High Step-Up Ratio DC-to-DC Converter with Recuperation of the Leakage Energy

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Abstract: - Increasing the efficiency of power converters is an important topic. The here proposed converter can be used to boost up the battery supply voltage e.g. for electric auxiliary drives to drive compressors in air conditioning devices in automotive applications. A special DC-to-DC converter is necessary to couple the batteries or fuel cells, operating at low DC-voltages, to the converter's DC-link. These converters with rather low input respectively high output voltage ratings have, due to the high current ratings, a relatively low efficiency. Therefore, a special design is required to adapt the different voltage levels and fulfill the requirements of loss reduction. In this paper, a possible solution for such a specific vehicle converter is presented: a DC-to-DC converter with a controlled active snubber circuit. The input voltage of 12 V or 24 V is adapted to a 400 V DC-link to supply a cheap and simple of-the-shelf inverter of the air condition unit. The total power to be managed on the output of the DC-to-DC converter is 500 W (12 V) respectively 1 kW (24 V) in our case. The proposed topology is also well suited for paralleling several power converters.

Key-Words: - DC-to-DC conversion, vehicle application, energy recuperation, efficiency increasing

1 Introduction

Conventional solutions [5, 7, 8, 9] for efficiency optimized low-to-high voltage DC-to-DC converters use large over dimensioning of all power semiconductors, reduced switching frequency, and hard switching topologies leading to bigger size and weight of the converters. In this paper a special design for the voltage adapting DC-to-DC converter is presented, where an additional converter is used to feed back most occurring snubber losses. This helps to increase the over-all efficiency of the first stage for about 2.5% compared to conventional solutions. Nevertheless, the switching frequency can be raised to a serviceable range (up to several 100 kHz) without appreciable losses in the main snubber.

For larger power application it also makes sense to operate several phase-shifted converter stages in parallel sharing the load to achieve better over-all efficiency. It is also useful for redundant systems e.g. cooling devices for transportations of medicines.

The presented solution is designed to adapt a 12 V or 24 V battery to a 400 V DC-link, well-suited to drive standard DC-to-AC inverters. The conversion ratio, depending on the input voltage range from 10..14.4 V (20..28.8 V) to output voltage range 380..400 V therefore varies from 1/26 up to 1/40 at 12 V. Another solution realized by a double stage step-up converter is shown in [6]. For solar application see [4], and for fuel cells [10].

The total power to be managed on the output of the DC-to-DC converter is about1 kW. In case of a single stage inverter, this leads to about 100 A input current (at 12 V), causing peak values in the power switches of up to 200 A! The resulting component stress is very hard and also the design is difficult to handle. So it is suitable to select a topology which is also well suited for paralleling the power switches leading to a scaleable solution with the possibility of a more optimal design in each stage. Here a structure was used where several converter stages can easily be paralleled due to their current source characteristics.

The principal energy flow of the first stage (DC-to-DC converter for voltage level adaptation) of the converter topology is given in Fig. 1. The different sections are marked:

1 over voltage protection device

2 main converter (consists of a DC-to-AC inverter, the main transformer and a rectifier)

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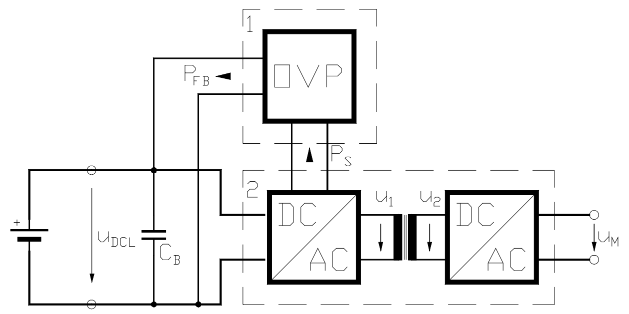

Fig. 1. Converter with passive clamping topology: 1-over voltage protection, 2-main converter section (DC-to-AC, AC-to-DC)

During normal operation both converters work simultaneously. Therefore synergies can be used to optimize the system structure leading to an effective design. The main goal of this investigation is to find a topology which overcomes the inconvenient system arrangement and to find a simple and robust solution. The chosen structure based on the well-known push-pull converter [3] is given in Fig. 2.

Due to the leakage inductance of the main transformer, a snubber circuit is required to protect the primary switches from over voltage. The energy, stored in the leakage inductor of the transformer

$$W_{Tr} = \frac{L_\sigma \cdot i^2}{2} \tag{1}$$

times twice the switching frequency has to be handled by the snubber

$$P_S = L_\sigma \cdot i^2 \cdot f\ . \tag{2}$$

Due to the rather high primary current (for 12 V operation about 200 A in the peak can be assumed), this leads to excessive additional losses of the converter which perceivably lowers its efficiency. During normal operation (without any transformer losses) the voltage across C_S is twice the input voltage U_{IN} (resulting from the push-pull concept). This also leads to snubber losses without any damping effect.

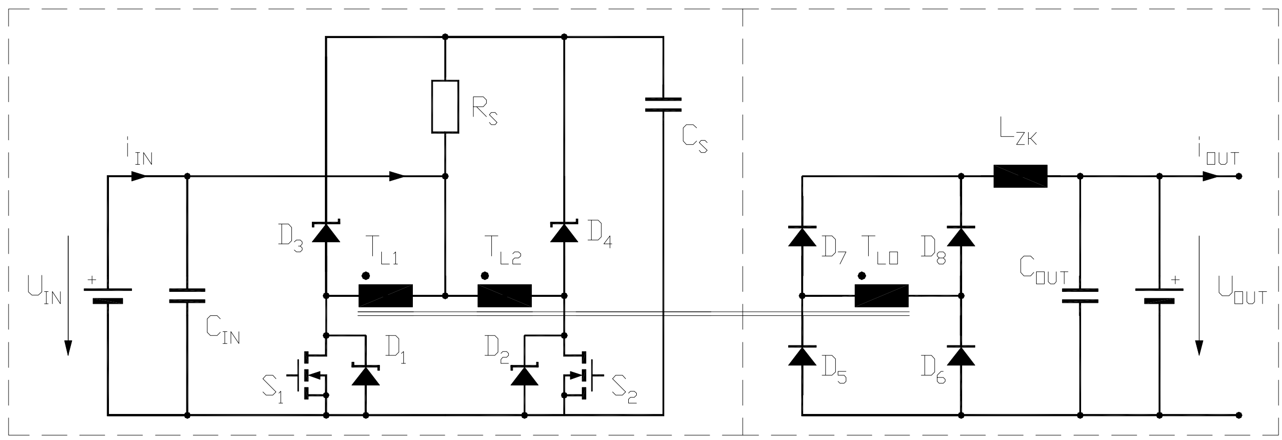

Fig. 2. Conventional Solution: Push-Pull converter with passive over voltage snubber circuit, built by R_S and C_S is used

2 Active Clamping Circuit

To increase the efficiency an additional, controlled DC-to-DC converter is used to feed back the energy stored in the leakage inductor of the transformer.

Figure 3 explains the principal operation. The converter proposed here uses the well-known push-pull converter in the up-link and a buck converter for energy recuperation. A special control circuit was implemented to optimize the system behavior. Input voltage was measured and current was estimated to control the snubber voltage. The usage of a dynamically controlled snubber voltage leads to a remarkable efficiency improvement. A buck-converter was added to control the energy flow from the storage capacitor of the snubber to the input section.

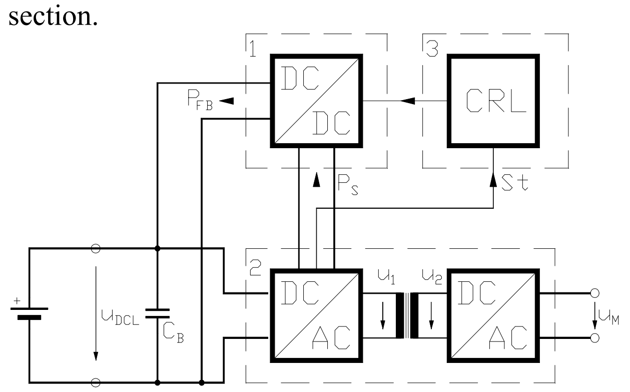

Fig. 3. Proposed inverter topology: 1-energy recuperation, 2-main converter section, 3-snubber converter controller

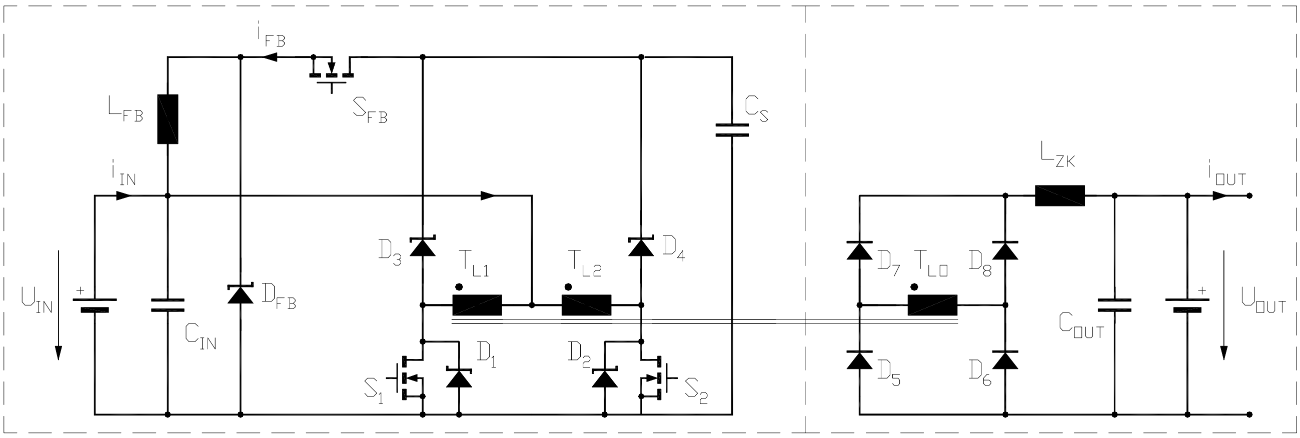

Fig. 4. Improved solution: active snubber circuit for energy recuperation (buck-converter formed by C_S, S_{FB}, D_{FB}, L_{FB})

The big advantage of this topology is that adaptive control of this converter helps minimizing system losses while the maximum voltage across the main switches can exactly be defined.

The result is an optimized converter structure with minimized component count leading to an easy-to-handle and robust design, well suited for paralleling.

Figure 4 shows a detailed circuit diagram of the complete DC-to-DC converter consisting of the push-pull stage with the active switches (S_1 and S_2), the overvoltage protection network with the diodes D_3 and D_4, the energy recuperation buck-converter formed by C_S, S_{FB}, D_{FB}, L_{FB}, and the secondary bridge rectifier with the diodes D_5 till D_8.

2.1. Modeling of the overvoltage protection with resistor

The necessary state variables are the current through the leakage inductor $i_{L\sigma}$ and the voltage across the snubber capacitor u_{CS}

$$\frac{d}{dt}\begin{pmatrix} i_{L\sigma} \\ u_{CS} \end{pmatrix} = \begin{bmatrix} -\frac{R_D + R_C // R_S + R_T}{L_\sigma} & -\frac{R_S}{(R_C + R_S)L_\sigma} \\ \frac{R_S}{(R_C + R_S)\cdot C_S} & -\frac{1}{(R_C + R_S)\cdot C_S} \end{bmatrix} \cdot \begin{pmatrix} i_{L\sigma} \\ u_{CS} \end{pmatrix} + \begin{pmatrix} \frac{R_C + 2R_S}{(R_C + R_S)L_\sigma} \\ \frac{1}{(R_C + R_S)\cdot C_S} \end{pmatrix} \cdot U_{IN} - \begin{pmatrix} \frac{V_D}{L_\sigma} \\ 0 \end{pmatrix} \quad (3)$$

Here he diodes are modeled by a series connection of a resistor R_D and a fixed voltage V_D representing the forward voltage of the diode. R_T is the resistor of one primary winding and R_C the series resistor of the capacitor C_S. $R_C//R_S$ is an abbreviation for the parallel connection of R_S and R_C. The description is valid after turn-off of one of the main switches (S_1 or S_2) until the current in the stray inductance L_σ reaches zero, then the limiter diode (D_1 or D_2) turns off. The initial conditions are I0 and U_{CS0}.

The necessary snubber resistor R_S can be calculated by a simple energy consideration

$$f \cdot \frac{L_\sigma \cdot I_0^2}{2} \cdot 2 = \frac{9 \cdot U_{IN}^2}{R_S} \quad (4)$$

with the switching frequency f of one transistor and four times the input voltage U_{IN} (a nearly optimal value) across the snubber capacitor C_S to

$$R_S = \frac{9 \cdot U_{IN}^2}{f \cdot L_\sigma \cdot I_0^2} \quad . \quad (5)$$

2.2. Modeling of the overvoltage protection with step-down converter

We have to distinguish between the charging mode, when the current through the stray inductance commutates into the over-voltage capacitor C_S

$$\frac{d}{dt}\begin{pmatrix} i_{L\sigma} \\ u_{CS} \end{pmatrix} = \begin{bmatrix} -\frac{R_T + R_D + R_C}{L_\sigma} & -\frac{1}{L_\sigma} \\ \frac{1}{C_S} & 0 \end{bmatrix} \cdot \begin{pmatrix} i_{L\sigma} \\ u_{CS} \end{pmatrix} + \begin{pmatrix} \frac{2}{L_\sigma} \\ 0 \end{pmatrix} \cdot U_{IN} + \begin{pmatrix} -\frac{V_D}{L_\sigma} \\ 0 \end{pmatrix} . \quad (6)$$

The factor two is due to the coupling of the transformer. The diode is modeled by a series connection of a resistor R_D and a fixed voltage V_D representing the forward voltage of the diode. R_T is the resistor of one primary winding and R_C the series resistor of the capacitor C_S. The second mode is the converter state for feeding back the energy into the input source.

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When the switches of the main converter (S_1, S_2) and the switch (S_{FB}) of the feedback converter are synchronized we get with the switching function (this is 1 when the switch (S_{FB}) is on and 0 when the switch (S_{FB}) is off) in continuous inductor current mode

$$\frac{d}{dt}\begin{pmatrix} i_{LFB} \\ u_{CS} \end{pmatrix} = \begin{bmatrix} -\dfrac{R_{LFB} + \bar{\sigma} \cdot R_{DFB} + \sigma \cdot R_{CS}}{L_{FB}} & -\dfrac{\sigma}{L_{FB}} \\ -\dfrac{\sigma}{C_S} & 0 \end{bmatrix} \cdot \begin{pmatrix} i_{LFB} \\ u_{CS} \end{pmatrix} + \begin{pmatrix} -\dfrac{1}{L_{FB}} \\ 0 \end{pmatrix} \cdot U_{IN} + \begin{pmatrix} -\dfrac{V_{DFB}}{L_{FB}} \\ 0 \end{pmatrix} \quad .(7)$$

R_{LFB}, R_{DFB}, R_{CS} are the loss resistors of the converter inductor L_{FB}, of the diode D_{FB}, and of the snubber capacitor C_S, respectively. The fixed forward voltage of the diode model is V_{DFB}.

3 Converter Design

To ensure a simple design an industrial standard buck voltage regulator was used as basics of the snubber-converter. Figure 5 shows the principal realization. In this design a simple PI-controller is used to specify a desired upper rail in the snubber voltage US. The usage of a fixed upper limit leads to a very simple design, where standard components can be used and additional measurement equipment can be avoided.

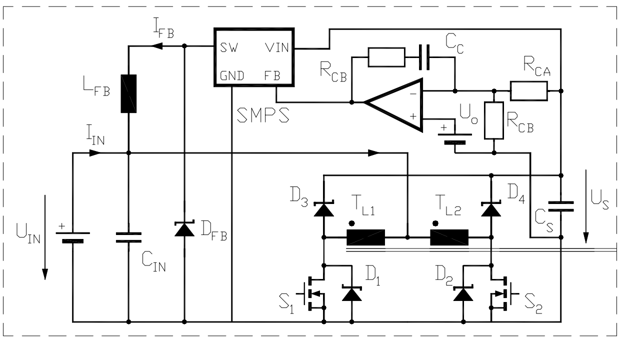

Fig. 5. Principle realization of the recuperation stage

3.1. Converter Design: Simulation

To explain the operation principle the proposed converter structure was simulated in PSPICE based on a circuit level model. A 1 kW converter was modeled and compared to conventional solutions. The technical characteristics of the simulation model are:

Input voltage:	12 V
Output voltage:	400 V
Max. output power:	1000 W
Switching frequency:	100 kHz

The simulation results are given in Table 1. One can see the significant improvement of the inverter's efficiency.

TABLE 1: Efficiency Comparison (theoretical improvements

P_L /W	50	100	200	300	500	1k
PWM-Top.[%]	77.6	86.6	91.6	92.7	92.6	89.5
Adv. Top.[%]	89.2	92.3	97.8	96.7	94.5	90.0

3.2. Converter Design: Realization

To verify the basic simulation results an advanced model was derived to check the full dynamic behavior. In this 'practical' model the linearized current sink (representing the recuperation converter) was replaced by a switching regulator model, with a transfer power of max. 10 A, and the results are compared to a conventional snubber solution.

TABLE 2: Efficiency Comparison

P_L / W	50	100	200	300	500	1k	1.2k
PWM-Top./ W	77.6	86.6	91.6	92.7	92.6	89.5	87.0
Adv. Top. /W	88.1	91.7	97.2	96.5	94.3	89.8	89,1

Table 2 shows the results when a state-of-the-art SMPS-circuit (LT 1170) for energy recovery was used. In all simulation models the duty-cycle was precalculated and fixed during simulation.

The comparison clarifies the improvement resulting from the altered topology. It should be mentioned that an M2 rectifier (Fig. 6) as output stage can further reduce the losses, as only one diode and no series connection of two diodes is necessary in the output stage. A drawback is the center tapped secondary winding.

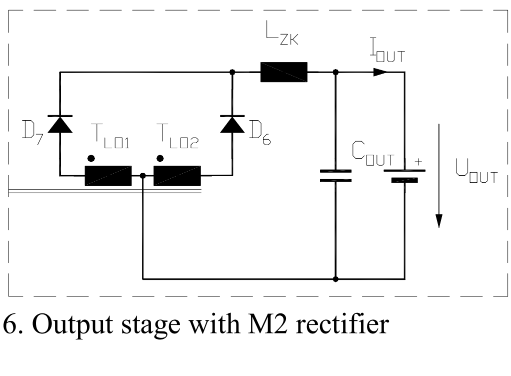

Fig. 6. Output stage with M2 rectifier

To explain the efficiency improvement of the new system more in detail a further simulation step was performed. Here, the practical operation condition of the converter has been taken into considerations. Figure 7 shows the energy flow for quasi-sinusoidal output conditions (when load is a single phase inverter; sinus inverters are useful in cars for laptop and other loads needing a low distorted supply).

From the minimum input voltage and the required output power the maximum average primary current can be estimated at about 110 A. The maximum voltage across the primary transistors S_1 respectively S_2 is twice the maximum battery voltage plus a margin defined by the auxiliary converter. To keep the transfer current within an acceptable range, it makes sense to use about twice or more than the input voltage range. So they have to withstand at least 40 V (12 V system) or 100 V (24 V system) respectively.

In our test application two IXFK120N20 have been used. Care has to be taken when dimensioning the Shottky diodes D_3 and D_4 and the storage capacitor. Here excessive pulse currents will occur. The blocking voltage is here slightly higher (max.). As diodes the 60 V type MBR6060 was used in the 12 V system.

In conjunction with practical current ratings of the auxiliary converter, further simulation results concerning the snubber voltage show an optimum of about four times of the input voltage. So in our case (12 V input voltage) the snubber rail will be at 50 V. This leads to a maximum current in the auxiliary converter of 10 A. As a result the over-all efficiency of the converter is maximized.

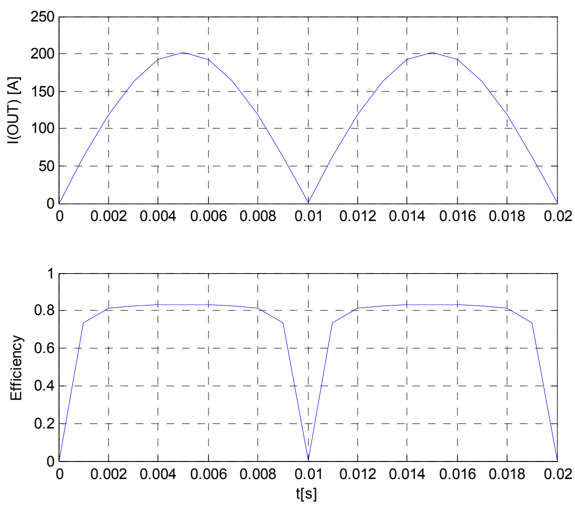

Fig. 7.a. Load current and converter efficiency with conventional snubber solution

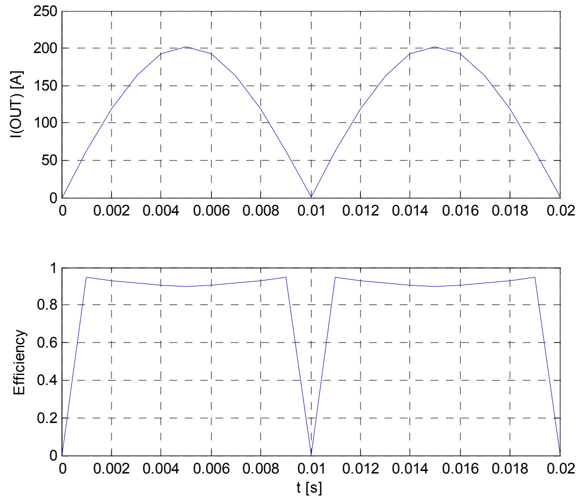

Fig. 7.b. Load current and converter efficiency with auxiliary converter solution, estimated at 120% load condition.

Fig. 8 shows an oscillogram of the voltage across the switches and the snubber capacitor.

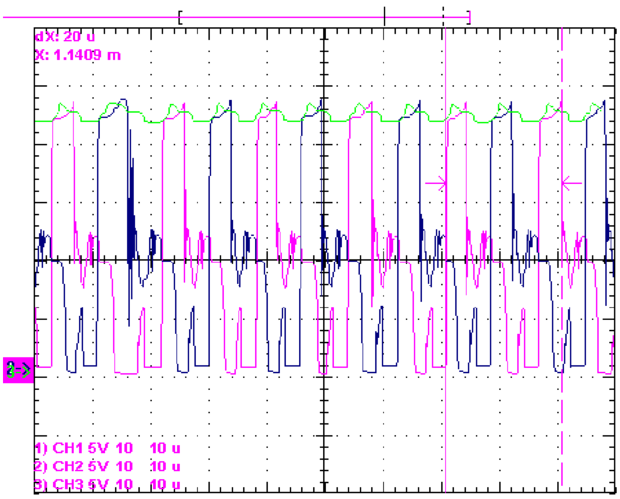

Fig. 8. Voltage across the switches and voltage across the snubber capacitor (above)

4 Conclusion

The stray inductance of transformer is a big challenge in power electronics converters, especially when high currents have to be transformed. The topology proposed here leads to several major advantages in the field of battery-buffered converters. One of them is the simple structure with a minimum of semiconductors and a minimum of heat dissipation due to its feasibility to feed back most parts of the energy stored in the transformer's leakage inductor [11].

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During the analysis of the laboratory prototype another very simple way of optimal snubber voltage control, a simple current mode controlled bang-bang controller was tested.

There are some similarities with turn-snubbers. The most important references are [5-7]. The basics of turn-on snubbers are described very well in [1, 2]. A basic work from McMurray is [9], further concepts are shown in [12 – 15].

The proposed topology is well suited in high current, low voltage applications, when the design deals with high efficiency, small size, and high switching frequency. Due to the current output characteristics of the structure, several converters can easily be paralleled to form a battery array (e.g. series or parallel connection of different devices). It is also possible to use a flyback converter with transformer to recuperate the energy charged in the capacitor C_S of the overvoltage snubber. In this case energy can be fed into the output. No potential barrier is necessary in this case, as the input side of the flyback converter (the voltage across the snubber capacitor C_S) has to be controlled.

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