

Bi-directional DC-to-DC Converter for Solar Applications with Battery Backup

K. H. EDELMOSER
Institute of Electrical Drives and Machines
Technical University Vienna
Gusshausstr. 27-29, A-1040 Wien
AUSTRIA

Abstract: - The application of battery backup systems automatically leads to inverter structures with relative low input voltage levels compared to the DC-link voltage. To guarantee the required system capability the power electronic system has to maintain the resulting high input current ratings. This leads to a problematic design with noticeable efficiency restrictions. To improve the overall efficiency of the inverter and to reduce the input capacitor, a possible solution is the parallel operation of several converter stages. Here, a special disadvantage has to be marked: The parallel operation of conventional DC-to-DC converters with voltage source characteristics mostly used requires special control mechanism to ensure correct power distribution. Contrary to this behavior, current sourced converter types can act in parallel without any special measurements. The solution proposed in this paper is capable to improve the parallel operation of power stages in conventional converters with modern current sharing techniques. Due to the reduced current in each of the paralleled output stages, the efficiency will increase significantly. The ripple of the input current is shared between the different stages, which helps to reduce the input capacitor in each string. In addition, the resulting frequency rises with the number of used stages when multiphase operation is used. This leads to a more silent (EMC) design. Another big problem, the output rectifier operating at the high DC-link voltage, can be disburdened significantly by using the suggested current sourced inverter structure. In this paper a bi-directional 12V / 500W current sourced inverter for solar battery applications is described. Due to the special design, it could be build up by the usage of cheap mass components. The power stage operates at 50kHz, supplying a 400V DC-link

Key-Words: - Bidirectional DC-DC Converter, Parallel Operation, Solar Converter

1 Introduction

Significant drawbacks of conventional isolated solar converter applications operating at low DC-input voltage ratings or battery converters are the high current ratings on the primary. To overcome this problem, mostly paralleled structures of voltage-sourced converters are used. The starting point of our investigations was the elimination of the additional control necessary when voltage sources are used. This automatically leads to the usage of current sourced inverter topologies.

To overcome the drawback of the high current ratings three possible solutions can be given:

1. A single string topology that uses several power switches operating in parallel can be chosen.
2. A multi-phase PWM structure can be used [4]. In this case, the effective resulting switching frequency is the switching frequency of the partial power stage times the count of the output stages. The result is an inverter with reduced

current stress in the single stage. In addition, due to the divided output current, it is much easier to handle the design.

3. A topology based on several current sources acting in parallel to one DC-link can be used [2]. In this case, every solar string can operate on its local MPP. Furthermore, the output rectifiers can be disburdened compared to voltage mode converters.

The basic topology (c.f. Fig. 1) represents a well known solar plant arrangement. The DC-link (400V) is supplied by two solar circuits operating in parallel (a,b). Each string is controlled separately to operate on it's own MMP. The PWM-carrier of the stages theoretically can be phase delayed to minimize DC-link current ripple. In practice, mostly two independent modules without any synchronization are used. The additional battery, operating in parallel to the DC-link (c,d) and the inverter (e) are topics of another papers [3,4].

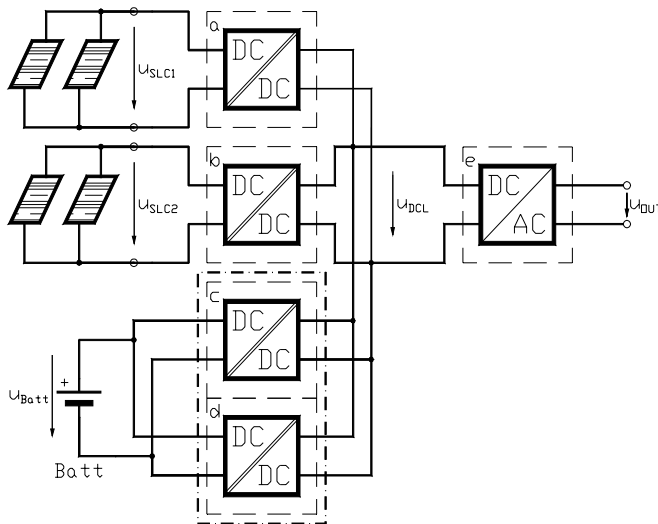


Fig. 1 Principal multi-source solar converter with battery support

A conventional realization scheme with two solar converters operating in parallel is given in Fig. 2. The two converters have to be controlled in a way to realize the current sharing, necessary for parallel operation.

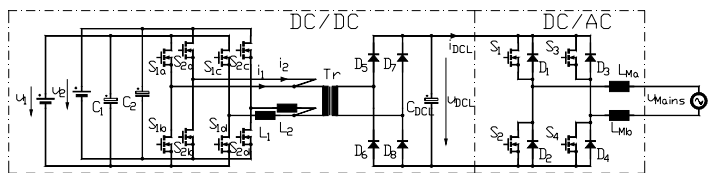


Figure 2. Conventional, parallel operating DC-to-AC inverter with voltage DC-link (consisting of DC-to-DC and DC-to-AC part, full bridge topology)

The solar plant (generator) voltage has to be fitted to the input voltage of the DC-to-AC power inverter. Besides, in most cases, an isolation barrier between the solar cells and the power grid is required which is mostly realized by a DC-to-DC converter. A major problem is the amount of the input capacitor (operating at low voltage levels), which is connected in parallel to the solar cells. Due to the 100Hz (120Hz) ripple in the output power of a single-phase inverter, big input and DC-link capacitors are required. Furthermore, filter inductors may be needed to keep the ripple in an acceptable range. To minimize the input voltage ripple at the solar cells, a DC-to-DC converter with constant power flow would be a big advantage. This lead to a system where most of the energy has to be stored in the DC-link capacitor operating at a higher voltage range resulting in significantly smaller (and therefore much cheaper) input capacitors. Constant power flow can be achieved by a controlled voltage ripple in the DC-link. The presettable voltage drop allows storing the required energy in an acceptable size of DC-link capacitors.

2 Current Sourced Converter

Contrary to the previous scheme the current source converter type proposed here has an inductive input and output characteristic (c.f. Fig. 3). The input current ripple is determined by the boost-inductors L_{1a} and L_{2a} . Because of the operating principle of the converter, which delivers current pulses into the DC-link, the structure is well suited for parallel operation (as well on the input as on output side). So, a multistring solar array arrangement can be realized in a rather simple way. When synchronization is used in between the power stages, the ripple in the DC-link can further be minimized.

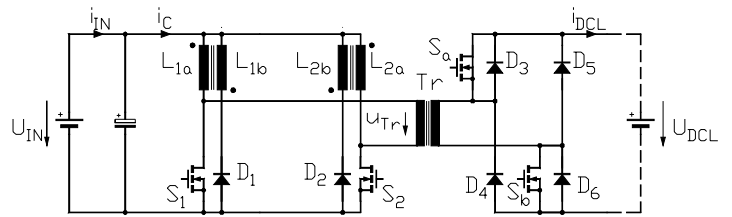


Fig. 3 Current sourced bi-directional DC-to-DC converter

An important point is the fact, that in the main current path only one active switching element is situated. This lead to a significant efficiency improvement compared to standard solutions because of the high current ratings on the primary. (Only the conduction losses of one switch have to be taken into considerations!) The inductive components located in series to the main switches require an active voltage clamping. The two auxiliary windings L_{1b} and L_{2b} on the inductors given in Fig. 3 in conjunction with the Diodes D_1 and D_2 are solving this problem. The energy restoring is used only at start-up or in case of fault condition. During normal operation the inductors demagnetizes via the transformer into the DC-link. In practice, additional small snubber circuits are necessary to avoid voltage peaks across the power switches.

Advantages of the presented topology

- simple structure, low component count
- straightforward control scheme
- only two power switches, operating on a common ground level, simple to control
- only one active switch in the main current path
- wide input voltage range due to step-up characteristics
- favorable transformer ratio
- improved input current ripple
- reduced component stress in the output rectifier

Disadvantages:

- At start-up and in case of fault condition a active demagnetizing circuitry is unavoidable to limit the voltage across the power switches

- An applicable stay value of the transformer is necessary to keep the losses in an acceptable way

3 Operation Principle

To clarify the operation principle of the converter proposed in Fig. 3 the two modes, the uplink (DC-link supply) and the downlink (charging mode) are presented in separate figures. Fig. 4 shows the simplified basic operation scheme of the circuit in uplink condition.

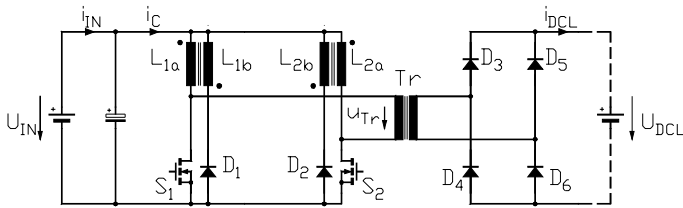


Fig. 4 Uplink operation (DC-link supply)

The opposite energy direction is given in Fig. 5. Due to the normally limited charging power here an asymmetric half bridge topology is chosen. In the figure also a solution using a full bridge structure is shown (dashed).

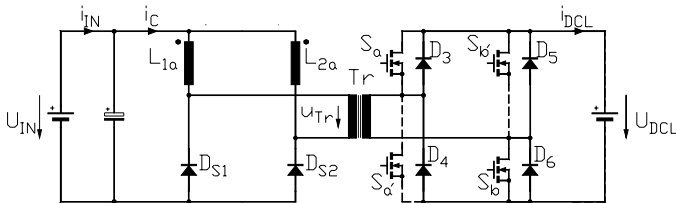


Fig. 5 Downlink operation (battery charging), asymmetric half bridge and optional full bridge topology (dashed)

Due to the practical battery handling normally the peak charging power is much less than the peak energy available by the battery. This behavior can be used to optimize the charging converter section. The required power can be made available by an asymmetric half bridge topology using the same transformer.

4 Simulation of the Converter

To explain the operation principle the proposed converter structure was simulated in PSPICE. A 200W converter was modeled. Figure 4 depicts the simulation model of the structure.

The technical characteristics of the simulation model are:

- Input voltage: 12V
- Output voltage: 400V
- Max. output power: 200W
- Switching frequency: 50kHz

To clarify the operation scheme the simulation was split into two different sections resulting from the existing energy directions of the structure:

4.1. UP-Link Operation Mode (DC-Link Supply)

According to the acting structure in case of upward conversion depicted in Fig. 4, the PSPICE-model was derived (c.f. Fig. 6).

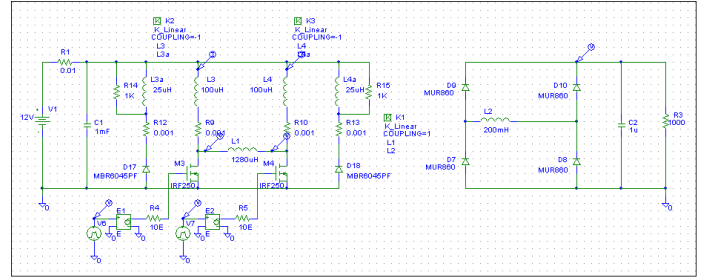


Fig. 6 UP-link PSPICE Model

The simulation results are depicted in Fig. 7 (partial load) and Fig. 8 (full load condition). From top to bottom one can see the output voltage of the transformer V[L2], the DC-link (output) current I[DCL], the battery (input) current, the inductor current I[L3], the inductor current I[L4], the drain current of the power switches I[M3], I[M4], the drain voltage of the power switches V[M3], V[M4] and the gate control signals VG[M3], VG[M4].

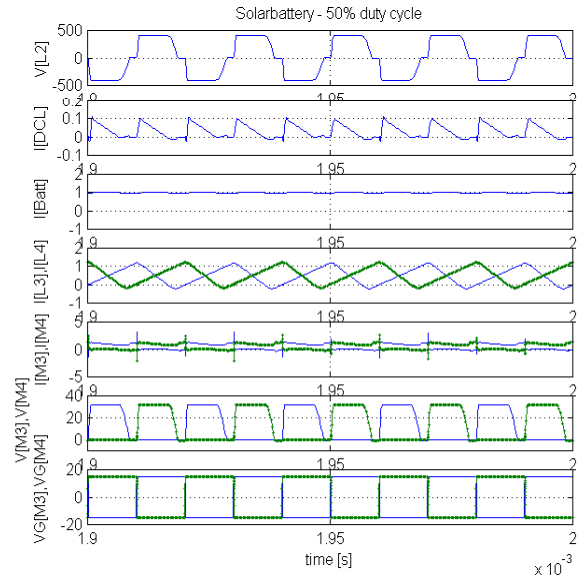


Fig. 7 UP-link operation at weak load condition

Due to the poor component models only quantitative simulation was preceded. An estimation of the expected efficiency would require exact models for the power switches and the coupled magnetic components leading to a problematic and rather slow simulation process.

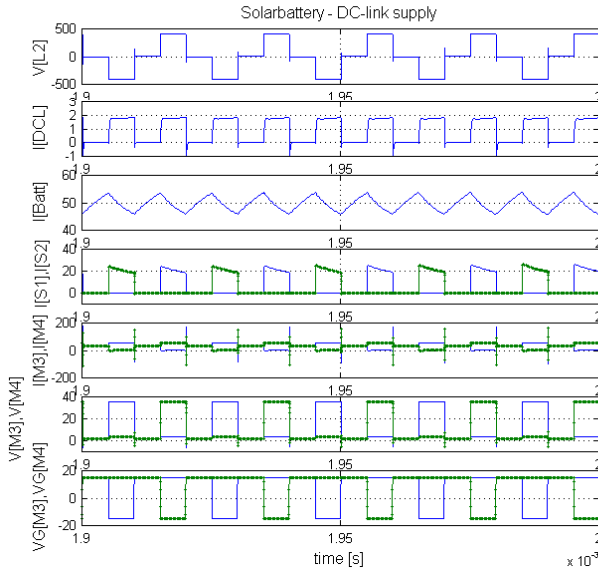


Fig. 8 UP-link operation at full load condition

4.2. DOWN-Link Operation Mode (Charging)

The circuitry decisive for the charging mode was formed in a PSPICE model for circuit level simulation (c.f. Fig. 9).

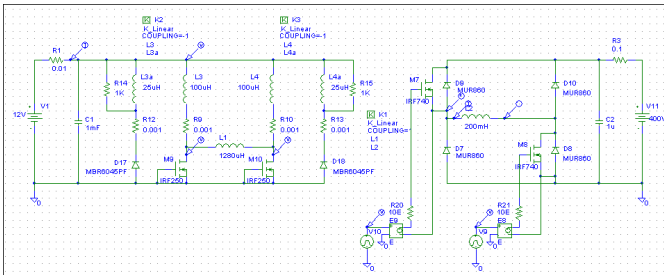


Fig. 9. DOWN-link (charging) PSPICE Model

Here also the inactive power switcher on the primary are taken into considerations. Without any control, the body diodes are used for forced rectification when current is transferred into the battery. Figure 10 depicts the charging mode of the converter. From top to bottom one can see the output (battery) current of the converter I[V1], the DC-link (input) current I[L2], the source voltage of M9 respectively the

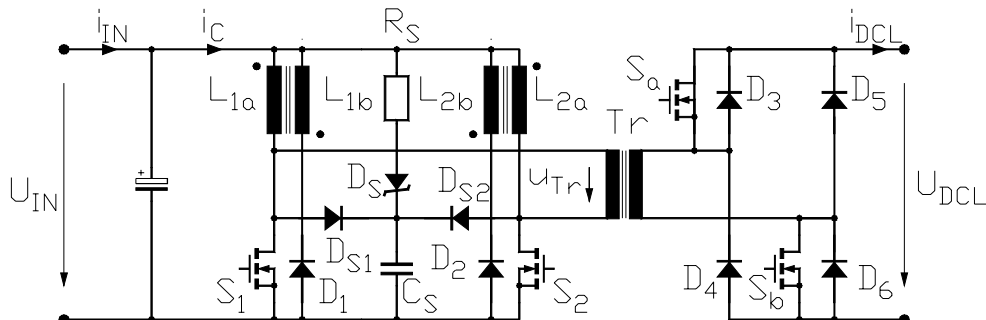


Fig. 11 Schematic of the prototype

drain voltage of M10 (V[M9], V[M10]), the voltage across the transformer V[Tr] and the gate control signals of M9 and M10, V[G].

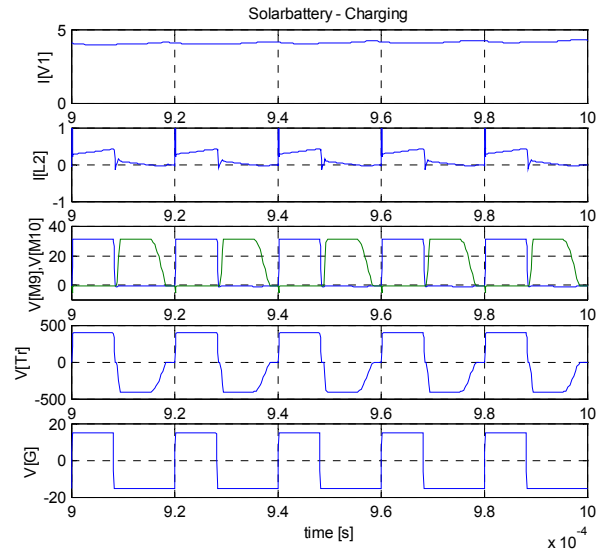


Fig. 10 DOWN-link operation (charging mode)

5 Practical Realization

For practical testing a 500W module was breadboarded operating from a 12V battery to a 400V DC-link. The switching frequency was set to 20kHz.

Power component characteristics:

voltage across the power switch:	<math><40V_{PK}</math>
max. switch current ($V_{IN}=8.5V$)	$40A_{RMS}, 60A_{PK}$
min. switch current ($V_{IN}=16V$)	$20A_{RMS}, 32A_{PK}$
transformer:	500VA
winding ratio:	1:12.5
input inductors (L1a and L2a):	100uH

Prototype components:

S_1, S_2 :	SUB75N08-10
D_1, D_2 :	MBR6045
D_3, \dots, D_6 :	MUR460
L_1, L_2 :	ETD49-core, N67
Tr:	ETD54-core, N67
D_{S1}, D_{S2} :	MBR20100
D_S :	P6KE33, 5pcs. in parallel (with R_S)
R_S :	22 Ω , 5pcs. in parallel
C_S :	10 μF

The detailed schematic of the converter was depicted in Fig. 11. The snubber circuitry, represented by D_S , D_{S1} , D_{S2} , C_S and R_S is required to keep the voltage overshoot across the mains power switches S_1 and S_2 in an acceptable range. The energy stored in the leakage inductors has to be dissipated. The control of the converter was realized by a programmed logic array (XC9572) in conjunction with a PIC16C73 microcontroller. The programmable timer array, implemented in the FPGA is given in Fig. 12. The flexible timing controller provides independent programmable pulse width and overlapping.

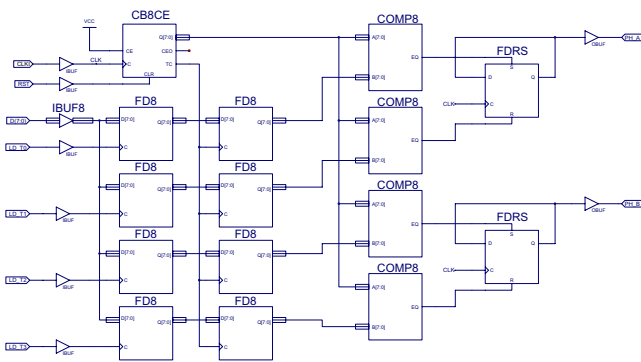


Fig. 12 PWM timing controller

The pattern generator is designed to individually program the on- and off-timing of each of the two-phase legs of the converter. The timing relates to a common eight-bit timer (CB8CE). The pattern update is double buffered and synchronized to the master timing frame to ensure glitch-free update.

6 Measurement Results

The proposed converter given in Fig. 11 was analyzed with regard to his practical operation in a battery supported solar power inverter.

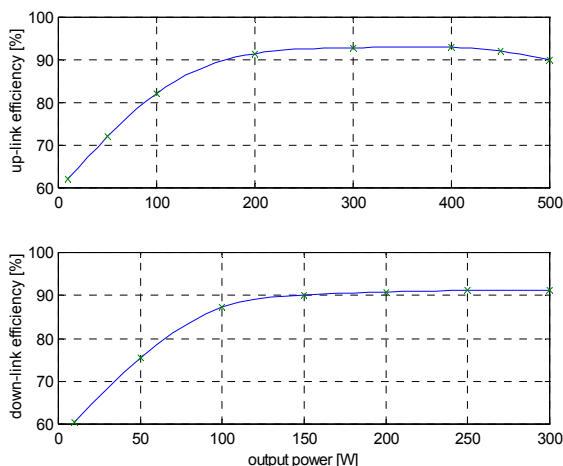


Fig. 13 converter efficiency in up-link (top) and down-link operation (bottom)

Here a point of major interest is the over-all efficiency of the structure. Figure 13 shows the

measured values in up-link and in charging mode. As one can see, the achievable efficiency also reaches acceptable values for battery backup operation.

7 Conclusion

The presented converter structure fulfills all requirements of DC-to-DC converters with very low input and high output voltage ratings. The relatively low efficiency which normally occurs due to the high current ratings is optimized due to the fact, that only one active switching element (MOSFET) is situated in the power current path. Because of its current source behavior the proposed converter type is optimal suited in power sharing environments where several power stages have to act in parallel. The breadboard sample converter shows a satisfying efficiency for the usage in solar power applications where high efficiency and an excellent reliability are points of major importance. The chosen design gives advantages in cooling and leads to a satisfactory power density. The implemented “automatic” charging feasibility helps to simplify the system design. So even when the battery is empty and no control of the primary is possible the system can start. In this case, the body diodes of the power switches will help to bring up the primary power supply automatically. When power is available on primary side, synchronous rectification can be used to improve the conversion efficiency.

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