Three Level DC-to-AC Power Inverter for Power Grid Operation

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Abstract: - In case of medium voltage (several tens 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 was chosen, where the efficiency in each stage is maximized by usage of the best-fit topology. Conventional power inverters used in mains connected applications fight with the disadvantage of the hard switched PWM power stage operating at high voltages [1,2]. Also soft switching topologies [6,7] do not give full benefits at all. In this paper the conjunction of simple boost- and buck converter stages gives the facility to realize an optimal design for power grid coupled inverters. The reduced voltage stress of each stage can lead to a significant improvement of the system losses. Furthermore it is shown, that a revised method of energy storage in the ‘weak’ DC-link can be used for smoothing the input current. Sharing of the energy flow in each power stage can also lead to reduced losses. The topology presented here shows a remarkable improvement of the switching losses and significantly reduced electromagnetic compatibility (EMC).

Key-Words: - Switching Stage, Inverter, Solar Inverter, PWM Stage, Switching Losses

1 Introduction

In grid coupled power conversion applications switching mode PWM inverters are industrial standard. The starting point of our investigations was a solar inverter for 1kW with the goal of very high efficiency, operating on the European power grid (230V). The converter was designed for minimum losses, so a non-isolated DC-to-AC type was chosen. It operates from a panel voltage of 50..80V with a DC-link voltage of 350V. For optimisation of the efficiency an average control mode was developed to minimize the losses in the input section of the converter by sharing the current over the mains period. The resulting solution shows the big potential of principal improvement of inverter topologies by intelligent control methods.

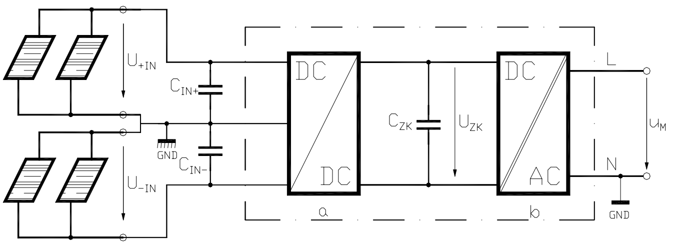

Figure 1. Grounded, direct coupled DC-to AC solar inverter with voltage DC-link

The main drawback of conventional PWM-inverters (cf. Fig. 1) operating from rather low DC-input voltages with a wide dynamic range are the high input current ratings, the voltage stress of the power components (DC-link voltage of about 400V in our case, causing to remarkable switching losses) and the required switching frequency (for minimizing the energy storage elements – inductors / capacitors) which leads to an expensive and complex design. Also the switching ripple in the output waveform due to the limited switching frequency of the inverter leads to the requirement of a complex EMC-filter. Furthermore the power pulsation of the load (the single phase power grid) results in big input capacitors and a rather poor MPPT of the solar cells due to non-ideal input current shape.

To overcome the known drawbacks for high performance solar inverters several possible solutions are given:

- To use the maximum efficiency of the solar cells it is necessary to feed a quasi-constant input current on DC side. One main drawback is the input capacitor C_{IN} operating at rather low input voltage ratings. This can also be reached by energy storage in the DC-link capacitor C_{ZK} operating at higher voltages leading to smaller components.
- A dynamically controlled DC-voltage shape can be used for a further reduction of the energy storage capacitor. This solution requires an improved control method where energy balancing was taken into consideration.
- Conventional PWM stages operating at a high switching frequency can be used. In this case the filter design is simple. The most drawback of this solution is the rising switching losses of the inverter stages, and the EMC problematic.
- A resonant operated switching stage can be used. In this case additional control requirements are necessary. Also the components have to fulfil the additional resonant component stress. This leads to

a much more complicated design. Also it has to be noticed, that the efficiency at partial load is normally lowered.

- A multi phase PWM solution can be used. This can help to get a more simple design due to the reduced current in each stage. The disadvantage of this solution is the more complex control stage and the increased component count.
- An optimised switching structure, which is introduced in this paper, can be chosen leading to a more effective design. Here a very simple control scheme (similar to normal PWM operation) can be used, while the efficiency is maximized.

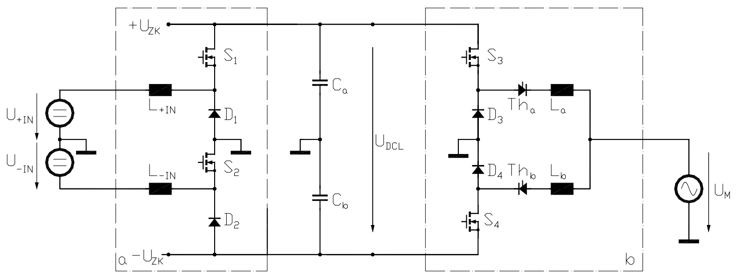

Fig. 2. Improved Power stages of the DC-to AC inverter

Figure 2 depicts the modified power stage. The input section consist of two simple boost converters supplying the DC-link. Alternatively here also a multi-phase arrangement of several converters can be used to share the input current. Due to power grid application a single-quadrant DC-to-AC inverter was used. The benefit of this topology is the reduced voltage stress of the power switch leading to reduced losses (S_3 respectively S_4). Simulation results show, that the losses can be decreased by a factor of more then 2 compared to a halve-bridge type. In case of grid connected inverter applications with a power factor of one the proposed inverter topology shows a maximum of efficiency.

2 Operation of the DC/DC Converter

Figure 3 depicts the operation to the DC-to-DC converter section. Due to the symmetric DC-source and the usage of a synchronized PWM pattern the ground current ripple can be minimized.

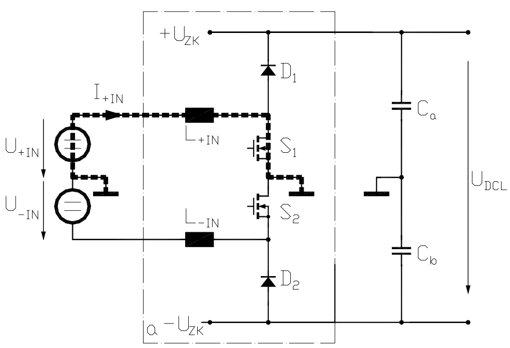

Fig. 3.aI. Operation of the positive rail boost DC-to-DC converter, charging phase

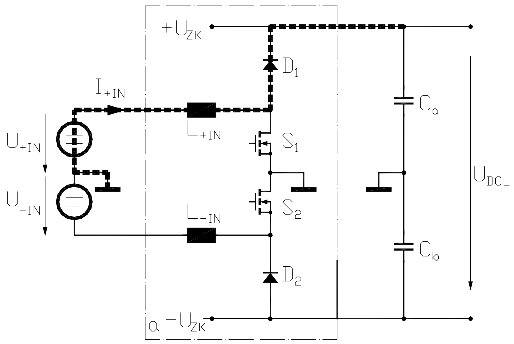

Fig. 3.aII. Operation of the positive rail boost DC-to-DC converter, free wheeling phase

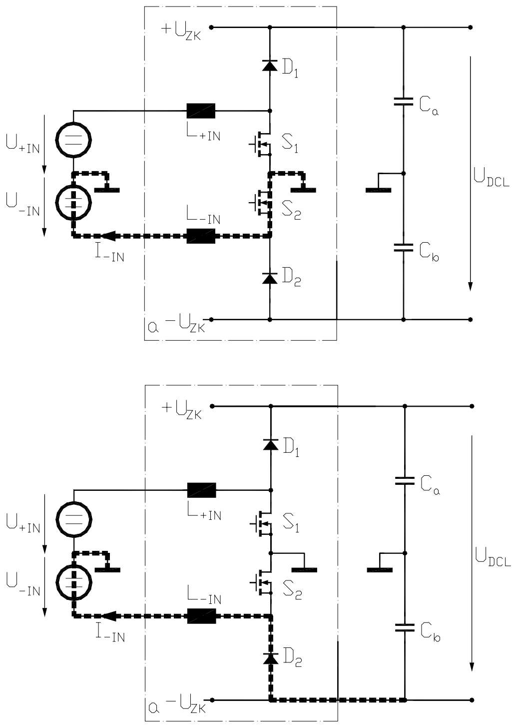

Fig. 3.b. Operation of the negative rail boost DC-to-DC converter

Operated in conventional mode the DC-link voltage is the feedback signal of the boost controller (U_{ZK}-control). Figure 4 shows the discontinuous input current of the inverter stages.

One of the major drawbacks of single-phase inverters – the input power pulsation – has to be handled. To overcome this problem either a big input capacitor (operating at low input voltage ratings) is required or energy storage at DC-link level can be used leading to smaller components. The energy stored in a capacitor is given by $W_C = \frac{C \cdot U^2}{2}$, so the usage of higher voltage levels can help to build up smarter designs. Further improvements can be achieved by the usage of a weak DC-link with special energy flow oriented control method.

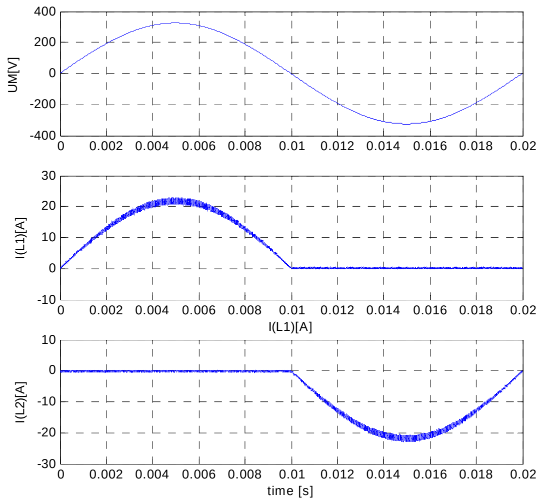

Fig. 4. DC-to-DC converter input current; mains current I_M (upper trace), positive input current I_{+IN}, negative input current I_{-IN} (lower trace)

Figure 5 compares a continuous input current flow with the current shape given by U_{ZK}-control.

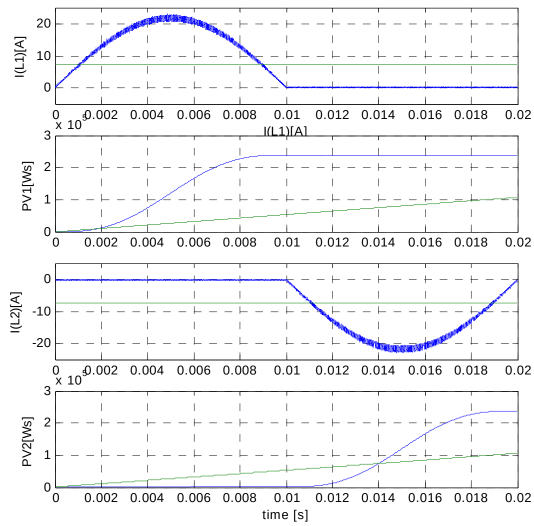

Fig. 5. DC-to-DC converter losses; load controlled (blue), current sharing (green), positive supply current (upper trace), losses, negative supply current, losses (lower trace)

One can see, that the losses of the boost-stage can be reduced by more than 50% when a simple current sharing method is implemented. Furthermore the input filter can also be minimized in this case.

Figure 6 depicts the DC-link voltage and the currents when an average control method is used. Here the goal is to keep the average value of the DC-link voltage at a constant value. Alternatively one can use a control method, where the voltage at the maximum of the load current (in our case at t=5ms for positive output and t=15ms for negative output voltage) is used for feedback.

The load current (and therefore the input current) is basically controlled by the Maximum Power Point Tracker of the solar cells. As a result this leads to a non-constant DC-link voltage (voltage variations of about 25% are usable).

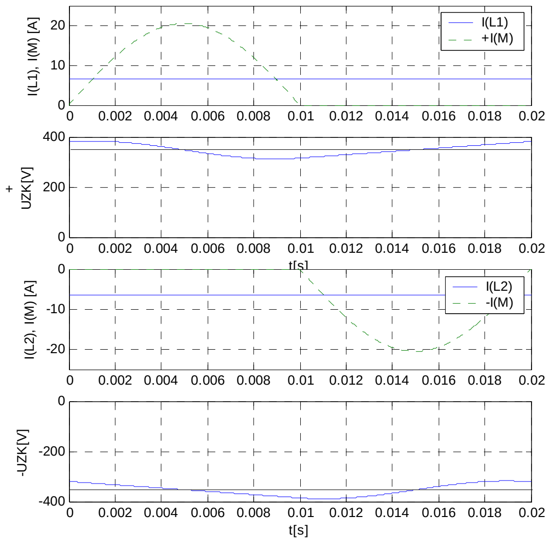

Fig. 6 continuous input current controlled converter; load current (green), input current (blue), positive stage (upper trace), DC-link voltage $+U_{ZK}$, negative stage, DC-link voltage $-U_{ZK}$ (lower trace)

It has to be marked, that the improvements of the current sharing methods require an optimal arranged control of the inverter system. As a benefit the more complex controller helps to simplify the design leading to a remarkable reduction in weight and size.

3 Operation of the DC-to-AC inverter

The DC-to-AC inverter consists of two alternated operated buck switching stages and a thyristor controller mains interface.

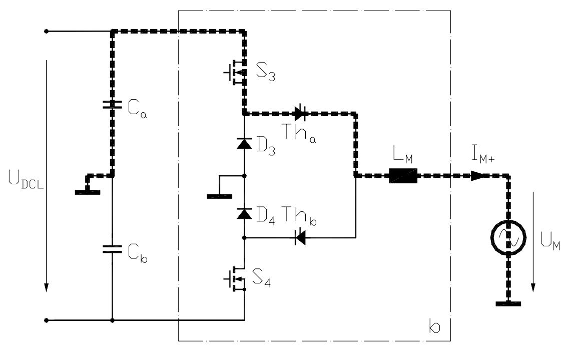

Fig. 7.aI. Operation of the DC-to-AC Converter, positive mains voltage, charging phase

The thyristor solution has chosen due to its ruggedness. During the positive output voltage shape Th_1 is fired and the current shape is controlled by S_3; opposite, Th2 serves negative mains voltages; the current shape is controlled by S_4.

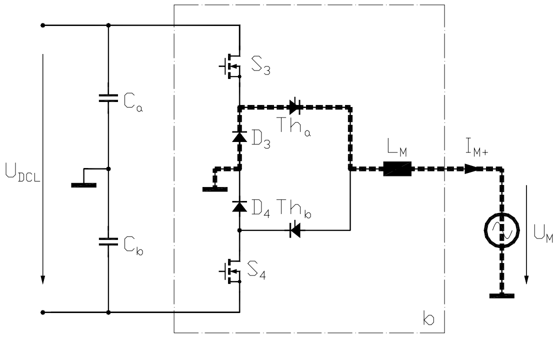

Fig. 7.aII. Operation of the DC-to-AC Converter, positive mains voltage, free wheeling phase

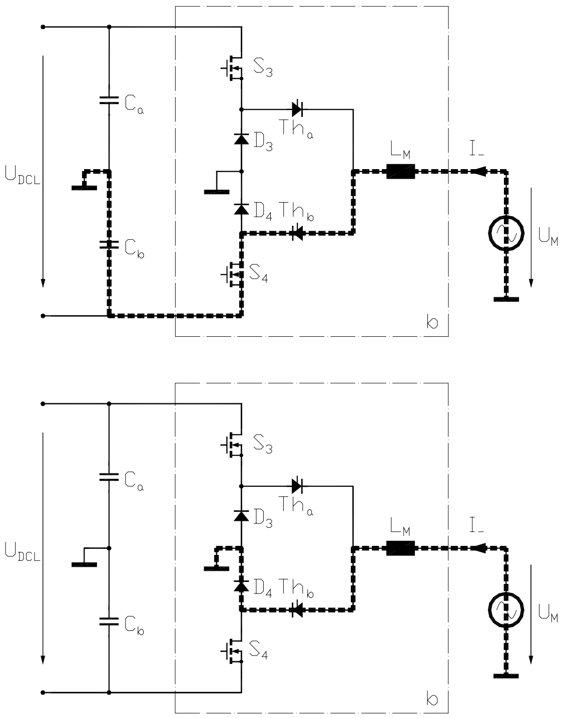

Fig. 7.b. Operation of the DC-to-AC Converter, negative mains voltage

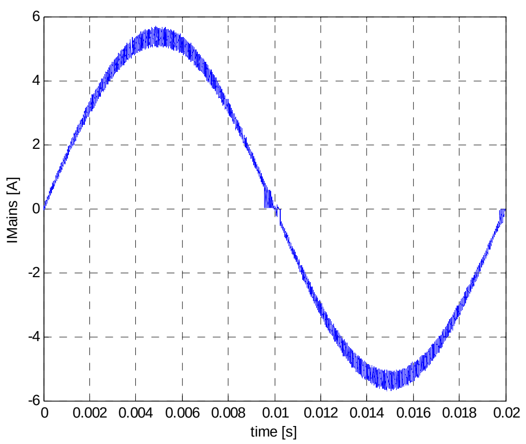

Fig. 8 Mains current shape (bang-bang controller)

Figure 8 depicts the simulation results of the inverter stage. Here no special mains coupling filters are used. In practice a simple noise rejection filter has to be used to fulfil the EMC-requirements. The control is realizes by a simple bang-bang controller and some additional logic for switching signal separation. The reference signal was directly derived from the mains voltage.

4 Simulation Results

The simulation results are compared to an isolated (transformer coupled) PWM DC-to-DC converter switching stage. In both cases the same component models are used 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 Buck- Boost solution [3]. 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. 2. (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) which can especially be seen at partial load.

Table 1 Efficiency comparison of the DC/DC converters:

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

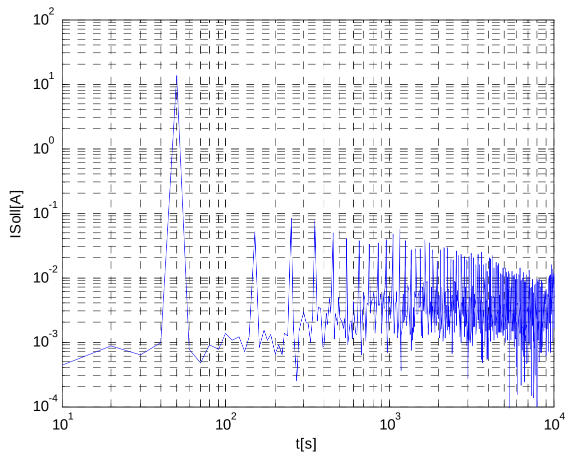

Fig. 9 Output spectrum of the mains current, without Filter

To determine the quality of the mains current one can see the output spectrum of the inverter in Figure 9. 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.

Table 2 Efficiency comparisons of the DC-to-AC inverters:

P_{out}	PWM - η	Buck Top. - η
100W	90,5 %	91,5 %
200W	94,1 %	95,5 %
500W	96,3 %	98,2 %
1kW	95,2 %	97,8 %

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

5 Conclusion

This new solution will reduce the disadvantage of hard-switched PWM power stages in conventional inverters. Due to the separation of the current paths, each switching leg can be optimized. 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 new control topology can also be used to build up redundant multiphase systems. 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.

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 optimally for parallel operation due to its current source characteristics. No additional external control is required.

As a result, an inverter is build up which reaches the goal of a small, lightweight and robust design. Most parts of there advantages are realized by an improved control method, which helps to simplify the design. Modern microcontrollers give us the feasibility to implement complicated algorithm operating in real time. The proposed inverter is a good example for such an application.

The concept caused switching voltage reduction will improve the disadvantage of hard-switched PWM power stages in conventional inverters. The limited voltage stress and the load power division affect the ruggedness of the inverter positively. Due to the separation of the current paths each switching leg can be optimized separately. The classical thyristor technique, which is used for DC-to-AC switching, didn’t show any disadvantage compared to other switching solutions.

References:

[1] N. Mohan, T. Undeland, W. Robbins, "Power Electronics," New York: John Wiley & Sons, 1995.

[2] H. Schmidt: “Single Cell Module Integrated Converter (SCMIC)”, 14th European Photovoltaic Solar Energy Conference, June 30 - July 4, Barcelona, pp. 355-360.

[3] G.R. Stanley, K.M. Bradshaw: “Precision DC-to-AC Power Conversion by Optimization of the Output Current Waveform - the Half Bridge revisited”, IEEE Transactions on Power Electronics, March 1999, Volume 14 , Issue 2 , pp.: 372 – 380.

[4] M.D. Manjrekar and T.A. Lipo: "A Hybrid Multilevel Inverter Topology for Drive Applications", Applied Power Electronics Conference APEC '98, pp. 523-529, Anaheim, California.

[5] K.H. Edelmoser, F.A. Himmelstoss: “Improved 1kW solar inverter with wide input voltage range”, IEEE International Symposium on Signals, Circuits and Systems, SCS 2003, July 10-11. 2003, Volume: 1, pp.:201 – 204.

[6] Kutkut N.H.,1997 “A Full-Bridge Soft Switched Telecom Power Supply with a Current Doubler Rectifier", 19th International Telecommunications Energy Conference, INTELEC 97, pp. 344 –351.

[7] Zeng X., Qiaoqiao W., Pit-Leong W., Lee F.C., 2000, “A Novel Integrated Current Doubler Rectifier”, Fifteenth Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2000, Vol. 2 , pp. 735 -740.