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BIDIRECTIONAL DC-to-DC CONVERTER WITH EXTENDED VOLTAGE TRANSFER RATIO

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Abstract: Conventional inverters used in local plant and power grid connected applications show the disadvantage of coupling the bypass-battery and the solar cells, operating at low DC-voltages, to the inverters' DC-link. These converters with rather low input and high output voltage ratings, respectively, have, due to the required transfer power, high current ratings, leading to relatively low efficiency. Therefore, only a special design can help here to adapt the different voltage levels in an acceptable way. Also, a second energy direction required for battery charging is necessary in most cases and can therefore be implemented principally into the concept. In this paper, a possible solution for such a specific solar converter is presented: a bi-directional DC-to-DC converter, well-suited for DC-link and charging operation. The input voltage of a (e.g. a solar buffered) battery (12V or 24V) is adapted to a 360V DC-link, operating in both energy directions, for a local grid power inverter supply. The total power to be handled at the output of the DC-to-DC converter is 400W (12V) or 800W (24V), respectively, at uplink and 200W for battery charging. The structure presented in this paper shows remarkable improvements of these topics.

Keywords: Voltage Transfer Ratio, DC-to-DC Converter, Battery Backup

1. Introduction

State of the art solutions for solar inverters with battery back-up systems are normally operating from a rather low input voltage rail supplying a DC-link, mainly defined by the required mains voltage. Therefore, a special design is required to adapt the different voltage levels. In this field of application it also makes sense to operate several converter stages in parallel sharing the load to achieve an acceptable over-all efficiency. The second energy direction, used for charging the battery, in most cases requires an additional converter. Special care must be taken to take the different voltage drop directions into consideration. The converter has to operate the DC-link at the upper limit from a rather empty battery as well as to guarantee correct charging from a link voltage near the lower limit. Even a possibility must exist to charge a completely empty battery (if no power is available on the battery side). The solution presented here is designed to adapt a 12V or 24V battery to a 400V DC-link, well-suited to the European 230V power grid. The conversion ratio, depending on the input voltage range from 10..14.4V (20..28.8V) to the output voltage range of 380..400V therefore varies from 1/26 up to 1/40 at 12V. The total power to be managed on the output of the DC-to-DC converter is 1kW. In case of a single stage inverter, this leads to about 100A input current (at 12V), causing peak values in the power switches of up to 200A!

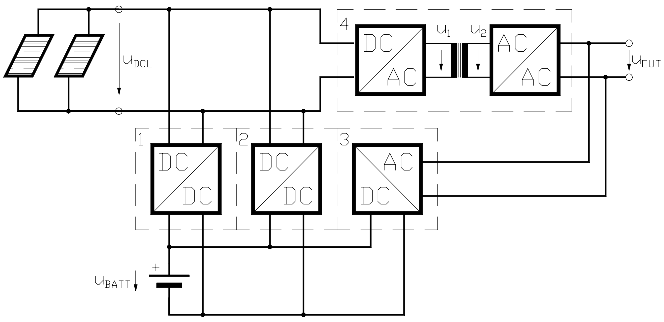

Fig. 1. Principal battery-buffered solar inverter topology: *1*-battery charger (downlink), *2*-DC-battery uplink, *3*-auxiliary charger, *4*-isolating DC-to-AC inverter (main inverter)

The resulting component stress is very hard and also the design is difficult to handle. So it makes sense to select a topology which is also well suited for paralleling the power switches. This gives a scaleable solution with the advantage of a more optimal design in each stage. Here a structure has been used where several converter stages can easily be paralleled due to its current source characteristics. The principal energy flow of a conventional solar inverter topology with energy storage (batt.) support is given in Fig. 1.

The different energy paths are marked:

1.) Battery charger (from the solar-DC-link).
2.) Battery switch (DC-link supported by the battery).
3.) Auxiliary battery charger (obtained from the mains), optional.
4.) The inverter itself (including the isolation barrier).

During normal operation a mixture of the states given will occur. Therefore, synergies can be used to optimize the system structure leading to an effective design.

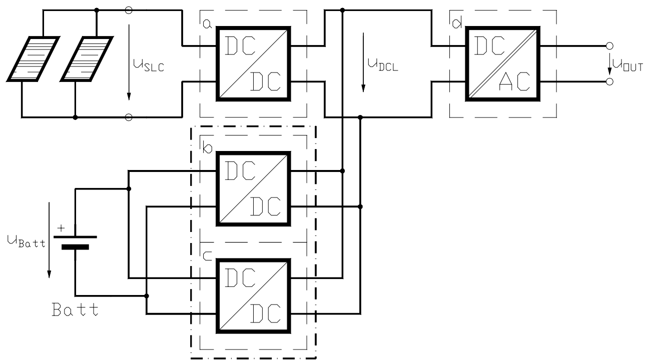

Fig. 2. Proposed inverter topology: *a*-DC-link converter, *b*-battery charger (downlink), *c*-DC-uplink, *d*-isolating DC-to-AC inverter

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.

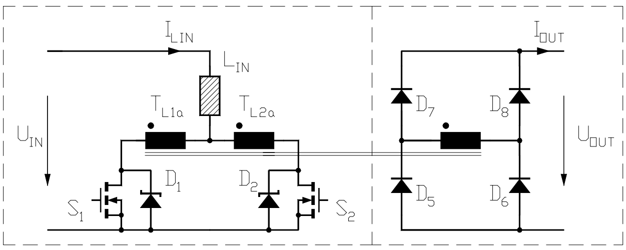

Fig. 4. Schematized uplink structure, equiv. circuit

A possible one is a solar battery operating from the high voltage DC-link [5]. This helps to make the system scaleable and flexible to changes of user requests. In this paper a special topology is used (c.f. Fig. 2).

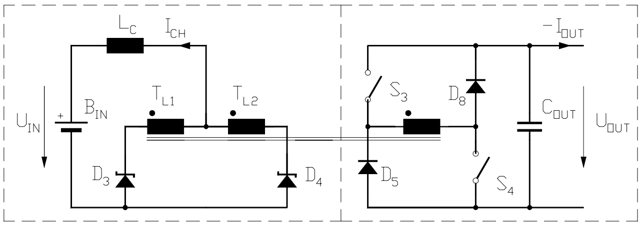

Fig. 5. Schematized downlink structure, equivalent circuit

Here, the battery is operated in parallel to the DC-link of the inverter. The stages a. and d. represent a standard solar power inverter. The battery, connected to the DC-link by the charger b and the level-adapting converter c can be seen as a stand-alone equipment. When a bi-directional DC-to-AC inverter is used, an auxiliary charging path (c.f. 3. in Fig. 1) is also possible. To optimize the battery interface, a bi-directional DC-to-DC converter [1,2] as presented in this paper can be used instead of *b* & *c* in Fig. 2. The result is a converter structure with minimized component count leading to an easy-to-handle and robust design, well suited for scaling.

2. Bi-Directional DC-to-DC Converter

The converter proposed here (c.f. Fig. 3) uses the well-known push-pull converter [3] in the up-link and the double-ended forward converter topology [4] in the down-link (charging). A dedicated switch (S_C) is used to adapt the transformer ratio in case of charging. The great advantage of this topology is that in case of DC-link supply from the battery, only one switching element is situated in the main current path on the primary side, so the losses can be minimized. During the charging phase of the battery, a center tapped rectification is used. The power switches S_1 and S_2 do not affect the current path. Only the charge control switch S_C is activated (here also a relay can be used). The special circuit in a two-switch forward converter is used to eliminate additional losses due to the poor body-diodes in the power MOSFETs S_3 and S_4. In general, here also the simple standard arrangement with two switches and two diodes can be used. The advantage of this topology is the

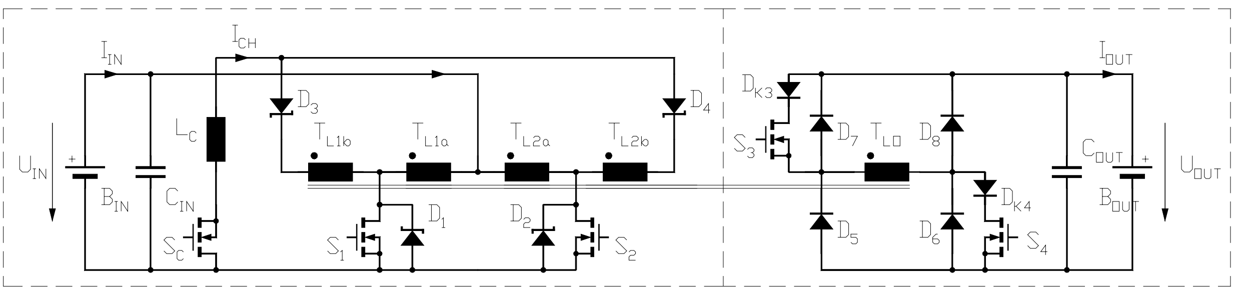

Fig. 3. Bi-directional DC/DC converter, optimized for solar battery application

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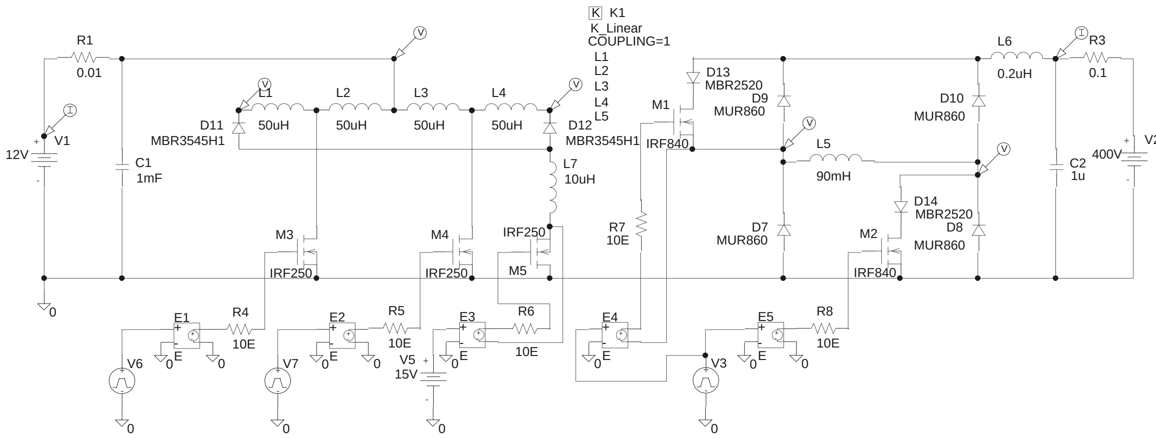

Fig. 6. Simulation Model

different effective transfer ratio depending on the energy flow. In the up-link path (c.f. Fig. 4) the transfer ($n_{(TL1a)} = n_{(TL2a)}$, $n_{(TL1b)} = n_{(TL2b)}$) ratio is given by $n_{(TLO)}$ / $n_{(TL1a)}$, while in the down-link direction (c.f. Fig. 5) $n_{(TLO)}$ / $[n_{(TL1a)}+ n_{(TL1b)}]$ defines the transfer ratio. This gives the possibility to optimize the converter for both energy directions.

3. Converter Design

To fulfill the requirements given above, the optimal components have to be chosen: Due to the fact that the charging requires much less power (depending on a battery conserving charging method) it is possible to use cheaper components in the downlink-path .

From the minimum input voltage and the required output power the maximum primary current can be estimated to about 110A. The maximum voltage across the primary transistors S_1 respectively S_2 is twice the maximum battery voltage. So they have to withstand at least 30V (for a 12V system) respectively 60V (for a 24V system). In our test application two SUP75N04-05 are operated in parallel. In the charging path, the Schottky diodes D_3 and D_4 and the switch S_C have to conduct only 20A. The blocking voltage is here slightly higher (max. $2*U_{IN}*([n_{(TL1a)}+ n_{(TL1b)}]/n_{(TLO)}))$ due to the up-link operation of the converter stage. In case of the diode a 60V type 30CTQ60 was used, while in case of the power switch S_C here also a SUP75N04-05 was applied. On the secondary side, IRF840 (S_3 & S_4) and MUR860 (D_5..D_8) are used.

4. Simulation

To clarify the operation scheme of the converter the structure has been simulated in PSPICE. Figure 6 gives the simulation model. To simplify the evaluation this model was designed for 200W operation. Therefore, standard libraries could be used.

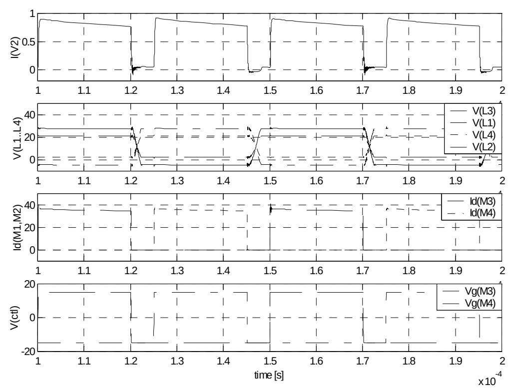

Fig. 7. Simulation results: Up-link operation: upper trace DC-link current (sink) $I_{(V2)}$, transformer voltages $V_{(L1)}$, $V_{(L2)}$, $V_{(L3)}$, $V_{(L4)}$, drain current of the power switches M3 - $Id_{(M3)}$ and M4 - $Id_{(M4)}$, control signals $Vg_{(M3)}$ & $Vg_{(M43)}$.

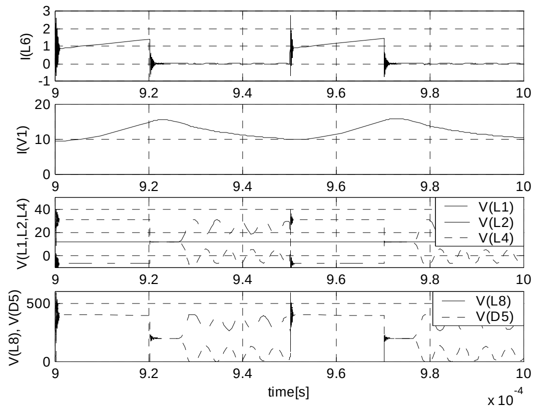

Fig. 8. Simulation results: Down-link operation: upper trace DC-link current (source) $I_{(L6)}$, battery current $I_{(V1)}$, transformer voltages (leftmost $V_{(L1)}$, center $V_{(L2)}$, rightmost ($V_{(L3)}$), switching voltages $V_{(L8)}$, $V_{(D5)}$

The two different operating conditions have been simulated in separate steps to clarify the operation of the converter and to show its advantages. The signals given in the simulation results in Fig’s 7 & 8 refer to the PSPICE simulation model given in Fig. 6. In

Figure 7 the up-link operation is presented, while Fig. 8 shows the battery charging phase. By varying the filter inductor L_7 (respectively L_C) the battery current ripple can be reduced further.

5. Measurement Results

To verify the simulation results, a prototype has been breadboarded and analyzed. The converter operates between a 12V battery and a 400V DC-link realized by a power supply unit.

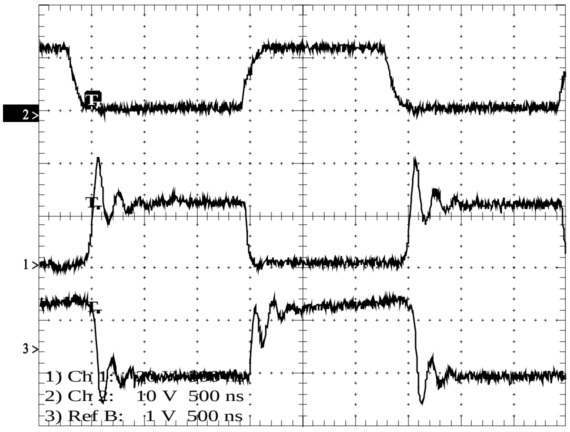

Fig. 9. Up-link operating condition, from top to bottom: gate control signal, voltage across corresponding switch, current through switch 1 (1V ~ 10A)

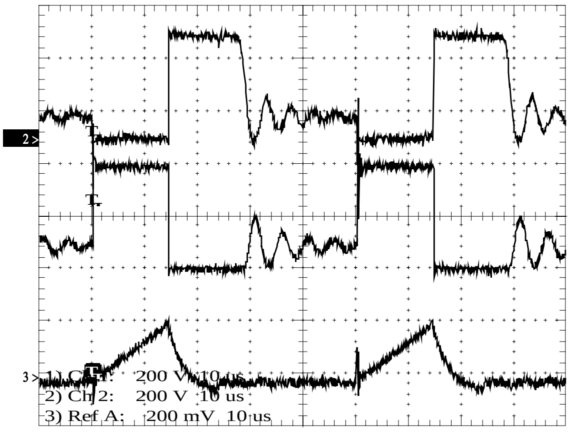

Fig. 10. Down-link operating condition: from top to bottom: voltage across D_5, voltage across D_6, high-side transformer current (2A/div)

Figure 9 shows the up-link operation of the converter. The signals of the left switching leg are given. In Fig. 10 the down-link operation of the converter is shown. The signals of the DC-link (output) side are presented.

The estimated efficiency of the breadboarded converter reaches 94% in the up-link path (at 12V, 400W-Pout) and 94.5% in the down-link path (400V DC-link, 200W charging power).

6. Conclusion

The proposed topology results in several major advantages for applications in the field of battery-buffered solar inverters. One of them is the simple structure with a minimum of semiconductors in the high-current path leading to a remarkable efficiency improvement compared to state-of-the-art solutions. Furthermore, the optimal voltage transfer ratio can be adjusted independently of each energy direction leading to a better component efficiency (improved duty-cycle in the switching elements). Moreover, in case of battery charging, different power levels can be installed leading to a significant cost reduction. In this case the downlink path, established for charging only, has to draw only the battery current, while in the uplink path several dynamic overload conditions have to be taken into consideration. Due to the current output characteristics of the structure, several converters can easily be paralleled to form a solar-battery array. Also, the feature of powerless starting of the battery should be mentioned. In case of empty batteries no power is available on the secondary to supply the power electronics. A benefit of the topology is the fact that in this case at least a fraction of the regular battery voltage is generated independently of the control state of the converter leading to a kick-start of the system.

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