Abstract—The authors have invented, developed, and successfully tested a new type of switched-mode electronic power converters. The theory of operation of this new converter type as well as first test results of a prototype have been published in [1]. In this contribution, the authors present new results of measurements which have been performed on the modified prototype, which achieves an extraordinarily high peak efficiency of almost 99.6%.

Keywords—converter, efficiency, ZCZVS

I. INTRODUCTION

In [1], the authors have presented a new type of switched-mode electronic power converter. By avoiding switching losses due to zero-current switching at turn-on and zero-voltage switching at turn-off of the power switches, this new converter type has the potential for exceptionally high efficiency, and an excellent EMC behaviour. Compared to other zero-current / zero-voltage switching converters – namely resonant converters – the proposed converter has a rather simple topology and is easy to drive. Moreover, the basic principle of this converter is flexible, which allows the implementation of all three basic converter functions, buck, boost and buck-boost. The basic topologies of these implementations are shown in Fig. 1.

The theory of operation of this new converter type is explained in detail in [1]. The following is a short summary. Regardless of the implementation, the proposed topology comprises two sub-converters in parallel mode. Therefore, the topology resembles the topology of interleaved converters. There are only two additional components: A small coupling capacitor (C<sub>c</sub>) and a small bypass switch (S<sub>3</sub>). These two components are connected in parallel between the nodes with the sub-converter's chopper voltages. The sub-converters work in discontinuous conduction mode. As opposed to an interleaved converter, there is no phase shift between the two inductor currents. Instead, the main switches (S<sub>1</sub> & S<sub>2</sub>) turn on simultaneously at the beginning of each switching cycle. Due to operation in discontinuous conduction mode, the activation of the switches happens at zero-current and is therefore virtually lossless. As soon as the inductor currents reach their desired peak value, the main switches are turned off. However, there is a slight delay between the turn-off of the two main switches. This allows the inductor currents of both sub-converters to be redirected through the coupling capacitor in the first moment after the deactivation of the corresponding main switch. By this, the coupling capacitor is charged (after deactivation of the first main switch) and discharged again (after deactivation of the second main switch). In both cases, the corresponding diode becomes forward biased and conducting only after the coupling capacitor's voltage has reached its stationary value. Due to the coupling capacitor, the gradient of the switching slopes of both sub-converters is much lower compared to a conventional, hard-switching converter. This has two major advantages: First, the charge redistribution of the coupling capacitor takes several times longer than the turn-off of the main switches. Thus, the main switches are at zero-current before the switching voltage has reached a significant value. Due to this, the main switches turn off almost at zero-voltage, which virtually eliminates the switching losses. Second, the low-gradient switching slopes lead to a very EMC friendly behaviour of the converter; unlike conventional converters, the electromagnetic interferences do not have to be filtered (which is treatment of symptoms) but are not even generated in the first place. When both diodes are conducting, the currents in both inductors fall back to zero. Because of the time delay between the turn-off of the first and second main switch, one inductor current will reach zero slightly before the other. This leads to a small cross-current, which flows between the sub-converters during the zero-current phase of the converter. To prevent an unwanted
charging of the capacitor by this cross-current, the bypass switch (S3) is turned-on as soon as the charging and discharging process of the coupling capacitor is finished and turned off again before the first main switch is turned off in the next switching cycle.

In [1], the authors presented test results of a functional prototype, which has been designed, assembled, and tested at BFH's Laboratory for Photovoltaic Systems. This prototype was designed for a nominal output power of 2 kW and was originally intended for bidirectional operation. This was achieved by using the topology of the buck-converter (see Fig. 1a), but by replacing the two diodes with an additional pair of switches (the details of bidirectional operation are discussed in [1]). This prototype achieved a respectable peak efficiency of 99.4%. It was however already mentioned in [1], that with a few modifications — lower input voltage and removing of the components for boost-mode — the efficiency has been improved even further. The results of this optimized prototype are presented and discussed in this paper.

II. RESULTS OF THE OPTIMIZED PROTOTYPE

After removing of the components for boost-mode, the topology of the prototype now matches the basic topology of the buck-converter. Fig 2 shows the efficiency of the optimized prototype versus the nominal output power. The peak efficiency of the optimized prototype is almost 99.6% at about 1360 W of output power. This means that the prototype dissipates less than 5.5 W. Due to this very low dissipation, there is only little heating of the components. However, the efficiency curve shows a clearly visible ripple. In [1], it was already explained, that this ripple is caused by inductor current ringing [2]. During the zero-current phase, when all semiconductors are blocking, there is a resonance between the inductors and the parasitic capacitance of the nodes of the chopper voltage versus ground. If the main switches are turned on, the energy stored in this capacitance is being dissipated. Due to inductor current ringing, the voltage over this capacitance is oscillating. If the main switches are turned off when the voltage is at its maximum value, the power dissipation is high, which causes the notches in the efficiency curve. Based on the oscillation frequency, the value of the parasitic capacitance can be estimated at roughly 350 pF. If the converter operates at 600 V input voltage with 50 kHz switching frequency, the losses caused by inductor current ringing can be estimated at

\[ P_{\text{loss}} = \frac{1}{2} \cdot 350 \text{ pF} \cdot (600 \text{ V})^2 \cdot 50 \text{ kHz} = 3.15 \text{ W}. \]

If we look at Fig. 2, we can see, that the efficiency rises about 0.3% between 1200 W and 1360 W of output power. 0.3% of 1200 W is 3.6 W, which is close to the estimate calculated with (1). Compared to the efficiency curve shown in [1], the ripple of the optimized prototype is much lower. This has two reasons. First, the capacitive losses caused by inductor current ringing are quadratic to the voltage. Because of the voltage reduction from 800 V to 600 V with the optimized prototype, we can estimate a reduction of the losses of about 44%. Second, by removing of the components for boost-mode, the parasitic capacitance has been decreased. The parasitic capacitance is mostly caused by the output capacitance of the power semiconductors. As half of them have been removed, the parasitic capacitance and the losses caused by inductor current ringing have also been reduced by nearly 50%.

III. DISCUSSION OF THE TEST RESULTS

We could show that with relatively small modifications only, the already respectable efficiency of the prototype of 99.4% before the optimization has been improved by another 0.2%. Although an improvement of 0.2% does not sound too spectacular, it must be considered, that the losses have been reduced by about one third. Consequently, the power dissipation and with it the heating of the components are once again significantly lower than with the original version of the prototype. This is a vital aspect when it comes to the reliability of the converter. As there are always two sub-converters needed, the complexity of the proposed converter topology is higher compared to standard, hard-switching topologies. This potentially increases the statistical failure rate of the device. However, statistical failure models for semiconductors assume an exponential rise of the failure rate with rising temperature. As it is possible to keep the power dissipation and with it the operating temperature very low with the proposed topology, highly reliable designs are feasible, because the positive effect of the low temperature can more than compensate for the disadvantages caused by the higher component count. If we assume a well-balanced, conventional power converter, where about half of the losses are caused by switching losses, we can also assume that the losses (and with it the heating) can be reduced by about 50% simply by using the proposed converter topology.

IV. CONCLUSION AND OUTLOOK

In [1], the authors assumed that due to savings in cooling effort and EMC suppression as well as due to energy savings caused by the high efficiency, the proposed converter topology may be a cost-effective alternative to common converter topologies. With the even better performance presented in this contribution, this assumption can be substantiated once again. It is not only the peak efficiency that has been improved, but also the average efficiency over a wide power range. If we look again at Fig. 1, we can see that an efficiency of 99% is exceeded continuously starting at 500 W of output power — a mere quarter of the prototype's rated power. This means that even due to the losses caused by inductor current ringing, the prototype's efficiency is continuously very high. In [1], the authors already proposed a way to eliminate these losses by use of a more sophisticated control unit which modulates both pulse width and switching frequency (with this, the main switches are only turned on if the voltage over the parasitic capacitance is low). In the next step, the authors intend to implement such a control unit in the prototype. With this, the authors assume that the efficiency...
curve will be smoothed even further and pass 99% at 300 W of output power or less. This would again be a considerable improvement of the prototype's performance.

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REFERENCES
