Topologies for Low Voltage Regulator Modules

Hermann Wetzel, Norbert Fröhleke, Horst Grotstollen
Institute of Power Electronics and Electrical Drives
University of Paderborn, Pohlweg 47–49, 33098 Paderborn, Germany
Phone: +49 5251 603157, Fax: +49 5251 603157, E-mail: wetzel@lea.upb.de

ABSTRACT

Three different topologies for low voltage regulator modules are compared in this paper. A Push-Pull converter (PPC) equipped with a novel hybrid gating scheme, which supports synchronous and external driving is proposed and compared to a Two-Transistor Forward Converter (2TFC) with a simple enhanced gating circuit of the MOSFET based rectification. Finally, an asymmetrical driven Half Bridge converter (AHBC) with integrated magnetic components and synchronous rectifier (SR) supplements the comparison. This topology was discussed only recently with respect to the low voltage topic. Prototypes for three topologies were developed, operated at 48 V input voltage and deliver 1.7 V at 18 A output current.

Keywords: *Low Voltage; Voltage Regulator Modules (VRM); Synchronous Rectification; Integrated Magnetics*

1. INTRODUCTION

Modern computers, automation equipment and telecommunication systems require high dynamic controlled low voltage DC/DC converters at output voltages of 1 and 2 Volt, which even fall below one volt in the near future. If supplying input voltages range nominally about 48 Volt only insulated converters qualify for this target application [1]. At first the operation principle of the three converters under consideration are reviewed. Gate drive concepts named self-, mixed- and full external driving are discussed with respect to various criteria. The low voltage regulator modules for all circuits were developed, operated at 48 V input voltage and deliver 1.7 V at 18 A output current. An increase of output currents is investigated momentarily influencing the ranking of the topologies. Out of the various design criteria being termed in this contribution the investigation of losses is addressed in more detail in [5]. This forms an efficient design base for new applications generated by the underlying industry project behind this contribution. The practical implementation of prototypes is outlined including component data supplemented by measured efficiency figures.

2. THREE ENHANCED TOPOLOGIES

The Push-Pull Converter (PPC) with synchronous rectification is the first topology treated in this paper. This double ended topology is often used for medium to large power levels. Recently, PPC are deployed also for the low voltage applications. Few versions of PPC are discussed in literature [2] and [3]. Fig. 1 shows the principle structure of the prototype circuit. The control is realized on the secondary side of the converter, because driving of the rectifying MOSFETs can be optimized to a higher degree and more easily. The primary sided control is also possible, was tested and can be used, if application demands it. The Push-Pull topology has a couple of advantages in comparison to the 2TFC: smaller current ripple and expenditure for input and output filters due to the more continuous energy flow, better utilization of transformer core and uninsulated primary gate drives. Disadvantages of this topology are the complexity of the transformer winding and its low utilization (two primary, two secondary windings), high voltage stress of primary MOSFET's (V_{dsmax}=(2...3)xV_{in}), hard switching and necessity for a snubber circuit. Snubber losses amount to about 10% of total losses. For reduction of snubber losses an active clamping circuit is used in [2]. In this case primary drives must be insulated. Moreover measurement of current gives problems due to oscillations between output capacitance of the primary side MOSFETs and the leakage inductance of the primary winding of the main transformer. Although the Push-Pull topology is affected by termed disadvantages, it is an interesting candidate, at least for high current applications.

Fig. 2 shows the Two Transistor Forward Converter (2TFC), the second compared topology in this paper. Although the 2TFC represents the "workhorse" in DC/DC converter industries in Europe, it is less used in the low voltage field. Two MOSFETs and two diodes at the primary side instead of one save the demagnetizing winding. The maximum theoretical duty ratio of the 2TFC is 0.5, if no tapped primary winding is utilized. The 2TFC topology is very simply, because of the transformer construction and driving of the primary MOSFETs. The voltage stress of primary MOSFETs is low. The turn-off of primary sided diodes is lossless, since the current slowly falls to zero. Hence, diodes do not show a reverse recovery current. Despite above mentioned advantages the following disadvantages have to be considered: Four semiconductors on the primary side, insulated gate drives for primary MOSFETs, extensive filtering on primary and secondary side, high volume of output filter inductor, high peak current stress of primary sided MOSFETs and largely discontinuous energy flow at the transformer interface. The utilization degree of the transformer is of course lower than for bridge topologies corresponding to only one conversion per switching period. Measurements on the prototypes of 2TFC show that the converter can be used at higher switching frequencies, if MOSFETs S1, S2 are selected sufficiently fast and the timing of the synchronous rectifiers is precise. The driving of the synchronous rectifiers in a 2TFC is a complex topic and is discussed in [5].

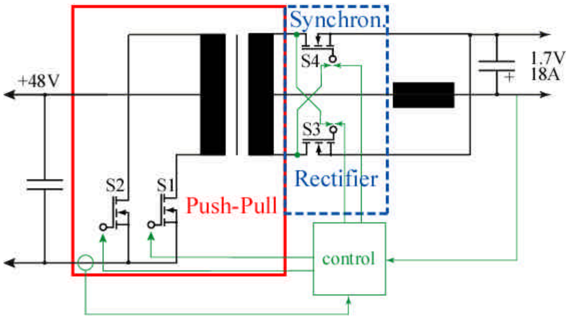

Figure 1. Push-Pull converter with synchronous rectification

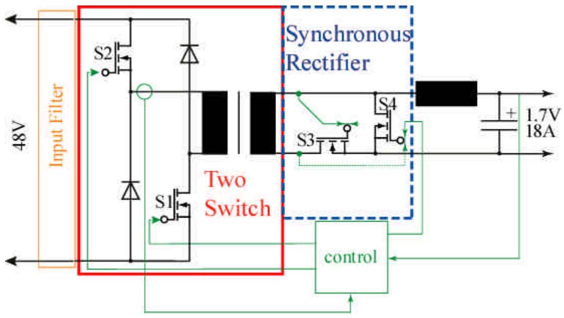

Figure 2. 2TFC with synchronous rectification

The asymmetrical driven Half Bridge Converter (AHBC) is the third topology discussed in this paper (see Fig. 3). On recent conferences half bridges were addressed in conjunction with the low voltage topic several times, e.g. [4]. Using the Full Bridge for low voltage converters at low power levels would be uneconomical from cost reasons. The asymmetrical driving permits zero-voltage switching (ZVS) and reduces primary sided switching losses in the AHBC. Utilization of the synchronous rectification in conjunction with the current doubler scheme eliminates secondary sided forward losses. The advantages of PPC and 2TFC are combined in the AHBC: low voltage stress of primary MOSFETs, good utilization of transformer core and continuous energy flow. Furthermore the transformer winding ratio can be selected much smaller than for the PPC or 2TFC reducing the core volume and the complexity of the winding. The disadvantages of both abovementioned topologies are reflected in the AHBC. The asymmetrical stress of all components is the main problem of AHBC. This problem complicates the choice of semiconductors and design of integrated magnetics. The modelling and control design of AHBC is intricate, because of a nonlinear transfer ratio.

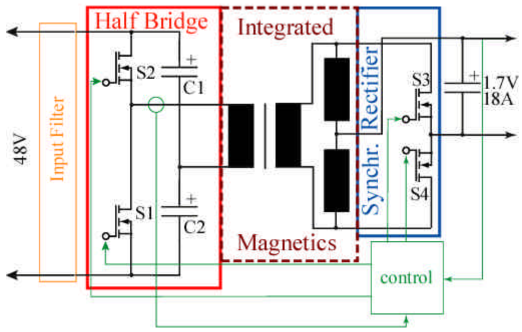

Figure 3. Asymmetrical Half Bridge converter with integrated magnetics and synchronous rectification

3. DIFFERENT DRIVING SCHEMES FOR LOW VOLTAGE REGULATOR MODULES

For power converters delivering low output voltages and power driver losses play an important role besides forward losses in the MOSFETs. Therefore in such MOSFETs with very low R_{DSON} several cells are connected in parallel internally, which result in a large gate charge (or large gate-source capacitance). Furthermore rectifying MOSFETs are connected in parallel if required. Thus the gate-source capacitances of primary sided MOSFETs amounts to about 1 nF and of parallel connected secondary sided SR-MOSFETs amounts to about 10 nF. In most cases gate and source of the driven MOSFET is shorted for fast turn off by a transistor. Thus, the driving energy is dissipated. Therefore such relatively high gate-source capacitances produce considerable driving losses and require powerful driving stages.

The driving of the primary sided MOSFETs is not critical, since their driving losses are small. These MOSFETs can be driven directly from a PWM controller or via a driving transformer. For the major concerned driving of the secondary sided MOSFETs generally four classes of driving are conceivable: "self driving" (from the secondary or auxiliary

TABLE I. DATA OF "PROTOTYPES 1" OF BOTH CIRCUITS

Circuit	Components	Driving	Advantages Disadvantages
Push-Pull converter (PPC)	U15x6 Transformer E18 Inductor 2 x 200V MOSFET 4 x 30V MOSFET	220 kHz self turn on ext turn off control and driving primary	+ small input and output filters + small current ripple + more continuous energy flow + better utilization of transformer core + uninsulated primary gate drives - complex transformer winding - high voltage stress of S1 and S2 - hard switching => snubber
Two Transistor forward converter (2TFC)	E18 Transformer E22 Inductor E14 Inductor 2 x 100V MOSFET 2 x 100V Schottky 4 x 30V MOSFET	400 kHz S3 self S4 ext control and driving secondary	+ very simple topology + low voltage stress of S1 and S2 - higher number of semiconductors - insulated primary gate drives - extensive filtering - high volume of filter inductors - high current stress of S1 and S2
Asymmetrical Half Bridge converter (AHBC)	EE22 Integrated Magnetics 2 x 100V MOSFET 4 x 30V MOSFET	400 kHz S3 ext S4 ext control and driving secondary ZVS	+ low voltage stress of S1 and S2 + better utilization of transformer core + small output current ripple + ZVS possible - insulated primary gate drives - high current stress of S1 and S2 - asymmetrical semiconductor stress

winding of main transformer), "external driving" (from an extra driver), "mixed driving" (a mix of the first and second) and "regenerative driving" with a partly saving of the driving energy. The latter is realized by resonant schemes, requires extra costs, pays only for high switching frequency and is not discussed in this paper.

Self driving is the low-cost method for driving of the rectifying MOSFETs, but it is suitable only for topologies without dead time of the transformer voltage (active clamped forward converter, asynchronous driven half bridge). Self driving is also not suitable for lowest output voltages, since the low secondary voltage (gating voltage) reduces the conductance of the rectifying MOSFETs.

A full external driving from a driving stage comprising two complementary bipolar transistors is the appropriate method for an exact adjustment of the turn on and off times. The signals from the PWM controller can be delayed, mixed with the transformer voltage or directly used for the driver. The full external driving requires auxiliary energy for the driver stage, contains several transistors and is only recommend in case of severe specifications. The prototype of AHBC, discussed in this paper, uses this method.

A mixing between self and full external driving yields best results in most cases. The kind of mixing depends on the particular topology. For example a rectifying MOSFET can be self and the other externally driven (2TFC), or both MOSFETs are self turned on and externally turned off (PPC).

A detailed description of different driving methods and schemes is elaborated in [5].

4. MEASUREMENTS

In order to compare the three treated topologies prototypes were designed for similar nominal operation conditions (s. Table I). The nominal switching frequency of the first prototype of the Push-Pull converter amounts to 220 kHz. The control and driving scheme was first implemented on the primary side of the converter. The rectifying MOSFETs were self turned on and externally turned off. A snubber circuit serves to reduce the voltage stress of primary MOSFETs. A classical U-core transformer was utilized for the first prototype of the PPC. A transfer of the control and driving circuitry to the secondary side was successfully tested on the first prototype of PPC. Thereby a driving transformer is used for driving of the primary sided MOSFETs. An active clamped version of the circuit [2], [3] was also investigated on the first prototype. Expected reduction of snubber losses was not attained in practice. This is to ascribe among others to the relative high leakage inductances of the U-core transformer. This in conjunction to capacitances generates a ringing during the freewheeling phase, which generates additional losses. Utilization of a planar transformer for next generation of PPC will solve this problem.

Fig. 4 shows the first prototype of a 2TFC. The first prototype was designed for a switching frequency of 250 kHz. The control and driving was placed on the

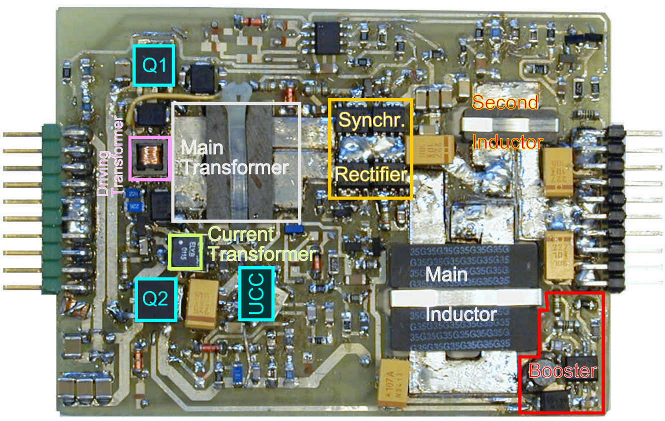

Figure 4. First prototype of the 2TFC

secondary side of the transformer. Auxiliary voltage for the driving and control was generated by an auxiliary power supply. The rectifying MOSFET S3 was self-driven from the main transformer. The freewheeling MOSFET S4 was fully externally driven by an extra driver. The MOSFETs on the primary side were triggered via a driving transformer. The primary sided current was measured using a current transformer. Two inductors (E22 and E14) with planar core were utilized for the filtering at the output of the converter. For the second prototype of 2TFC the switching frequency was increased from 250 kHz to 400 kHz and the output current was increased from 15 A to 18 A, using the same transformer core sizes. Subsequently the magnetic components needed to be redesigned. Windings of the main transformer were interleaved for reducing leakage inductances. Efficiency diagram of the second prototype of the 2TFC including driving and control losses is shown in Fig. 5.

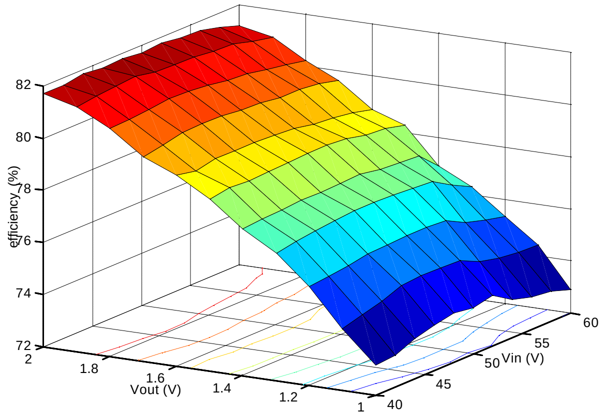

Figure 5. Efficiency of the second prototype of 2TFC at 18A output current and 400kHz switching frequency. All losses inclusive.

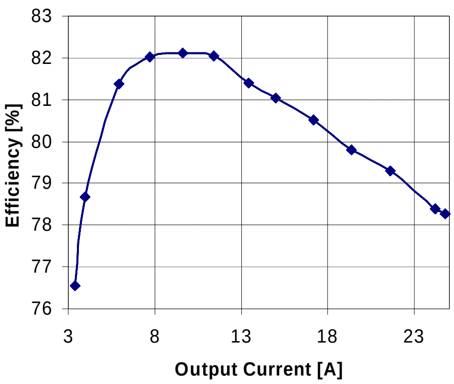

Figure 6. Efficiency of AHBC at 40V input voltage and 400kHz switching frequency

The prototype of AHBC was designed for switching frequency of 400 kHz, due to ZVS. The integration of the magnetic components of the AHBC was planned from the outset. Integrated magnetics using single planar core E22 is more compact than in the previous circuits and yields good results regarding current ripples. Fig. 6 shows an efficiency diagram of AHBC including all losses.

5. SUMMARY AND OUTLOOK

Three topologies and enhancements for low voltage regulator modules are presented and compared in this paper. For low power ($P_{out} < 30$ W) the 2TFC qualified best, while the PPFC showed more potential for higher power levels ($P_{out} > 30$ W). The AHBC is a good compromise for medium power levels, if the asymmetry of gating signals remains within restricted bounds. The use of integrated magnetics using solenoidal or planar windings yields in either case a strong influence on power density and costs but its design is of course more engaged.

REFERENCES

1. Basile Margaritis, Peter Ide, "Contemporary Architectures for Power System Considering Future Trends," *Proceedings of the 23rd IEEE International Telecommunications Energy Conference (Intelec)*, Edinburgh, UK, 14-18 Oct. 2001.
2. Peng Xu, Fred C. Lee, "Design of High-Input Voltage Regulator Modules With A Novel Integrated Magnetics," *IEEE Applied Power Electronics Conf. Proc. (APEC)*, Anaheim 2001, pp. 262-267.
3. Peng Xu, Jia Wei, Fred C. Lee, "The Active-Clamp Couple-Buck Converter - A Novel High Efficiency Voltage Regulator Modules," *IEEE Applied Power Electronics Conf. Proc. (APEC)*, Anaheim 2001, pp. 252-257.
4. Jian Sun, Vivek Mehrotra, "Unified Analysis of Half-Bridge Converters with Current-Doubler Rectifier." *IEEE Applied Power Electronics Conf. Proc. (APEC)*, Anaheim 2001, pp. 514-520.
5. Hermann Wetzel, Norbert Fröhleke, Peter Ide, Franz Meier, "Comparison of Low Voltage topologies for Voltage Regulator Modules," *IEEE Industry Applications Society Proc. (IAS)*, October 2002, Pittsburg, Pennsylvania, USA, Vol.2, pp. 1323-1329.