi_L.

$$K_\Delta = \frac{\Delta i_{out}}{\Delta i_L} = \frac{N\left(D - \frac{m}{N}\right)\left(\frac{m+1}{N} - D\right)}{D\,(1 - D)} \quad (3)$$

The value m corresponds to the maximum integer that does not exceed the product of the number of phases (N) and the duty cycle (D). The waveform of the normalized common current ripple for a built converter can be seen in Figure 6, if all three modules operate with the same duty cycle. Such effect enables the use of a smaller inductance that improves the transient response.

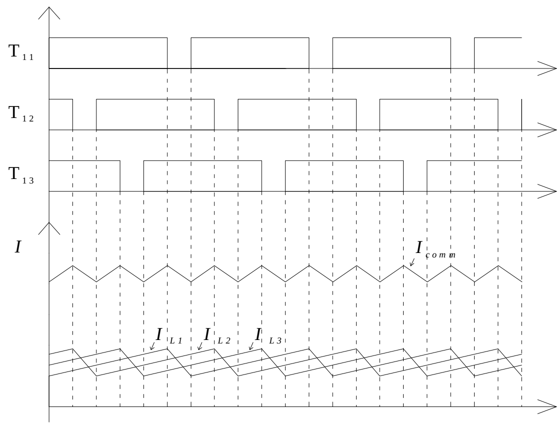

Figure 5. Characteristic waveforms of three parallel modules in a buck mode

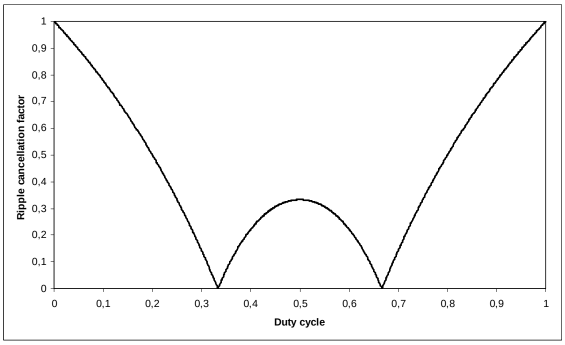

Figure 6. Normalized common current ripple vs. duty cycle

3 Transistors switching strategies

The proposed synchronous non-inverting buck-boost converter in Figure 3 offers three operating modes that are implemented due to variable input voltage [5].

When an input voltage U_{in} is higher than the controlled output voltage U_{out}, the converter is set up for a buck mode. In this mode, the transistor T_4 is always on, transistor T_3 is always off, while transistors T_1 and T_2 are in a complementary mode, therefore switched on and off sequentially. Turning transistor T_1 in an on-state (transistor T_2 is consequently switched off) the magnetization cycle of the inductor L begins and the supply energy is transferred to the load. In the demagnetization cycle (transistor T_1 is switched off and transistor T_2 is switched on) the energy stored in the inductor L is delivered to the load and current decreases nearly linearly, until transistor T_1 is switched on again.

If the input voltage drops below the desired output voltage, the boost mode of the converter is implemented. In such mode, the transistor T_1 is always on, transistor T_2 is always off and the output transistor pair (T_3 and T_4) is being switched complementary. While transistor T_3 is on, the inductor is being magnetized by the input current and the capacitor is supplying output current to the load. At the end of the duty cycle, the transistor T_3 is switched off and transistor T_4 is switched on. Until the beginning of the next cycle, the stored energy in the inductor is delivered to the capacitor and to the load.

The proposed topology of the DC/DC converter also permits the use of a buck-boost operating mode when the input voltage is close to the controlled output voltage. In this mode, the transistors T_1 and T_3 represent one switching pair and are responsible for magnetizing the inductor like in the boost mode, while transistors T_2 and T_4 form another pair that carries the stored energy to the output, similar to the demagnetizing buck mode.

Due to the use of a 4-transistor buck-boost converter and its symmetrical topology, the flow of energy can be reversed. Such an operation is viable in the case of a low or no solar radiation, thus delivering the stored energy from batteries to the load.

3.1 Implementation of the PWM controller

The described switching strategies are implemented using a Microchip microcontroller, which enables the converter to operate in either voltage or current mode.

For hydrogen generation by means of electrolysis, a voltage control mode is being applied. Its block diagram is seen in Figure 7. The output voltage U_{out} of the converter is controlled in the outer control loop. The voltage error ε_u is an input to the proportional-integral (PI) controller which sets a reference I^* for the inner current loops. Due to the interleaved control, each module has its own current control, consisting of its inductor current feedback and a PI controller, adjusting a duty cycle for the switching transistors. One module contributes one-third of the overall load current and its commutation cycle is phase shifted by 120° compared to other two modules. The presented current control loops prevent the uneven distribution of current through modules, especially during transients, due to slight differences between modules that occurs during construction.

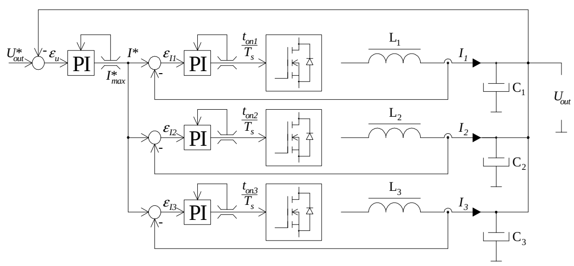

Figure 7. Voltage and current control loops

Such control scheme also permits a current control mode for charging batteries. In such mode, the user can directly set the current reference and therefore the value of the load current. Here, the output voltage feedback is used only for measuring purposes.

Apart from a microcontroller and its peripheral circuits there is also an electrical circuit that monitors inductors' currents. If the inductor current during demagnetizing period of the switching cycle falls to zero, it prevents discharging of the output capacitor C_{out} through the inductor back to the source by switching off transistors T_1 and T_4.

4 Experimental results

A 600 W - prototype of the described DC/DC converter was built and tested (Table 1, Figure 8).

$C_{1,2,3}$	4400 µF
$L_{1,2,3}$	30 µH
U_{out}	12 V
f_s	40 kHz
MOSFETs	IRFB4310Z
Microcontroller	dsPIC30F2023

Table 1. Parameters and relevant components of the DC/DC converter

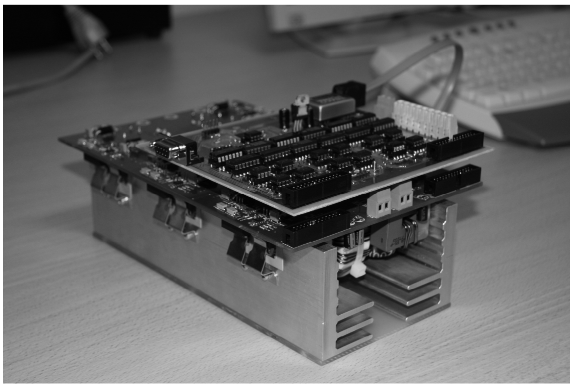

Figure 8. Prototype of an interleaved synchronous non-inverting buck-boost converter

The main focus of the testing setup was to verify and experimentally determine the efficiency increase of a 4-transistor buck-boost converter compared to a 2-transistor buck-boost converter. All of the presented results were measured using a resistive load with a constant input voltage of 24 V for buck mode and 9 V for boost mode.

Comparing the synchronous and 2-transistor converter (Figure 9), an average increase of 5,8% in efficiency was measured when operating in a buck mode. In the boost mode, the increase is 3,6%. One can further notice that in the boost mode the efficiency is decreasing rapidly with the output power increase, due to dominating conduction losses [6]-[8]. There is also a noticeable increase in efficiency when the converter operates interleaved with all the three modules active apart from the single buck-boost converter. The reason for such increase is in the distributed current through the interleaved converter. The conduction losses are decreased since they are a square function of the load current. In the region where the output power is low, the switching losses of the MOSFETs are predominant and therefore a single buck-boost converter has the advantage regarding efficiency. The current waveforms of various operating modes and hardware set-ups are presented (Figure 10 - Figure 13).

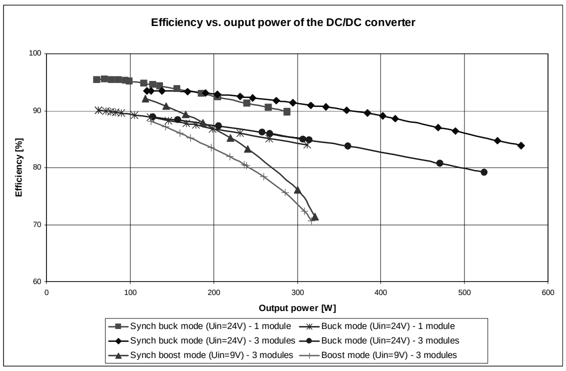

Figure 9. Efficiency of the buck-boost converter as a function of the output power in various hardware settings

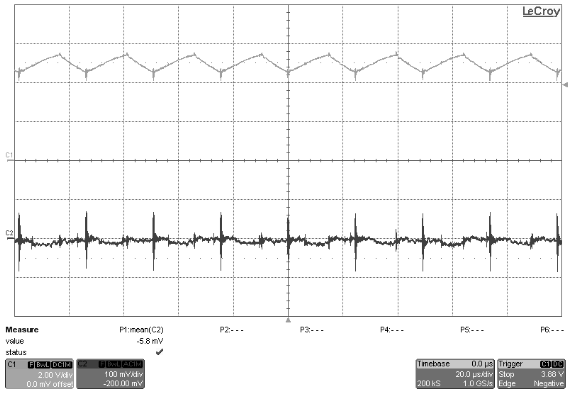

Figure 10. Buck mode, single module; U_{in} = 24V; I_{out} = 25A; Ch1 – Inductor current (k_{IL} = 10A/div), Ch2 – Output current ripple (k_{IR} = 100mA/div); k_t = 20µs/div;

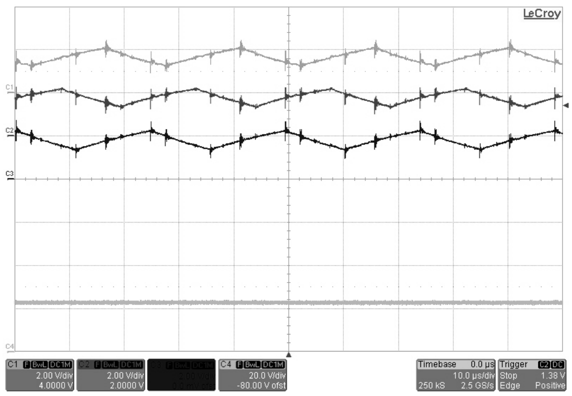

Figure 11. Synchronous buck mode, three modules; U_{in} = 24V; I_{out} = 25A; Ch1,2,3 – Inductor currents I_{L1}, I_{L2} and I_{L3} (k_{IL} = 10A/div), Ch2 – Output voltage (k_U = 10V/div); k_t = 10µs/div;

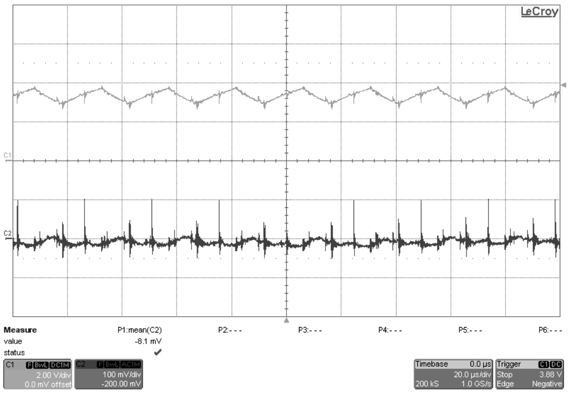

Figure 12. Synchronous buck mode, three modules; U_{in} = 24V; I_{out} = 50A; Ch1 – Inductor current (k_{IL} = 10A/div), Ch2 – Output current ripple (k_{IR} = 100mA/div); k_t = 20µs/div;

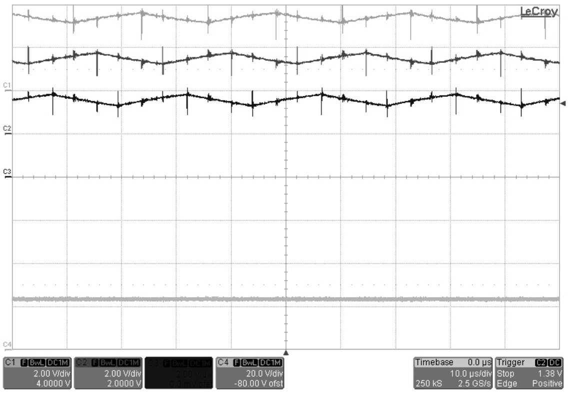

Figure 13. Synchronous boost mode, three modules; U_{in} = 9V; I_{out} = 25A; Ch1,2,3 – Inductor currents I_{L1}, I_{L2} and I_{L3} (k_{IL} = 10A/div), Ch2 – Output voltage (k_U = 10V/div); k_t = 10µs/div;

5 Conclusion

In the paper, a DC/DC converter that is to be used in a process of hydrogen generation with an electrolyzer and supplied from a solar panel is described. The main attention was paid to the variable input voltage from the solar panel due to a non-constant solar radiation. The proposed converter consists of four MOSFET transistors with low-voltage drops to minimize the energy losses. In order to implement low current MOSFETs, a modular topology of the converter is introduced and analyzed. The topology consists of three modules that are connected in parallel and therefore have the same input and output voltage. On the other hand, the load (output) current is divided equally (or upon a certain rule) among the modules. Another benefit of the modular topology is a lower common current ripple due to an interleaved current control principle.

As seen in the presented results, there is a substantial increase in the interleaved converter efficiency compared to the single synchronous converter and 2-transistor buck-boost converter with freewheeling diodes. The measurements indicate that the proposed topology of the converter is a promising option for achieving higher efficiency in power transformation systems.

The focus of the future work will be on determining an optimum operating point for a system consisting of a PV panel and its maximum output power point, DC/DC converter and electrolyzer with its hydrogen production efficiency.

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