The Optimized Bridge-Leg Power Switch

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Abstract: - Modern power electronic equipment (inverters, converters, switching mode amplifiers, etc.) mostly are based on switching technique realized by MOSFETs or IGBTs. The requirement of higher output signal quality, reduced size and weight as well as improved power density forces the design engineer to increase the switching frequency into the range of up to several hundred kilohertz, which only can be realized using optimized MOSFET topologies. Nevertheless, all these solutions deal with the disadvantage of the 'weak' body diode of these components. To overcome this drawback, several solutions have been presented in the past. In this paper a novel method is presented which helps to avoid the known disadvantages of the body diode (reverse recovery current, recovery time). The application of an external switching diode (e.g. based on SiC-technology) permits switching frequency increased by a factor of more than two without additional losses.

Key-Words: - Switching Stage, Inverter, Switching Mode Amplifier, PWM Stage

1 Introduction

Conventional switching mode PWM inverters and amplifiers today are industrial standard in the field of power conversion applications. The starting point of the presented research is a power switching stage with the goal of very high efficiency and switching speed operating from a 400V DC-link. Driving stages for high dynamic actuators and ultra fast inverters are another field of application. Furthermore, the proposed switching leg can also be used for high quality Class-D amplifiers in the field of audio applications. In this paper a novel circuit topology is proposed which gives an increased switching speed to meet high output voltage quality and improved power density (reduced converter weight and size). By avoiding the current peaks in the diode of the power switch during the reverse recovery process, the efficiency of the enhanced power stage can be kept in an acceptable range.

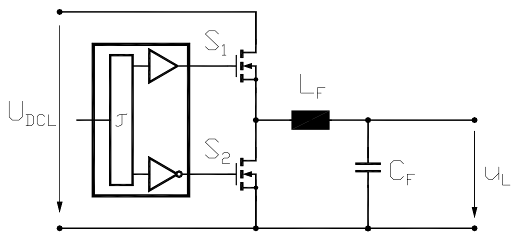

Fig. 1. Conventional switching stage equivalent circuit

The main drawback of conventional PWM-switching stages (cf. Fig. 1) operating from a 400V DC-link is the wide range of the duty cycle (up to 0..100%) to achieve a good output voltage utilization. A high output signal quality requires a very fine resolution of the PWM signal, while minimizing of all filter elements leads to a high switching frequency. Both demands lead to high PWM carrier frequencies (up to several hundreds of kilohertz) and minimal dead time in the control circuit (down to some ten of ns). Also the switching ripple in the output waveform has to be kept in an acceptable range even with small filters to satisfy the EMC requirements. In the past especially two solutions have been chosen to avoid the disadvantage of the high reverse current peak in the power components [6,7] (cf. Fig. 2). In Fig. 2a an asymmetric separation of the power paths for both current driving directions is shown. Due to the application of selected external high-speed switching diodes (D_1, D_2) the reverse current peak can be kept in an acceptable range. The solution presented in Fig. 2b uses a slightly modified topology. Here only a single main inductor (L_{Fb}) has to be used with the disadvantage of slightly reduced system benefits. The circuit is more difficult to be controlled in this way due to the dependency of the path separation on the leakage inductance [4].

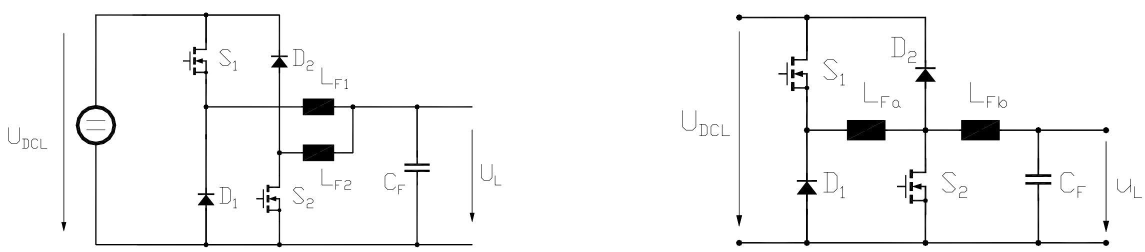

Fig. 2. Improved power switching stages: a.) by path separation, b.) simplified low cost solution

2 The Improved Power Switch

Figure 3 shows the derivation of the proposed novel structure. This solution basically improves the power switch S itself in its switching behavior by forcing the inverse current to go trough an external diode D.

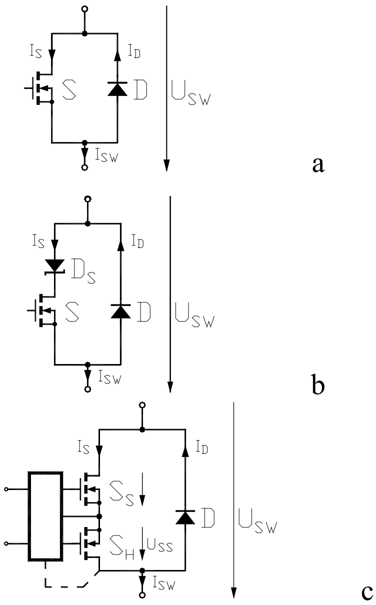

Fig. 3. Improved power switch (derivation):

a. external diode connected in parallel to the switch
b. standard solution with pinch-off of the MOSFET
c. advanced solution with controlled pinch-off “Diode”

The simplest solution (Fig. 3.a.) shows only a theoretical implementation. Due to the normally lower forward voltage of the MOSFET’s (S) body diode as compared to the fast external diode D the free-wheeling current in the bridge leg will not commutate to D. To force current commutation, therefore usually an additional (Schottky) diode D_S has to be added (cf. Fig. 3b). This well known solution forces the reverse current into the external diode D but shows also the drawback of additional conduction losses of the whole switch due to D_S. This drawback, however, can be avoided by using the proposed novel topology depicted in Fig. 3c. Here, an additional (low voltage, mΩ-$R_{DS,ON}$) switch S_H has been added which takes on the function of D_S.

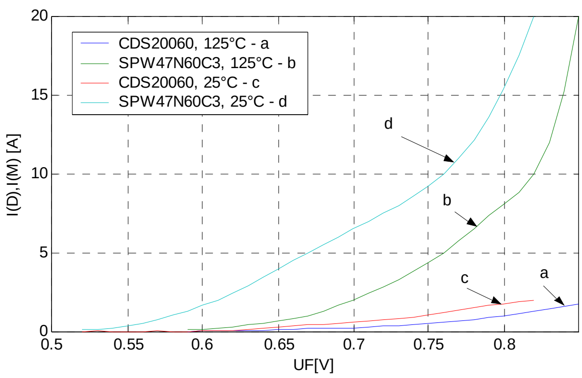

Fig. 4.a Current sharing of MOSFET SPW47N60C3 & Diode CSD20060 (cf. Fig. 3a).

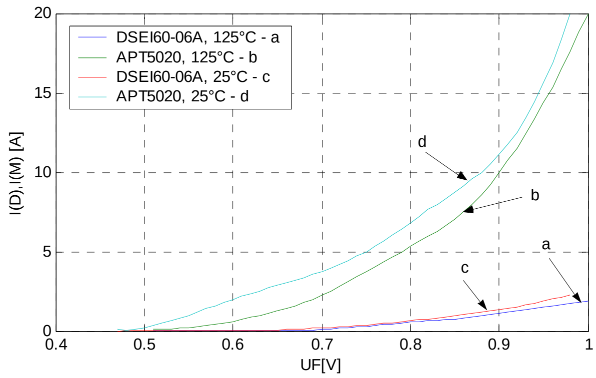

Fig. 4.b Current sharing of MOSFET APT5020 & Diode DSEI60-06A (cf. Fig. 3.a):

By external active control of S_H the conduction voltage of its body diode (operating initially as current separation diode) can be shorted leading to a considerable reduction of the conduction losses.

Figure 4a depicts the current sharing between a modern CoolMOS (C3) MOSFET and a SiC-Diode without a pinch-off diode, compared to a system using a standard MOSFET and a fast recovery epitaxial diode (cf. Fig. 4.b.). One can see that the external diode conducts only a minor percentage of the MOSFET’s current. With the novel solution given in Fig. 3.b. the current fully commutates into the external fast switching diode D.

3 Simulation Results

To demonstrate the improvements of the topologies given in Figs. 3a-c a circuit level based PSPICE simulation has been performed. Figure 5 depicts the basic simulation test circuitry.

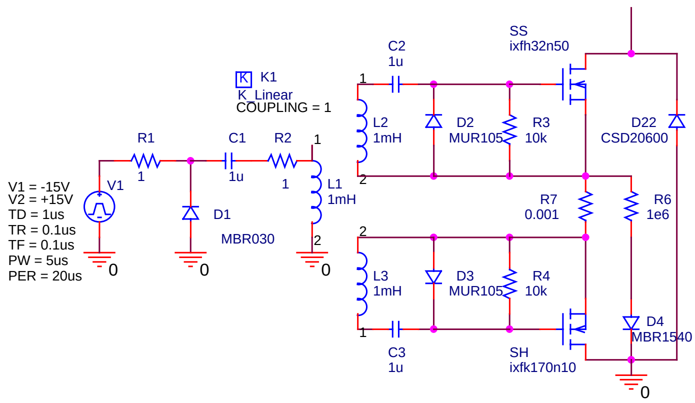

Fig. 5. PSPICE model of the switching stage

To clarify the necessity of body diode clamping the circuit given in Fig. 5 is compared to a conventionally operated hard switched half bridge. The stage operates at 10kHz with 50% duty cycle. Fig. 6 shows the excessive current peaks resulting from hard switching based on the poor switching behavior of the MOSFET body diode. The resulting high switching losses lead to a substantial switching frequency limitation.

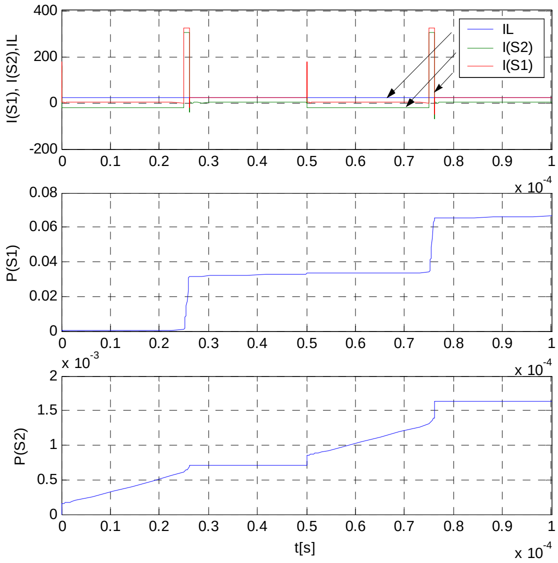

Fig. 6. Half bridge switching leg losses (cf. Fig. 3a): S_1 and S_2 are operated alternatively, unidirectional load current (ΔP_{S1} = 32mWs for test condition)

To overcome the known drawbacks, a topology according to Fig. 3.b. has been tested where the inverter stage largely is relieved from switching reverse current peaks. As indicated by Fig. 7 the losses are reduced by a remarkable factor.

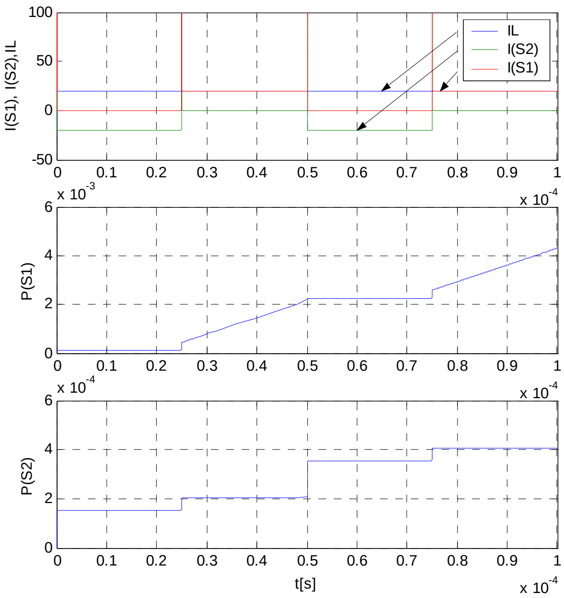

Fig. 7. Half bridge switching leg losses (cf. Fig. 3b) S_1 and S_2 operated alternatively, unidirectional load current (ΔP_{SS} = 0.35mWs for test condition)

To clarify the improvements of the active clamped body diode the different topologies are analyzed and compared in more detail. Fig. 8 shows the passive solution, while Fig. 9 uses a MOSFET operated as 'controlled diode'. The switches S_H and S_S are controlled from the same source.

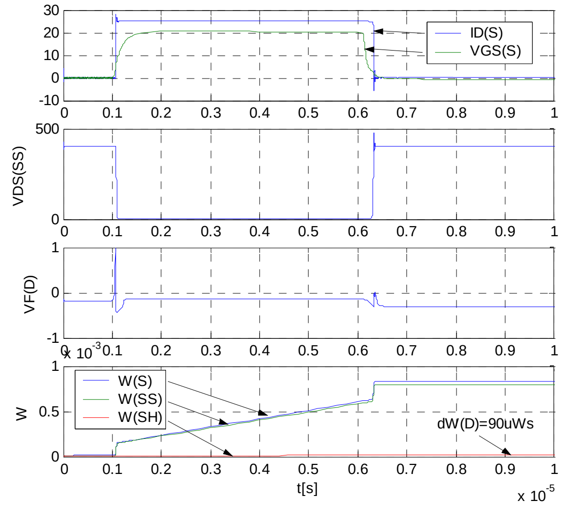

Fig. 8. Switching leg (cf. Fig. 5) with SiC diode SDT12S60 and Schottky clamping diode MBR1530

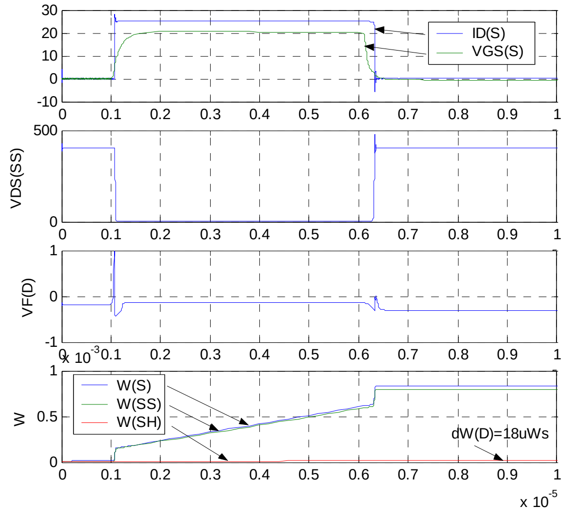

Fig. 9. Switching leg (cf. Fig. 5) with SiC diode SDT12S60 and active (MOSFET) clamping

Table 1. System loss comparison (SW – main switch, Sup. - supplementary element, rel.-relative performance)

Topology:	W(SW)	W(Sup.)	W(tot)	rel.
cf. Fig. 3.a IXFH32N50	 4.2mWs		4.2mWs	100%
cf. Fig. 3.b IXFH32N50 MBR1540 MUR3040	 2.2mWs	 0.1mWs 0.15mWs	2.45mWs	58%
cf. Fig. 3.b IXFH32N50 MBR1540 CSD20060	 0.8mWs	 0.05mWs 0.05mWs	0.9mWs	22%
cf. Fig. 3.c IXFH32N50 IXFK170N10 MUR3040	 2.2mWs 0.02mWs	 0.15mWs	2.37mWs	56%
cf. Fig. 3.c IXFH32N50 IXFK170N10 CSD20060	 0.7mWs 0.02mWs	 0.02mWs	0.74mWs	16%

In Table 1 all simulation results are compared. It is clearly shown that the usage of a "passive" clamping method (Fig. 3.b in connection with a conventional high-speed Si-diode D) leads to about half of the original switching losses W(tot). The application of a modern SiC diode gives a further significant improvement. Especially for the latter case the proposed active clamping according to Fig. 3.c opens an interesting additional possibility to minimize the losses of the switching leg.

4 Measurement Results

To verify the simulation results a laboratory testing circuit has been built up (100kHz switching frequency, duty cycle of 0.5, 400V DC-link voltage, cf. Fig. 10).

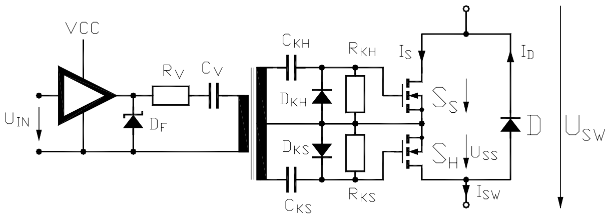

Fig. 10. Test circuitry

Table 2 Components

S_S	APT5014 (140mΩ type)
S_H	STB140NF75 (7.5mΩ) / MBR1540
D	DSEI60-06A / CSD20060
R_K	10kΩ
R_V	1Ω
D_F, D_K	SB140
C_V, C_K	1µF
IC	IX6R11 (one halve)

The topologies given in Figs. 3.b and 3.c are compared with two different free wheeling diodes (Si, SiC) and clamping components ("passive" Schottky-diode and "acive" MOSFET). The results are shown in Table 3.

Table 3. Loss comparison (open-circuit operation)

Topology	I_{IN}	Rel.:
3.b. – Si-based	0.53A	350%
3.b. – SiC based	0.19A	125%
3.c. – Si-based	0.48A	320%
3.c. – SiC based	0.15A	100%

Table 4. Loss comparison (15A peak load current)

Topology	I_{IN}	Rel.:
3.b. – Si-based	0.75A	375%
3.b. – SiC based	0.25A	125%
3.c. – Si-based	0.65A	325%
3.c. – SiC based	0.2A	100%

In Table 4 the switching leg drives a high-Q resonant tank to determine the losses under load condition (losses of the resonant network are neglected).

5 Conclusion

The proposed new solution reduces the disadvantage of hard-switched PWM power stages in conventional inverters based on MOSFET bridge-legs. Due to the separation of the different current paths, each component can be optimized separately. Furthermore, the problem of the weak body diode can be overcome. The result is a stage with significant lowered switching current peaks and improved EMC, especially if modern (e.g., SiC) diodes are used.

As demonstrated Tables 3 and 4 the optimization of the power components gives a reduction of the losses of about 30% compared to the worst case of clamped solutions. The usage of modern SiC diodes can show here its full benefit.

The proposed topology presented in this paper is a simple and effective solution for medium and high power applications when MOSFETs are used operating at higher switching frequencies.

The concept is well-suited for high quality / high speed switching mode amplifiers, high dynamic power inverters, wind-, solar-, and renewable energy systems as well as for aerospace applications, where efficiency and switching speed is a major goal.

References:

[1] P.J. Wolfs, “A current-sourced DC-DC converter derived via the duality principle from the half-bridge converter”, IEEE Transactions on Industrial Electronics, Volume 40, Issue 1, Feb. 1993, pp. 139-144.

[2] V.J. Thottuvelil, G.C. Verghese, “Analysis and control design of paralleled DC/DC converters with current sharing”, IEEE Transactions on Power Electronics, Volume 13, Issue 4, July 1998, pp. 635-644.

[3] A.Tuladhar, H. Jin, T. Unger, K. Mauch and Burnaby, B.C: "Control of Parallel Inverters in Distributed AC Power Supply with Consideration of the Line Impedance Effect", Applied Power Electronics Conference APEC '98, pp. 321-329, Anaheim, California.

[4] K. H. Edelmoser: "Bi-directional DC-to-DC Converter for Solar Applications", Proceedings of the 6th IEEE International Conference on Circuits, Systems, Communications and Computers CSCC '03, July 7-10, 2003, Corfu, Greece, CD-ROM, ISBN: 960-8052-63-7, 457-183.pdf.

[5] K. H. Edelmoser: "High Efficiency DC-to-DC Power Inverter", Proceedings of the 6th IEEE International Conference on Circuits, Systems, Communications and Computers CSCC '04, July 12-15, 2004, Athen, Greece, CD-ROM, 487-206.pdf.

[6] K. H. Edelmoser, F. A. Himmelstoß: “High Efficiency Inverter Switching Stage”, Proceedings of the ACEMP 2004, May 26-28, 2004, Istanbul, Turkey, pp. 205-209.

[7] K. H. Edelmoser: "Inverter Stage With High Small Signal Bandwidth", to be published in Proceedings of the international Power Conversion Conference PCIM'05, Nuremberg, Germany, June 7-9, 2005.