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# Very High Frequency Resonant DC/DC Converters for LED Lighting

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*Abstract*— This paper presents a very high frequency DC/DC converter for LED lighting. Several resonant topologies are compared and their usability discussed. At the end the resonant SEPIC converter is chosen based on the achievable power density and total bill of material. Simulations of a 51 MHz converter with 40 V input and 15 V output are made. The simulation shows possibility of achieving efficiency up to 87 % even with a HEXFET Power MOSFET. Three prototypes of the simulated converter are implemented showing good correlation with simulations. The prototypes have efficiencies up to 84 % and power densities up to 8.9 W/cm$^3$ (146 W/in$^3$).

## I. INTRODUCTION

During the last decade the focus on green and environment friendly energy usage has been constantly increasing. This has lead to a large increase in the use of Light-Emitting Diodes (LEDs) for lightning. These bulbs are still quite expensive due to both expensive LEDs and the power converter needed to supply these. Hence there is a strong demand for small, cheap and efficient power converters.

The power density of Switch-Mode Power Supplies (SMPS) is limited by their passive energy storing elements. As both the physical size and price of these scale with the switching frequency ($f_S$), increasing $f_S$ into the Very High Frequency band (VHF, 30-300 MHz) will make it possible to achieve higher power density and lower cost. Increasing the switching frequency has several other advantages, which has been discussed in [4], [6], [15] and [16].

The high increase in $f_S$ causes several new problems to arise. Some of these have been solved [4], [11] and [18], but many still need to be investigated. One of the main problems is the switching loss, which increases linearly with $f_S$. As $f_S$ increases into the VHF band the switching losses becomes so severe that it will be impossible to cool the switching device and keep the efficiency high. Several researchers [2]- [5] and [7] have tried to use different types of resonant converters with Zero Voltage Switching (ZVS) and/or Zero Current Switching (ZCS) in order to reduce or ideally eliminate these losses.

Due to the resonating behaviour of these converters it is however very difficult to control these converters for varying loads efficiently. For now the most efficient way is to use burst mode control to simply Pulse Width Modulate (PWM) the converter in order to achieve the desired output [4], [9] and [21].

When working continuously in open loop these converters will have an almost constant current output for a given input voltage. This makes them very well suited for LED applications where it is the current that needs to be controlled. As the output current is constant for a given input voltage the current through the LED will be constant even as the forward voltage changes due to changes in temperature. The life time of LED bulbs are limited by the electrolytic capacitors needed, increasing the switching frequency will eliminated this need and hence increase the life time of the bulb.

This paper will give an example of the design of a VHF resonant DC/DC converter for LED lighting. First an appropriate topology is selected in section II, then a simulation is made and component selected in section III. Section IV covers the implementation and measurements and finally section V concludes the paper.

## II. SELECTION OF TOPOLOGY

When designing resonant DC/DC converters it is very common to split the converter in to two parts; 1) a resonant inverter converting the DC input voltage to a sinusoidal output current 2) a resonant rectifier rectifying the AC current to a DC output [1], [8], and [14].

The most commonly used rectifier is the class E rectifier [8], [17] and [19]. Other alternatives exist [1], [7] and [10], but due to the very simple schematic with a single diode the class E rectifier is chosen for this converter.

For the inverter part several topologies has been used [2], [3] and [5], each with their own pros and cons.

The class DE inverter (used in [5], [10] and [11] and shown together with the selected rectifier in Figure 1) is the topology with the lowest stress on the switches due to the direct connection to the input, but it requires a high side driver. This is complex to design for these frequencies and it will increase both the complexity, size and price of the converter.

The class E inverter (used in [6] and [8]) shown in Figure 2 has only a low side switch and is therefore much simpler to drive, however it imposes a huge voltage stress on the switch. As the drain of the switch is connected to the input through an inductor, the average drain-source voltage ($V_{DS}$) of the switch has to be equal to the input voltage. Even if $V_{DS}$ is assumed constant when the switch is closed, the peak voltage will be
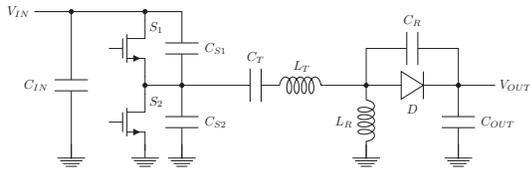
Fig. 1. Schematic of the class DE inverter and class E rectifier.



Fig. 4. Schematic of the SEPIC converter.

two times $V_{IN}$ for a duty cycle of 50 %. In reality the voltage across the switch is more like a half wave rectified sine wave in order to achieve ZVS, which result in a peak voltage of 3.56 times $V_{IN}$ [12].
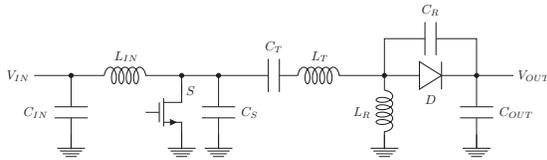


Fig. 2. Schematic of the class E inverter and rectifier.

In order to reduce this huge peak voltage the class $EF_2$ (or $\varphi_2$), which is a hybrid between the class E and class $F_2$, has been developed ( [13] and [14]). It introduces an extra resonant circuit ($C_{MR}$ and $L_{MR}$ in Figure 3) across the drain and source of the switch with a zero at the second harmonic of $f_S$. If tuned correctly this adds the third harmonic of $f_S$ on top of the sine wave seen with the class E. This results in a trapezoidal waveform across the switch. This reduces the peak voltage a bit, but increases complexity and results in additional losses due to large AC current at three times $f_S$.
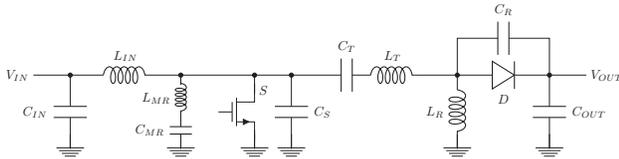


Fig. 3. Schematic of the class $EF_2$ inverter and class E rectifier.

The SEPIC converter [20] shown in Figure 4 is similar to the circuit in Figure 2 with $L_T$ removed. However the waveforms are different, as this converter cannot be split into an inverter and a rectifier. The changed waveforms results in a much smaller input inductor than needed for the class E inverter, thus the achievable power density is higher due to fewer and smaller inductors.

Based on the analysis of the four converter topologies the SEPIC converter was chosen as it gives the highest power density and lowest cost.

## III. SIMULATION AND COMPONENT SELECTION

A model of a resonant SEPIC converter has been set up in spice based on the tuning procedure explained in [20]. The converter is designed to have the specifications given in table
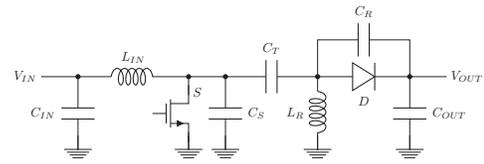
I. The converter will be used to supply a string of LEDs with a combined forward voltage drop of 12-15 V, depending on temperature and power level.

TABLE I
DESIGN SPECIFICATIONS

| Specification | Symbol | Value |
|---|---|---|
| Input voltage | $V_{IN}$ | 40 V |
| Output power | $P_{OUT}$ | 5 W |
| Output Voltage | $V_{OUT}$ | 15 V |
| Switching frequency | $f_S$ | 51 MHz |

From the simulations it is seen that the MOSFET should have a break down voltage of at least 100V (see Figure 6), however if the duty cycle is adjusted closer to 50 % the peak voltage will get close to 143 V (3.56 times the input voltage as for the class E). For this reason it was decided to build the prototype around an IRF5802 MOSFET from International Rectifier. The MOSFET has a break down voltage of 150 V and small parasitic capacitances compared to its competitors.

The peak voltage is slightly above 40 V (see Figure 6 where $V_{AC}$ is anode-cathode voltage) and a MBR0540 40 V Schottky diode has therefore been selected. $C_R$ needs to be 105 pF which is more than the parasitic capacitance of a single diode (35 pF), thus it is necessary either to add a 70 pF capacitor or use three diodes in parallel. The last solution have the benefit of sharing the current between the three devices. As the forward voltage drop of the diodes increases with the current running through them, this will lead to reduced losses and this solution was therefore selected.

The inductors are all square air core inductors (1515SQ-68N, 1515SQ-82N and 2222SQ-161) as they have a fairly high Q factor and are available off the shelf which ease implementation. The $C_T$ capacitor is implemented with 4 parallel capacitors as it was found that this increased the efficiency of the converter with 1-2 % compared to using a single capacitor of the same value. For the input and output capacitors standard 1 $\mu$F X7R capacitors was selected.

## IV. IMPLEMENTATION AND MEASUREMENTS

A prototype of the simulated converter has been implemented and is shown in Figure 7. The prototype had an efficiency of 84 %, this is slightly lower than the simulated efficiency but still on level with other state of the art VHF converters. The output power was 5.7 W at 40 V input, which is significantly higher than the expected. The increase in output
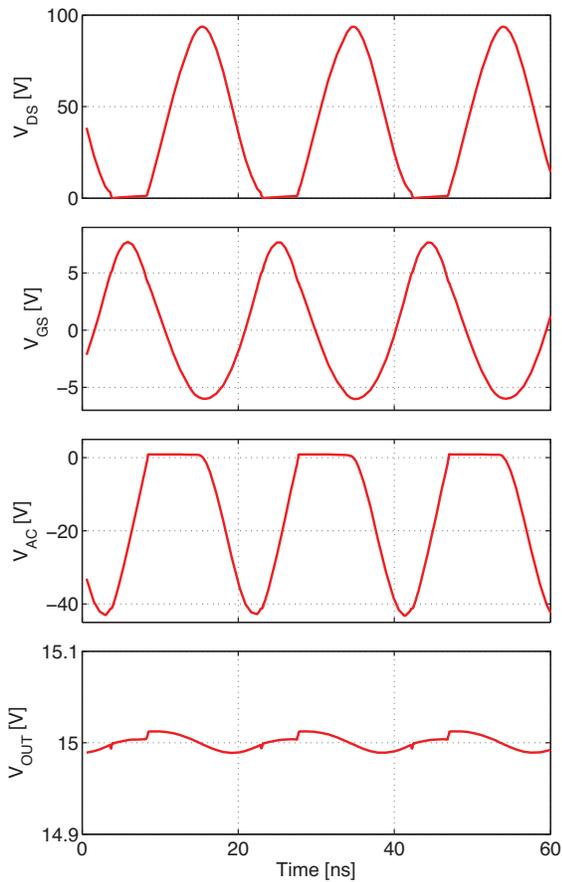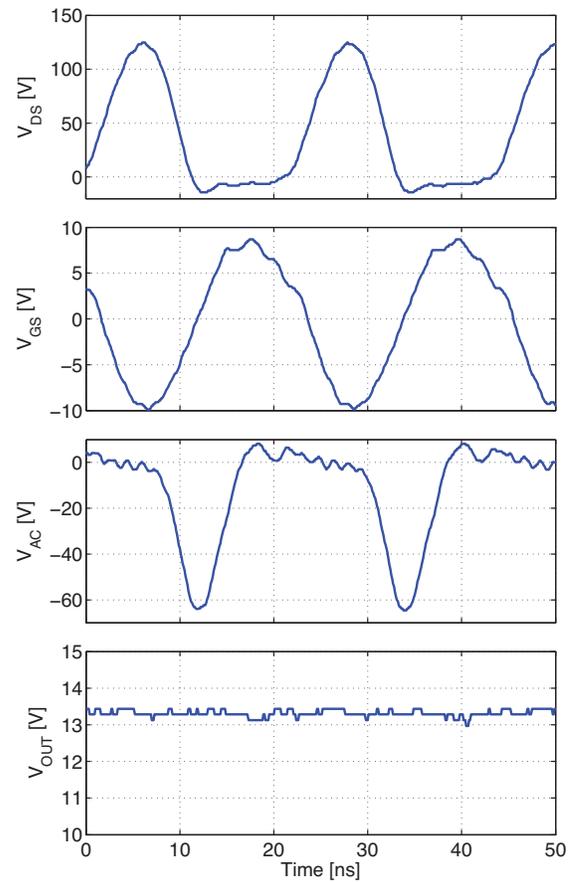
Fig. 5.   Simulation results



Fig. 6.   Measured waveforms

| Component | Simulated | Prototype | Type |
|-----------|-----------|-----------|------|
| $C_{IN}$ | 1 $\mu F$ | 1 $\mu F$ | Capacitor (X7R) |
| $L_{IN}$ | 160 $nH$ | 160 $nH$ | Inductor |
| $S$ | | IRF5802 | n-channel MOSFET |
| $C_S$ | 22 $pF$ | Parasitic | Capacitor |
| $C_T$ | 40 $pF$ | 4 · 10 $pF$ | Capacitor (NPO) |
| $L_R$ | 82 $nH$ | 82 $nH$ | Inductor |
| $D$ | | 3 · MBR0540 | Schottky diode |
| $C_R$ | 105 $pF$ | Parasitic | Capacitor |
| $C_{OUT}$ | 1 $\mu F$ | 1 $\mu F$ | Capacitor (X7R) |



Fig. 7.   Picture of the implemented prototype on a 15x22 mm PCB

power was achieved by reducing the switching frequency to 46 MHz and increasing the duty cycle.

The gate and output voltages were measured with the standard probes for a Rohde & Schwartz RTO1024 digital oscilloscope. The capacitance of the probes are 10 pF, adding this between the drain and source of the MOSFET would change the resonance of the converter making it hard switch and thereby destroy the switch. To avoid this a voltage divider was made by adding a 1 pF capacitor in series with the probe, this reduces the effectively added capacitance to 0.9 pF. This
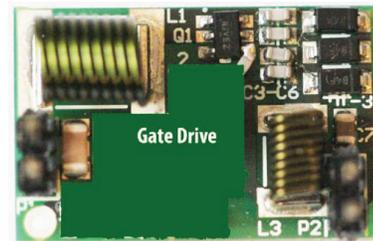
still affect the behaviour of the converter, however as seen in Figure 6 the converter is still operating close to ZVS. In order to get the correct DC level a resistive voltage divider was added in parallel with the probe and the 1 pF capacitor. The same principle was used to measure the voltage at the anode of the diode, at this node 10pF would not be as crucial but it is still necessary to keep the converter close to ZVS.

From the measured waves it seems like the gate drive is a few nano second to slow when turning on the MOSFET. Whether this is actually happening or if it is due to a small delay caused by the resistive/capacitive voltage division made to measure the drain voltage is not certain. If the gate drive is actually turning on the MOSFET to late, it is partly saved

(a) Top of offline prototype



(b) Top of commercial supply



(c) Front of offline prototype



(d) Front of commercial supply



(e) Bottom of offline prototype



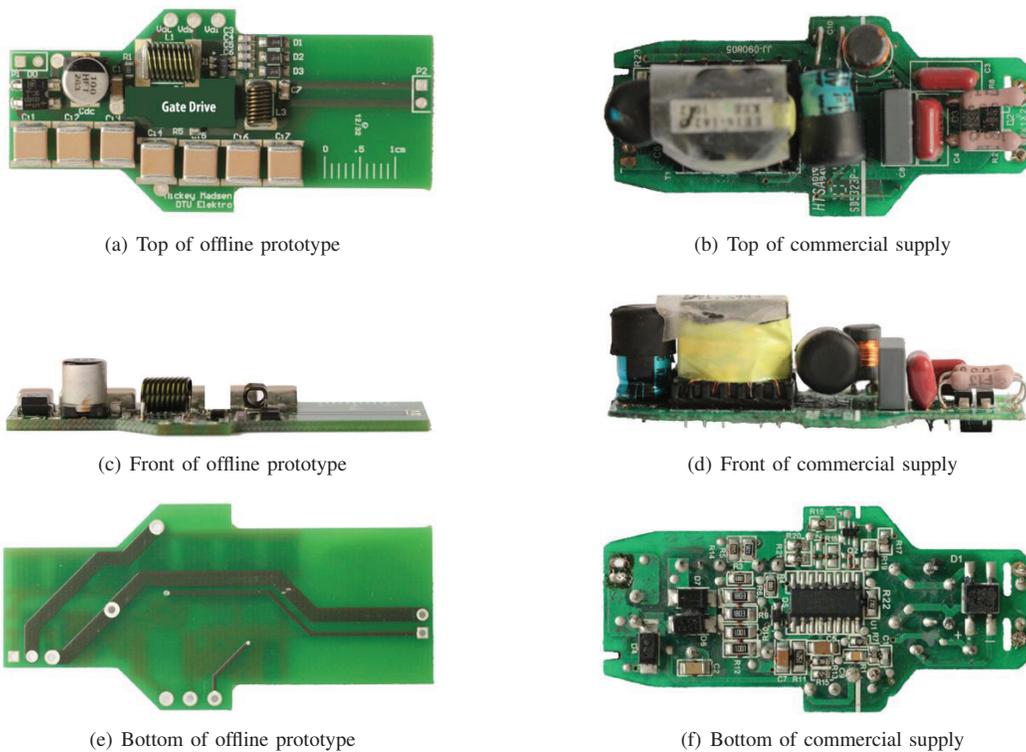(f) Bottom of commercial supply

Fig. 8.   Comparison of first VHF based prototype and commercial available 230 V power supply
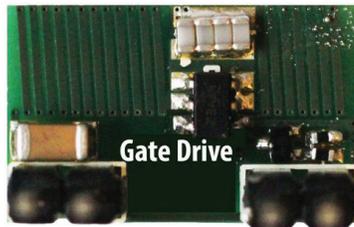


Fig. 9.   Top side of prototype with PCB inductors (10x16mm PCB)

by the body diode of the MOSFET and the efficiency can therefore still be acceptable. However in this situation fine tuning of the gate drive could increase efficiency a few percent as the body diode is a quite lossy device.

The peak voltage across the diode is far above the rated limit. This is mainly caused by the reduced switching frequency which makes the impedance of the inductor decrease while the impedance of the parasitic capacitance increase, this increases the duty cycle of the diode and there by increases the peak voltage. The increased power is also contributing to an increased peak voltage, but this will only cause a slight increase.

The ripple seen at the output is clearly some digital noise cause by the oscilloscope and not something that can be used to determine the output ripple of the converter.

### A. Alternative implementations

The main reason for the increasing the output power was to get the same amount of power as the commercial supply shown in Figure 8(b), 8(d) and 8(f). This supply is made for the european mains (230 V) and has an efficiency of 77 %, i.e. 7 % below the 40 V VHF converter with the same output in a much smaller footprint. In order to make a fair comparison a prototype was made with a mains rectifier and a capacitive voltage divider to reduce the input voltage of the VHF converter (the offline prototype is shown in Figure 8(a), 8(c) and 8(e)). The offline prototype has an efficiency of 78 % and a volume which is reduced by approximately 80 % compared to the commercial supply. Hence it offers slightly increased efficiency in a dramatically reduced volume.

It should however be noted that the power factor of the offline prototype is very poor (below 0.5) whereas the commercial has a power factor of 0.82. Furthermore the commercial supply is galvanic isolated which the offline prototype is not.

In order to push the power density even further, a prototype has been made were the inductors are implemented as PCB solenoids. The complete converter has a footprint of 16x10x4 mm (LxWxH) and can handle an output power of up to 5 W. This gives a power density of 7.8 W/cm$^3$ and if the connectors (2 times 2x5 mm on the PCB) are disregarded the power density is 8.9 W/cm$^3$ (146 W/inch$^3$). All the components used for this prototype are the same as for the one shown in Figure 7 (except for the inductors), but both sides of the PCB has been used. The series resistances of the PCB inductors are a

bit higher than their discrete counter parts and this causes the efficiency to drop to 80 %.

## V. CONCLUSION

A very compact and cheap converter with state of the art efficiency for VHF converters has been implemented. It is shown that resonant VHF converters using standard MOSFETs can be implemented reducing price and making it possible to design for higher input voltages.

The paper has covered three different prototypes; 1) a basic design of a resonant SEPIC converter with a standard n-channel MOSFET and 84 % efficiency, 2) a offline (230 V$_{AC}$) prototype with a volume reduced by 80 % compared to a commercial supply and 3) a prototype with PCB inductors and a power density of 8.9 W/cm$^3$.

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