High Efficiency DC-to-AC Power Inverter

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Abstract: In case of medium voltage (several tenth up to hundred volts on DC-side) solar inverter applications a DC-to-DC converter for voltage level adaptation is required in front of the DC-to-AC inverter. This leads to a two-stage concept with accumulation of the losses. In our case a concept has to be chosen, where the efficiency in each stage is maximized by usage of the best-fit topology. The given requirements force the application of a non-isolated design to avoid additional transformer losses. In this paper a 60V-120V DC (input) to 230V AC (output) / 1kW converter with minimal conversion losses is derived. A simple modification in the inverters output section lead to a significant improvement of the losses in the inverter system. Only three additional components (two diodes and one inductor) are necessary to optimize the inverters power stage. The topology presented here shows a remarkable improvement of the switching losses and significantly reduced EMC. It is well suited for solar power inverter applications.

Keywords: Inverter, Solar Power, PWM, efficiency

1. Introduction:

Switching mode PWM inverters are industrial standard in the field of power conversion applications. The starting point of our investigations was a solar inverter with the goal of very high efficiency operating on the European power grid (230V). Driving stages for high dynamic actuators and small motor drives are another field of application. The proposed inverter circuit can also be used as a high quality Class-D amplifier for audio applications. In this paper a new concept is shown which increases the output signal quality to meet high power quality, and reduces the electromagnetic disturbance caused by the current peaks of the power switch diode reverse recovery. As a result the over all efficiency is major improved.

The main drawback of conventional PWM-inverters (cf. Fig. 1) operating from a 350V DC-link is the wide dynamic range of the output voltage (0..320V in our case), and the required switching frequency (for minimizing the energy storage elements and coupling filters) which leads to an expensive design and increasing losses. Also the switching ripple in the output waveform due to the limited switching frequency requires a complex EMC-filter.

In conventional solutions mostly standard halve-bridge switching legs where used [3]. The main disadvantage in these topologies is the dedicated current peak when the opposite power switch is turned on. Due to the poor body diodes (even modern power MOSFET’s imply a rather weak diode compared to dedicated discrete components) the switching losses of the system will increase. Furthermore also the EMC will become more problematic. To overcome these topics normally the switching speed of the power semiconductor has to be limited explicit resulting in a further increase of the losses [4].

To overcome the known drawbacks a topology was chosen, where the inverters power stage discharged from switching current peaks. The separated components (power switch and diode) are used to

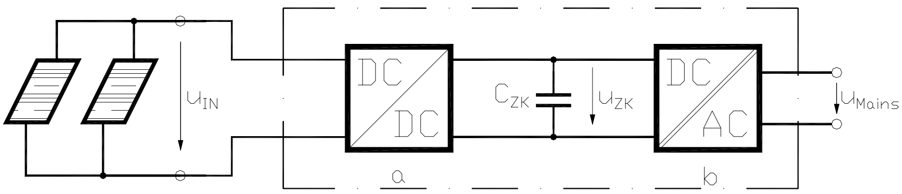

Fig. 1. Direct-coupled DC-to AC solar inverter with voltage DC-link

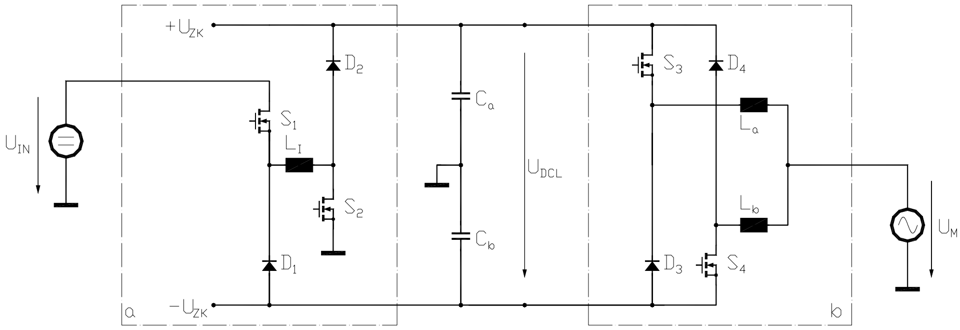

Fig. 2. Improved Power stage of the DC-to AC inverter

optimise the systems behaviour. So the switching speed can be increased and the required EMC-filter will be minimized. The optimised switching structure introduced in this paper leads to a more effective design. Furthermore a very simple control scheme (similar to normal PWM operation) can be used, while the efficiency is maximized.

Figure 2 depicts the converters topology. It consists of two stages, a DC-to-DC converter (a) and a DC-to-AC inverter (b).

The step-up / inverting DC-to-DC converter uses an optimised structure for alternating operation. Depending on the load current polarity normally only one direction has to be operated. During positive load current shape the step-up structure, formed by S_2 & D_2 is used (S_1 turned on continuously). At the opposite load current direction the inverting structure formed by S_1 & D_1 is used (S_2 turned on continuously) is used. The improvement compared do standard solutions are the omission of one inductor. Furthermore only one power switch is PWM-operated resulting in switching losses; the second one shows only conduction losses.

In the inverter stage (b) a modified halve bridge structure is used. Simulation results shows, that the switching losses can be reduced by a factor of more then 10 compared to conventional hard switching halve bridge stages, when modern components are used. The excessive current peaks in a switching leg resulting from the hard switched opposite body-diode of a power MOSFET in conventional halve-bridge inverters can be avoided. The application of modern diodes (SiC) can be used here for further optimisation.

2. DC/DC Converter Operation

Figure 3 shows the four switching states of the proposed inverter. In Figs. 3.a and 3.b the step-down operation is clarified while Figs. 3.c and 3.d show the step-up operation.

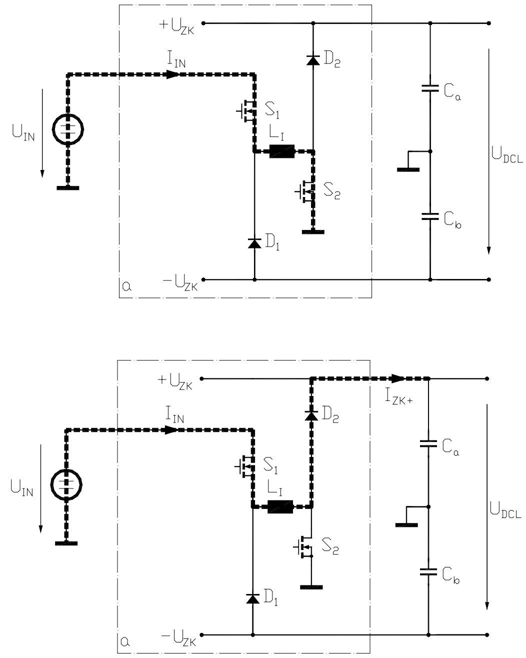

Fig. 3.a. & 3.b. Operation of the step up DC-to-DC Converter

The tow operating modes are used in conjunction with the inverters output voltage polarity. Depending on the output current direction the energy flow into the positive respectively negative DC-rail can be separated by an intelligent controlling algorithm leading to a minimization of the switching cycles in the DC-to-DC converter.

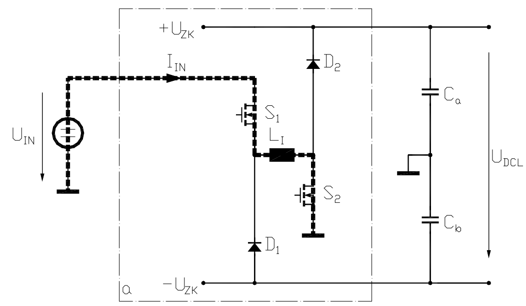

Fig. 3.c. Operation of the inverting DC-to-DC Converter (driving phase)

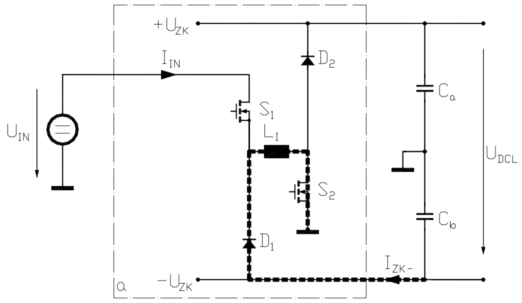

Fig. 3.c. Operation of the inverting DC-to-DC Converter (free-wheeling phase)

Especially a weak DC-rail (high dynamic internal resistance generated by the voltage regulator) can be used for further efficiency improvement.

3. DC-to-AC Inverter Operation:

The DC-to-AC inverter operation can also be divided into four sections depending on output polarity and switching state:

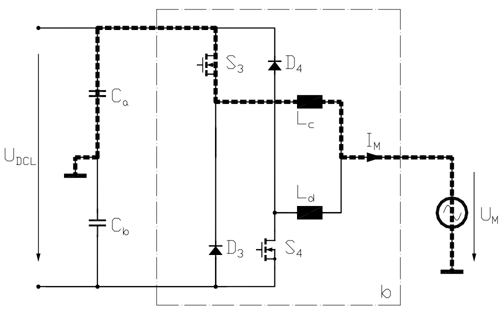

Fig. 4.a. Operation of the DC-to-AC Converter, positive output voltage, driving phase

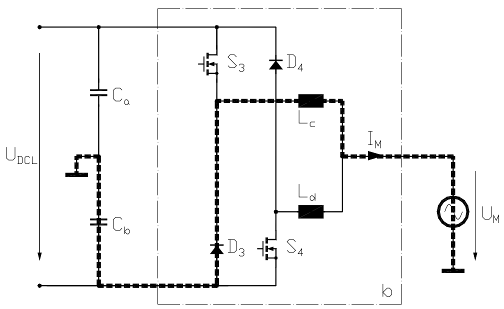

Fig. 4.b. Operation of the DC-to-AC Converter, positive output voltage, freewheeling phase

During positive output current (I_M) flow the switching leg formed by S_3, D_3 and L_c has to be used. Opposite to this state during the negative output current shape the second switching leg (S_3 D_3 & L_d) has to be used.

The output current of the step-down stages is formed by the control law (approximation) depending on the switching states:

Driving phase (S_3 is turned on); duty cycle d, cycle duration T: 0 < t < d * T:

$$i_{L(t)} = i_{L(t=0)} + \frac{U_{DCL}/2 - U_M}{L} \cdot t$$

1.) Free-wheeling (current path through D_3): d * T < t < T

$$i_{L(t)} = i_{L(t=t_{ON})} - \frac{U_{DCL}/2 - U_M}{L} \cdot t$$

This leads to

$$i_{L(t)} = i_O + \frac{U_{DCL} - 2 \cdot U_M}{L} \cdot d \cdot T - \frac{U_{DCL}/2 - U_M}{L}.$$

When the DC-link voltage and the mains voltage is known (can be measured directly) the output current of the inverter can therefore directly be controlled by the duty-cycle of the switching stage.

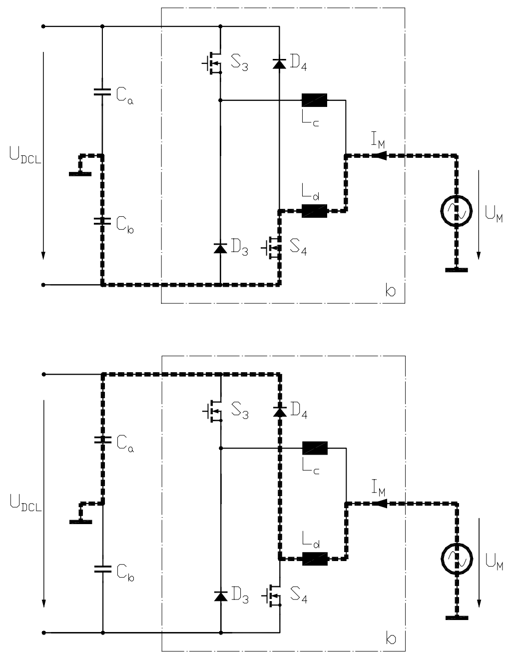

Fig. 4.c. & d. Operation of the DC-to-AC Converter, negative output voltage

The Inverters section can handle both voltage and both current directions and therefore especially well suited for local voltage generation (island applications).

4. DC-to-DC Converter Simulation

To determine the system behaviour o circuit level based simulation (PSPICE) of the converter stage was performed. The results are depicted in Fig. 5 (step up operation, ref. Fig's 3.a. & 3.b.) and Fig. 6 (inverting operation, ref. Fig's 3.c. & 3.d.) (converter start up).

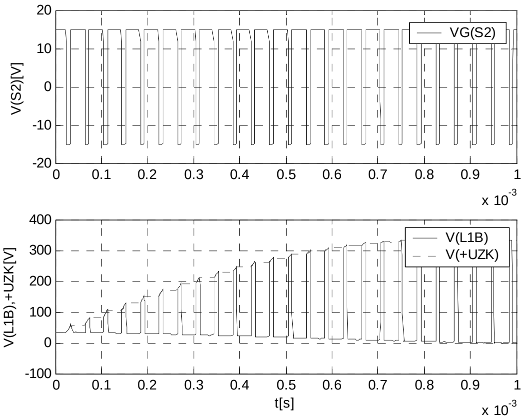

Fig. 5 DC-to-DC converter in Step-Up mode

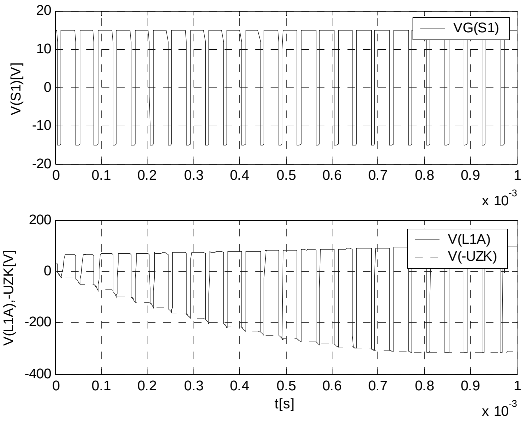

Fig. 6 DC-to-DC converter in inverting mode

The simulation results are compared to a conventional Step-Up / Step-Down and an isolated (transformer coupled) PWM DC-to-DC converter switching stage. Every case uses the same component models so that simulation results can be compared directly. The conclusion is given in Table 1. As one can see the used topology can compare with a conventional Step-Up / -Down solution. As an advantage here only one inductor is required. The simulation based on the supply of the DC-to-AC inverter stage as depicted in Fig. 4. (alternating current flow with mains frequency, power factor of one). The isolated topology deals with the disadvantage of the two-step energy conversion (DC-to-AC – PWM stage, transformer. AC-to-DC – rectifier, Filter).

P_{out}	New Top. - η	UP/DN. - η	Isolated- η
100W	92,4 %	92,4 %	85,5 %
200W	96,1 %	96,0 %	94,1 %
500W	98,5 %	98,6 %	96,3 %
1kW	97,6 %	97,9 %	95,2 %

Table 1 Efficiency of the DC-to-DC converter

5. DC-to-AC Converter Simulation

In this section the combined inverter stage is simulated and compared to a conventional hard switched PWM stage operated at the same ambient conditions. In this model a load power factor of 1 is assumed, so that the polarity of the mains current I_M depend only on the polarity of the mains voltage shape. Figure 7 shows the simulation results of the power stage. In the upper trace one can see the reference current (standardized mains voltage), below the resulting output current shape is shown. The lower trace depicts the PWM signals of each power switch (S_3 respectively S_4).

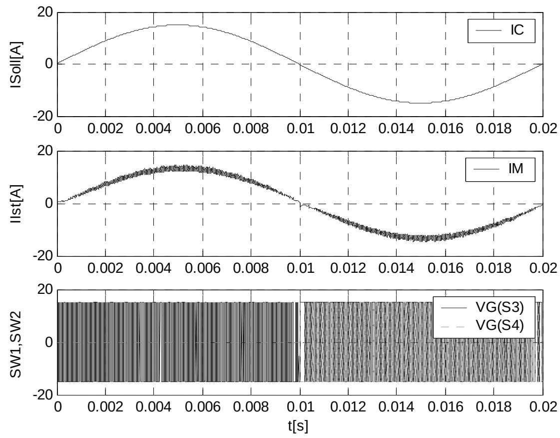

Fig. 7 switching behaviour of the improved inverter stage

To determine the quality of the mains current one can see the output spectrum of the inverter in Figure 8. Here no additional filter is used. A simple mains coupling filter (which is always required in practical applications but not taken into considerations here) will lead to a further improvement of the switching harmonics.

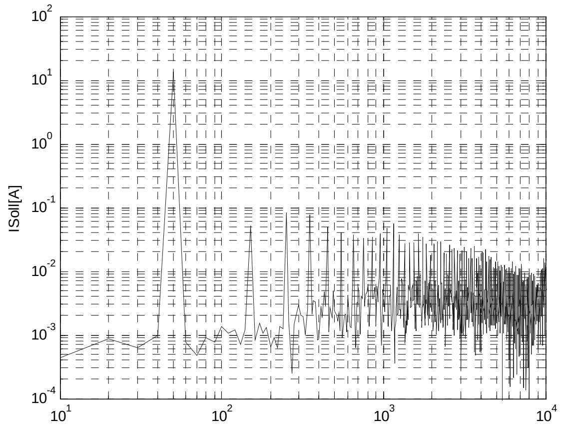

Fig. 8 Output Spectrum of the mains current, without Filter

The control is realizes by a simple bang-bang controller and some additional logic for switching signal separation.

Table 2 compares the proposed switching stage with a conventional PWM inverter. The improvement of the advanced topology can raise the efficiency by about 2%.

P_{out}	PWM - η	New Top. - η
100W	90,5 %	92,5 %
200W	94,1 %	96,1 %
500W	96,3 %	98,2 %
1kW	95,2 %	97,9 %

Table 2 Efficiency conversion of the DC-to-AC inverter

6. Conclusion

This new solution will improve the disadvantage of hard-switched PWM power stages in conventional inverters. Due to the separation of the current paths each switching leg can be optimised. Furthermore the problem of the weak body diode can be overcome. The result is a stage with significant lowered current peaks when modern (e.g. SiC) diodes are used.

The presented inverter stage leads to an improvement of about 2% in over all efficiency. This helps to simplify power inverters in the medium power range (several kilowatts).

Another advantage is the scaleable output power. The stage is optimal appropriated for parallel operation due to its current source characteristics. No additional external control is required.

The simple control principle of the step-down power stages can easily be implemented in a modern microcontroller without additional logic support for the pulse pattern generator. A simple PWM stage fulfils all the requirements. Also the maximum power point tracking for the solar cells can be implemented simply by monitoring the system signals (U_{DLC} and i_M). The main drawback of the topology is the additional required for the separated power stage.

The new control topology can also be used to build up redundant multiphase systems. The inverter presented in this paper is a simple and effective solution for medium power applications. The concept is well suited for wind-, solar- and renewable energy as well as aerospace applications. Because of the improved efficiency e.g. battery lifetime can be increased without any quality reduction.

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