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Evolution of Very High Frequency Power Supplies

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Abstract—The ongoing demand for smaller and lighter power supplies is driving the motivation to increase the switching frequencies of power converters. Drastic increases however come along with new challenges, namely the increase of switching losses in all components. The application of power circuits used in radio frequency transmission equipment helps to overcome those. However those circuits were not designed to meet the same requirements as power converters. This paper summarizes the contributions in recent years in application of very high frequency (VHF) technologies in power electronics, shows results of the recent advances and describes the remaining challenges. The presented results include a self-oscillating gate-drive, air core inductor optimizations, an offline LED driver with a power density of 8.9 W/cm^3 and a 120 MHz, 9 W DC powered LED driver with 89 % efficiency as well as a bidirectional VHF converter. The challenges to be solved before VHF converters can be used effectively in industrial products are within those three categories: components, circuit architectures and reliability testing.

Index Terms—VHF circuits, power conversion, DC-DC power converters, resonant inverters, zero voltage switching

I. INTRODUCTION

The continuing trend of miniaturization in industrial and consumer electronics is continuously driving a demand for smaller power supplies. Weight and cost reduction demands accompany this trend. Within power supplies the major size, weight and cost drivers are typically the passive components. Increasing the switching frequency of power converters can reduce the size, weight and therefore the cost of those. For substantial size and weight reduction, the switching frequencies are increased up to the very high frequency (VHF) band (30 MHz to 300 MHz), which leads to a merge in circuit technologies used in radio frequency transmitters [1]–[6] and the classical power electronics circuits.

The VHF amplifiers are designed for DC-AC conversion, where the AC simultaneously is the switching frequency. Generally those circuits [1], [2] drive a known load impedance, typically a 50Ω antenna. Traditionally the topologies used for those circuits have been characterized as classes with running labels following the alphabet. Class-A, class-B and class-C are described in [2], [7]. These classes are characterized through the relative amount of time, the power transistor is conducting the load current with respect to the period of the VHF signal. For class-A the transistor conducts the load current 50 % of the time. Class-B operates between 25 % and 50 % and class-C between 0 % and 25 %. This leads to theoretical

maximum achievable efficiencies of 50 %, up to 78.5 % and up to 100 % for class-A, B and C respectively. Their power electronics counter parts are linear regulators. Class-D is described in [8] and the first power circuit topology, that allows for theoretical 100 % efficiency under all operating conditions. The equivalent are strictly all hard-switched power converters. Class-E as described in [3], [4] and class-F as demonstrated in [5], [6] correspond to all power converters, that apply zero voltage switching (ZVS) and zero-current switching (ZCS) techniques respectively.

Similarly to switch-mode power supplies, those VHF amplifiers convert the constant supply voltages into a high-frequent voltage by operating power semiconductors in the triode region only. The major difference is that VHF amplifiers do not convert the energy back into a constant voltage or current level. Numerous research works have been published [9]–[20], filling this gap and making VHF technologies available for power electronics. This paper describes the individual contributions of those in greater detail. However there are still some challenges left, before VHF switch-mode power supplies can relieve their advantages for products in industrial and consumer electronics.

This paper elaborates on the most recent advances, showing prototypes and measurement results in section II. Section III describes the remaining challenges based on previous work and characterizes them. Section IV concludes the paper.

II. RECENT ADVANCES

Recent research results enhanced the state-of-the art in VHF converters. Most of the work in recent years has focused on class-E derived topologies.

A. Optimal operation

The class-E based power circuits allow for a second degree of soft switching. Despite turning the power switches on, when the voltage across them is zero (ZVS), also the derivatives of these signals are taken into account. This is called ZdVS and ZdCS respectively. The technique has been applied to power converters in [19]. The schematic in Fig. 1 shows the adoption of the principles of a class-E oscillator, e.g. shown in [21]–[23], to a class-E based power self-oscillating VHF converter (DC-DC) [19], [24]. A converter achieving both ZVS and ZdVS at all times operates in optimal mode.

Other implementation replaced either the resonant tank [25],

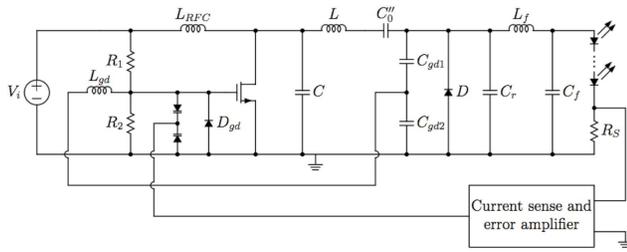


Fig. 1: Schematic of a self-oscillating VHF converter [24] with LED load.

[26] or the input inductor [11], [27] with a transmission line. The resulting waveforms of this circuit have been reported in e.g. [28]–[33] and Fig. 2 repeats the simulated waveforms of this converter, where v_s and i_s are the voltage and the current across and through the switch and v_D and i_D are voltage and current across and through the rectifier diode. v_G is the control signal of the power switch and V_o and V_i are input and output voltages of the converter. The top graph v_s visualizes the optimization of the converter for both ZVS and ZdVS.

Fig. 3 is a photograph of the implementation of this converter. The overall efficiency of the 97 MHz converter is 55 %.

The advantage of this converter is, that it is based on a widely documented circuit topology from the communication electronics applications. As implemented here, it also provides means of output regulation. The downside is the voltage stress across the power switch, 3.6 times higher as in hard-switched converters.

B. Suboptimal operation

Due to the tight adjustment of the turn on instance of the power switch for achieving ZVS and ZdVS the degrees of freedom in this converter are low. That limits the input and output voltage ranges. Furthermore the efficiency is not acceptable. In this case, the majority of the losses are due to conduction losses in the power semiconductors, which are due to the on-resistance of the power switch. As the gate voltage is not significantly higher than the threshold voltage, the devices minimum on-resistance could not be achieved.

Suboptimal operation of class-E converters as described in [4] opened for higher degrees of freedom in the design of class-E based DC-DC converters. This means that the ZdVS condition is only fulfilled under nominal load conditions and only ZVS is fulfilled otherwise. The resulting converter waveform in the optimal and suboptimal operating regions are shown in Fig. 4. The effects of these operation mode as described in [34] have been extended in [20] to LED lighting applications.

Note that the body diode of the MOSFET is conducting in the beginning of the MOSFETs conduction period. This is due to wrong timing in the turn-on of the power device. The energy lost in the body diode ruins the efficiency of this particular converter.

Furthermore [20] provides a detailed analysis of the power components parasitics and the effect of their nonlinearities. The basis for this analysis has been, among others, laid in

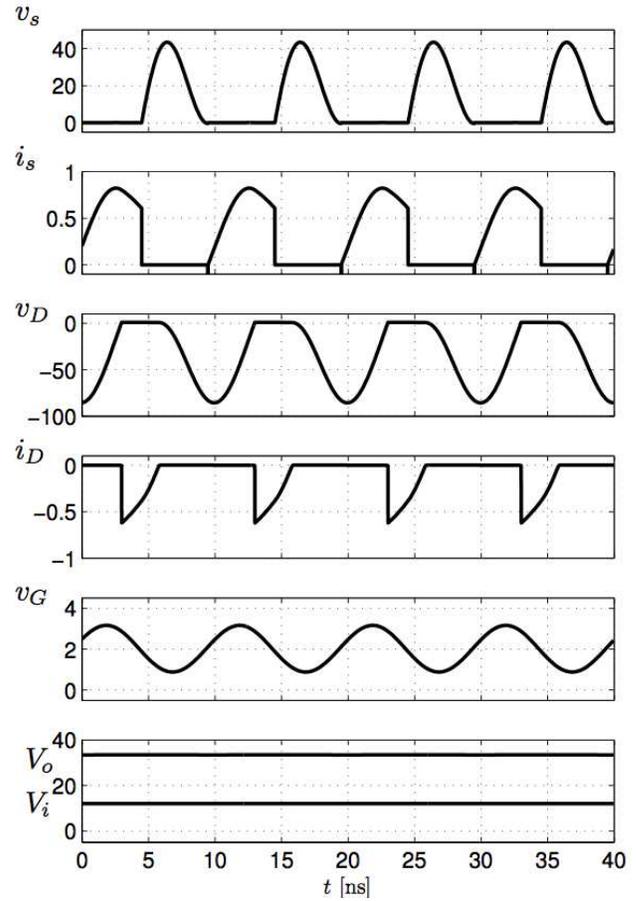


Fig. 2: Simulated waveforms for a ZVS and ZdVS class-E based converter from [19].

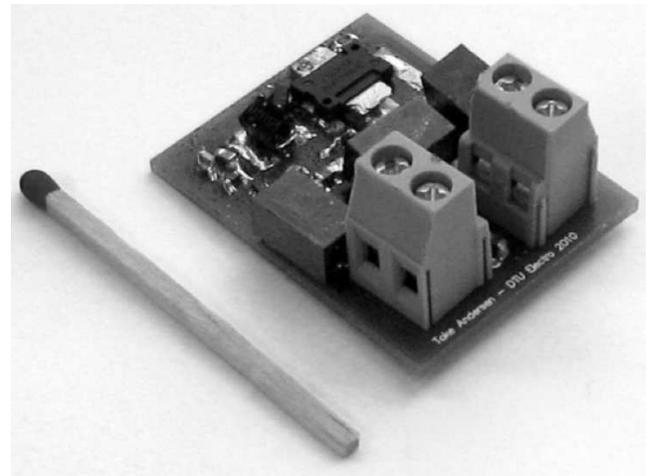


Fig. 3: Photograph of the self-oscillating VHF converter from [24].

[35], [36] for the analysis of class-E amplifiers, which is fully applicable to class-E based power converters when tuning the rectifier to act as an ohmic load. The most relevant parasitics of the power switch are the input and output capacitances. The later is the most critical for the design of the converter.

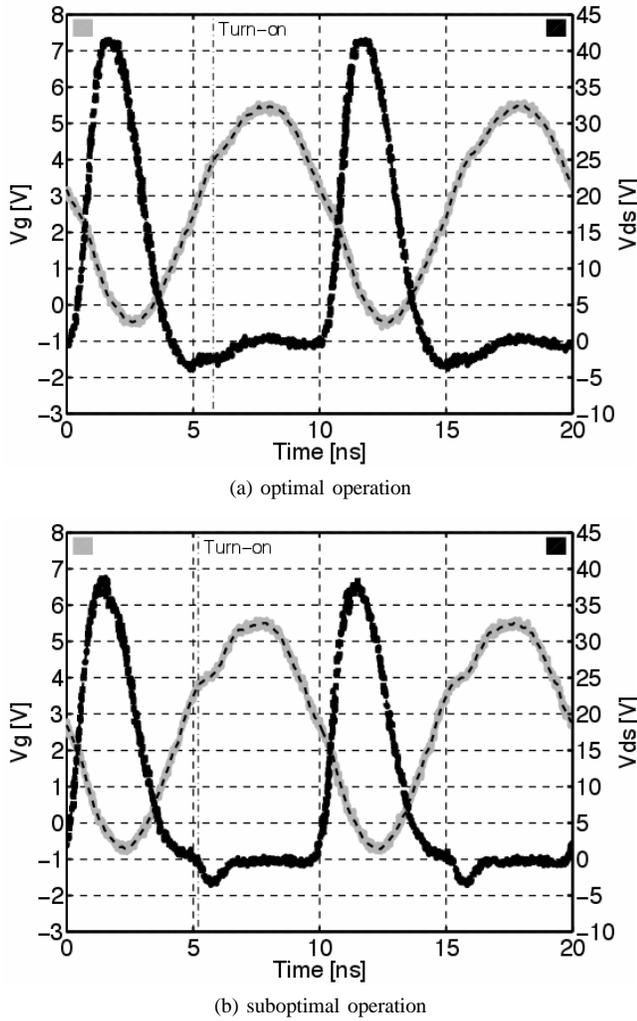


Fig. 4: Measurements of gate-source and drain-source voltages V_{gs} and V_{ds} of the power switch and the turn-on instances. Note that the drain-source voltage has an offset of -0.5 V, due to the oscilloscopes offset.

Simultaneously the output capacitance is highly nonlinear, which was taken into account in the analysis in [20]. There the nonlinearity of the output capacitance C_{ds} is modeled with (1)

$$C_{ds}(V_c) = \frac{C_{j0}}{\left(1 + \frac{V_c}{V_{bi}}\right)^\gamma}, \quad (1)$$

where

- C_{j0} is the junction capacitance at 0 V,
- V_{bi} is the built-in junction potential, typically 0.5–0.9 V [29],
- γ is the junction sensitivity or gradual coefficient. Typically $\gamma = 1/3$ for gradient junctions, while $\gamma = 0.5$ for abrupt junctions [1] hence junction diodes [29], and
- v is the junction voltage.

This results in a voltage waveform V_c of the power switch as a function of the converters input current I_{in} and the above

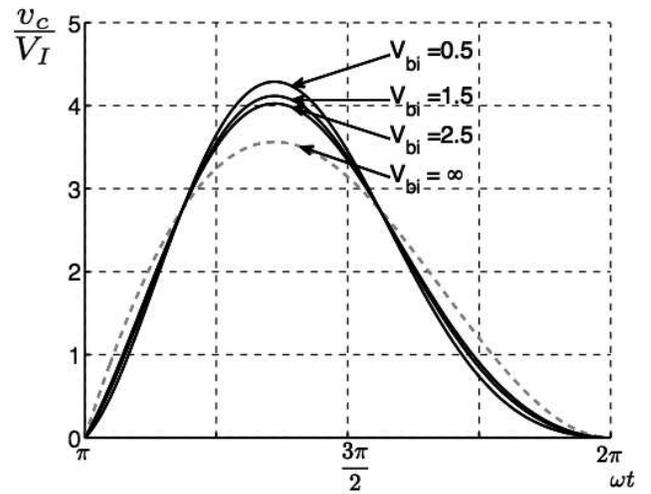


Fig. 5: Voltage waveform of the power switch in relation to DC input voltage for a nonlinear output capacitance from [20]. V_{bi} is the junction potential of the process.

output capacitances parameters as given in (2).

$$V_c = V_{bi} \left(\left[\frac{I_{in}(1-\gamma)}{\omega C_{j0} V_{bi}} \left(\omega t - \frac{3\pi}{2} - \frac{\pi}{2} \cos \omega t - \sin \omega t \right) + 1 \right]^{\frac{1}{1-\gamma}} - 1 \right) \quad (2)$$

Fig. 5 shows the relative voltage waveform of the power switch as a function of time and junction potential V_{bi} for a junction sensitivity of $\gamma = 0.5$.

The remaining components of the power stage have been investigated in [20] as well. Thereby most focus is on the inductors, as these are the most volume consuming parts, have the biggest weight and typically a big impact on the overall price of the converter. Therefore the inductors have been integrated as toroids into the printed circuit board (PCB). This process is described in [37] and Fig. 6 shows the principle.

A power stage has been designed to operate in suboptimal mode under consideration of the power switches nonlinear output capacitance. The converters efficiency is in the same area as the one presented in II-A and again limited by a high on-resistance, which is due to a low gate drive voltage. While giving up on the single operating point operation in optimal operation mode, the suboptimal operating converters theoretically allows for different conduction angle operation on the cost of tighter timing to operate in ZVS.

C. Class-E based SEPIC converter

For dealing with the efficiency challenge, [38] compared a number of power switches both in simulation and experiment. Furthermore multiple air-core inductors were calculated, designed and implemented. An extraction is shown in Fig. 8. The prototypes reach Q-values beyond 100 and resonance frequencies up to 340 MHz. Fig. 9 shows a photograph of the implemented converters. On top of that an effective line- and load regulation scheme was realized in those. The designs were verified in a SEPIC converter (Fig. 7) [39], based on the topologies presented in [40], achieving a power density of

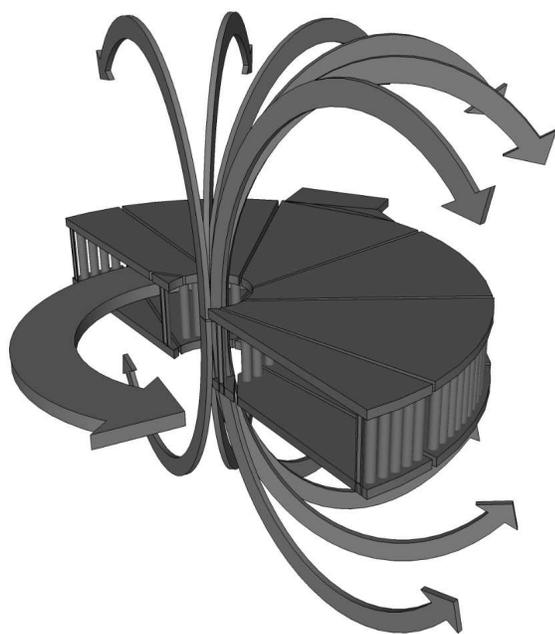


Fig. 6: PCB integrated inductor from [37]. The cross-section of the PCB toroid and the resulting flux arrows are shown.

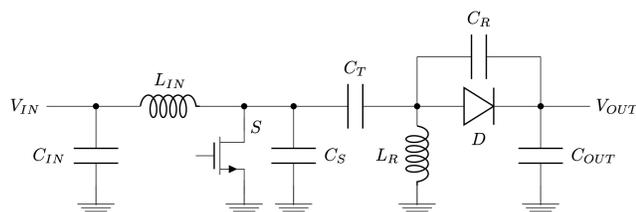


Fig. 7: Schematic of a class-E based SEPIC VHF converter [39].



Fig. 8: Photograph of various air core inductors [38].

8.9 W/cm³ (146 W/in³) by switching at 51 MHz for offline LED applications.

Fig. 10 shows the implementation of the final prototype with 70 MHz switching frequency. The voltage step-down ratio of the converters is 10 and the output power range is between 1 and 4W at an efficiency within this range beyond 70 %.

Compared to the above reported converters, the SEPIC converter is not based on an inverter that delivers a sinusoidal output. The later is crucial in telecommunication applications, when using the class-E inverter as a transmitter, but completely unnecessary demand as an intermediate VHF link within a DC/DC power converter. Relaxing this requirement removes the resonant tank inductor, and therefore the resonant tanks bandpass behavior. On the other hand the rectifier can no

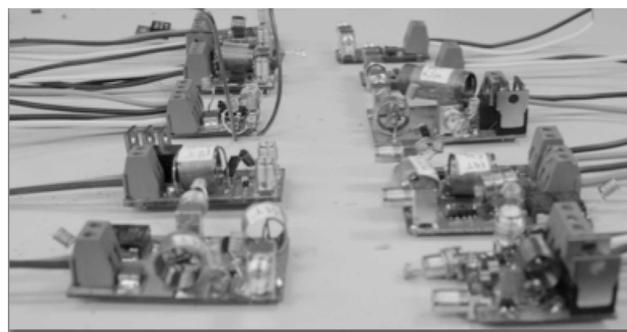


Fig. 9: Photograph of numerous prototypes for comparing measured efficiency with simulations [38].

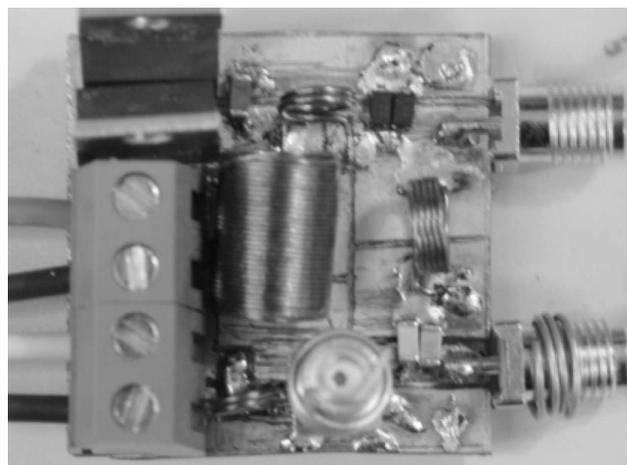


Fig. 10: Photograph of a closed loop low-power VHF converter with an efficiency beyond 70 % from [38]. The TO220 components in the upper left corner are the dummy load resistance.

longer freely be chosen between several topologies, but has to be implemented with a diode, not referenced to ground, which is a disadvantage in some implementation technologies, such as integrated circuits.

D. Interleaved VHF converters

Additionally the self-oscillating principle from [19], [24] was combined with the interleave principle from [41], [42] in [43], resulting into a significant efficiency improvement. Interleaving two converter legs allows furthermore to use the ripple cancelation as described in [44] and applied in [41]. The complete schematic of the open loop implementation is shown in Fig. 11. The realized converter is switching at 120 MHz, i.e. beyond the FM band, converts an input voltage between 6 and 9 V into an output current between 0.4 and 0.5 A and has an efficiency between 80 and 89 % within this operation range. The output power range is 3 to 9 W, corresponding to an output voltage range between 7 V and 20 V. The converter is designed to drive LEDs. Fig. 12 shows both a SPICE based simulation and a the measurement of the power switches voltage waveforms. Fig. 13 shows the efficiency graph of this converter.

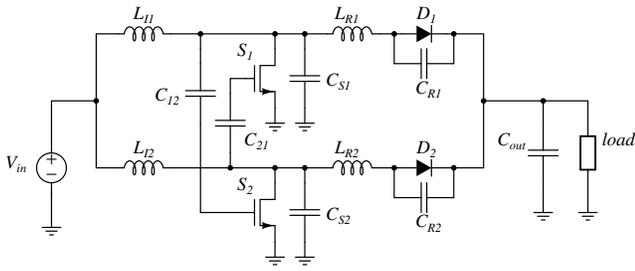
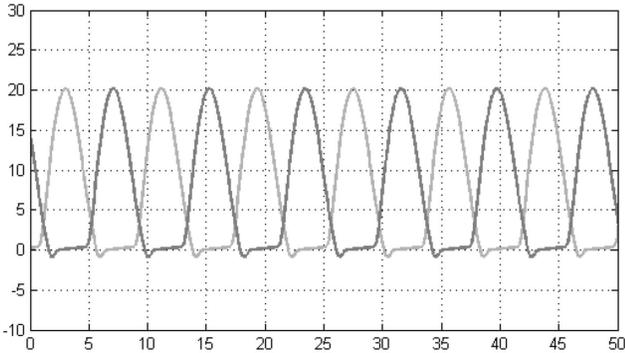
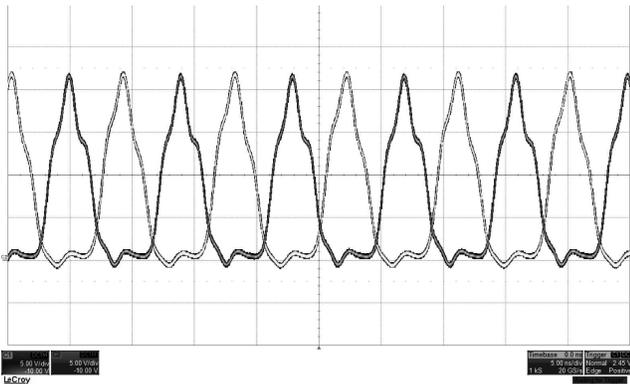


Fig. 11: Full schematic of the open-loop interleaved class-E converter from [43].



(a) simulated waveforms



(b) measured waveforms

Fig. 12: Drain-source waveforms of the two power switches in the interleaved converter from [43].

Interleaved converters allow for input and/or output ripple cancellation, segmented power stages, which enables higher power levels [45]. But those converters suffer from different optimal frequencies due to tolerances for each leg, which either might result in beat tones, when operating each of them at its own optimal resonant frequencies, or a non-optimal operation point with respect to efficiency for all legs, when operating all legs at the same frequency.

E. Bidirectional VHF converter

Replacing the diode in Fig. 1 with a transistor, the class-E amplifier and the class-E synchronous rectifier form a symmetric schematic as shown in Fig. 14. This was realized in [46] and resulted in a bidirectional converter with the same

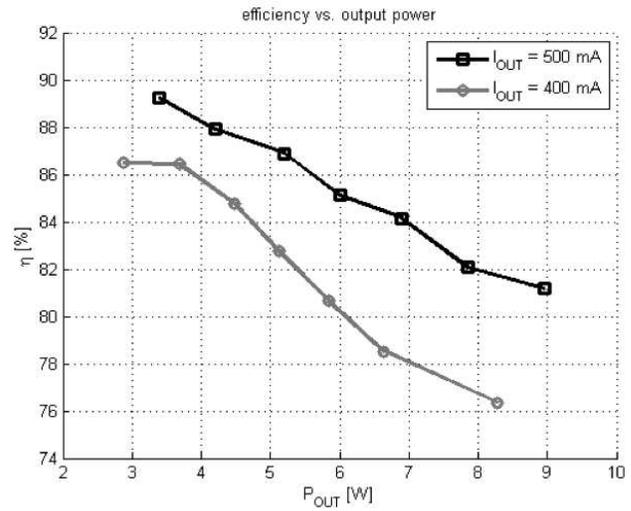


Fig. 13: Efficiency of a battery driven LED driver switching at 120 MHz [43].

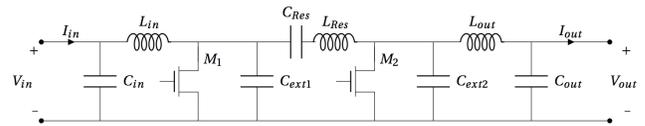


Fig. 14: Schematic of a VHF converter with class-E inverter and synchronous class-E rectifier [46].

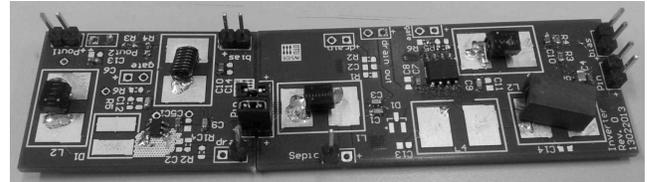


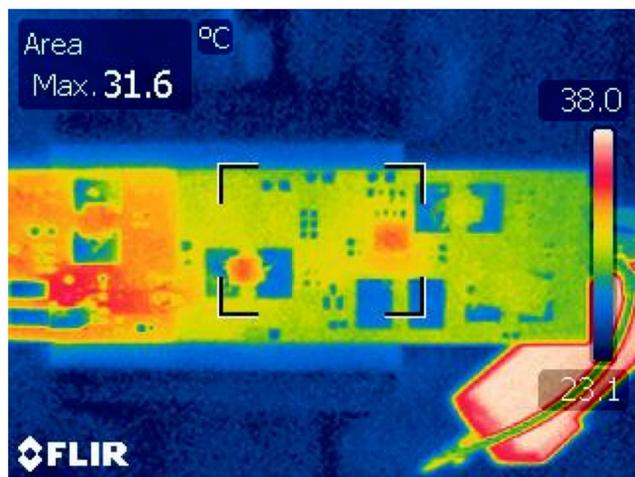
Fig. 15: Photograph of a bidirectional VHF converter [46].

conversion ratio from both sides. Operating in the forward mode, the transistor M_1 is the power switch, operating in class-E mode, and M_2 is used as synchronous rectifier in class-E operation. In the reverse operating mode, the voltage designated V_{out} is acting as the input voltage and M_2 becomes the inverter switch, while M_1 turns into the synchronous rectifier. The maximum achieved efficiency with this topology was 70 % switching at 30 MHz. A photograph of the prototype and thermal pictures of the converter are shown in Fig. 15 and Fig. 16 respectively.

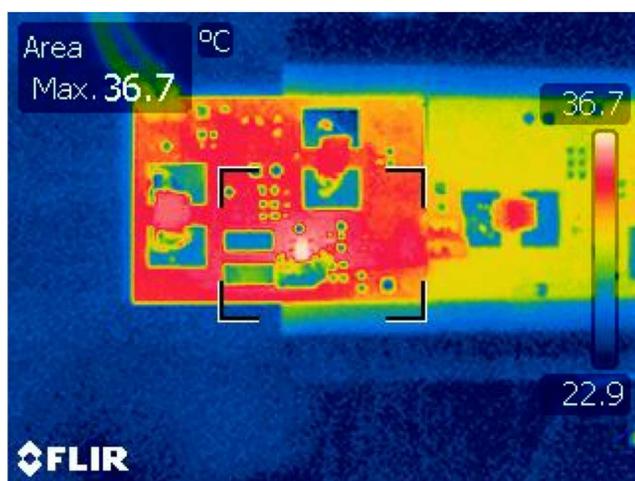
The bidirectional converter allows for lower conduction losses in the rectifier and allows for two-quadrant operation at the cost of an extra gate, which needs a control signal.

III. CHALLENGES OF VHF CONVERTERS

Lately remaining research challenges have been described in [47], [48]. This section is summarizing the remaining challenges common in all above described converters with respect to implementation in products. It is dividing the major



(a) class-E inverter



(b) class-E synchronous rectifier

Fig. 16: Thermal photographs of bidirectional VHF converter in thermal equilibrium [46].

remaining show stoppers into three categories and describes those afterwards with respect to existing products on the power supply market, with switching frequencies below the VHF range.

VHF operation of power supplies differs from sub-megahertz operated power supplies (here called traditional power converters) mainly by the following subjects:

- Electronic components, both active and passive,
- Circuit architectures for power stages and control parts,
- Adjacent behavior, such as electromagnetic compatibility (EMC), mechanics and other reliability tests.

A. Components

Especially inductive components are size, weight and cost optimization limitations in nowadays power circuits. Simultaneously VHF converters provide a major opportunity to overcome those.

Among the challenges are core losses, skin and proximity effect [27], [49]–[54]. For driving further miniaturization of VHF power supplies an obvious next step is to integrate

the whole converter in a package (Power Supply in Package (PSiP)) or even on a single chip (Power Supply on Chip (PwrSoC)). The most challenging part for this goal is the integration of the inductors. Great progress has been made and summarized lately in [55], [56]. However realizations of integrated inductors with Q-values beyond 100 in the relevant frequency ranges remain to be seen. Hybrid concepts as shown in [57] might be applicable. Another challenge within passive components for VHF is the creation of a galvanic isolation barrier [58]–[60].

Despite passive components also active components, i.e. the power semiconductors, need to fulfill other requirements than in usual power supplies [61]–[63]. The parasitic components have a big influence on the design of the overall converter, as they are part of the design parameters. Unlike traditional power stages, the parasitic elements are therefore not considered undesired, but form an integral part of the stage. An example is the output capacitance C_{oss} of the power semiconductor in a class-E based power supply. According to [19] it is dependent on output power P_{out} , input voltage V_{in} and switching frequency f_{sw} as shown in (3).

$$P_{out} = 2\pi^2 f_{sw} C_{oss} V_{in}^2 \quad (3)$$

This means that the output capacitance C_{oss} is limiting the maximum switching frequency for a given application, which specifies P_{out} and V_{in}

B. Architectures

Where traditional power electronics circuits use square wave gate drive signals, the presented VHF converters so far utilized sinusoidal gate drive [18], [24], [64], [65]. This is mainly due to the input capacitance C_{iss} of VHF power semiconductors, which require a high peak current at extremely high speed. To consider the drive voltage trapezoidal its rise and fall times have to be less than 1 ns [65]. A trapezoidal or square wave drive would minimize the time of the power switch in linear operation and therefore decreases the losses.

The degrees of freedom in terms of modulation principles are less for VHF converters. Whereas power electronics circuits usually use pulse width modulation or phase modulation, the VHF converters efficiency is dependent on those parameters. Therefore they need to be adjusted statically to avoid losses by leaving the ZVS (or ZCS) range. A way to get around this is to apply burst mode control [17], [64], [66]. This method however introduces another low frequency component in the spectrum, which has to be buffered or filtered at both the in- and output of the converter. A requirement that enforces the use of bulky components and therefore is counterproductive to the intended advantages of VHF converters in the first place. While the VHF converters offer good possibilities for fast transient regulations, their low frequency control performance is limited by intrinsic bandpass behaviors through serial capacitors. Even though some rectifiers are available with parallel capacitances and impedance transformation [19], [67], more suitable architectures are missing. Thereby it needs to be taken into account, that the original VHF power circuits are designed to match a defined load (typically the impedance of

the antenna) and therefore impedance transformation circuits can be realized in a passive way. Power converters however are connected to highly varying loads, i.e. load circuit in idle - drawing no energy from the supply - and full load - demanding the maximum output from the supply. Therefore active and lossless impedance matching circuits are required. Having such circuits at hand opens for utilization of the high gain bandwidth in VHF converters for line and load regulation.

C. Adjacencies

Lastly the interaction of VHF converters with its physical environment is different than the one of traditional power converters.

On one hand, the electromagnetic interaction between circuits increases, the higher the relevant frequencies are [68]–[71]. Fields are distributed easier both inside the converter and to its surroundings. The electrical behavior also becomes highly dependent on electromechanical interfaces, such as cooling and housing. However the harmonics of the resonant waveforms are falling faster, than the harmonics in hard switched traditional power converters [20]. Also the harmonics of the fundamental switching frequency are spaced wider. That means the distance can be used to place strategically important EMC bands, dependent on the application.

On the other hand, the carefully adjusted operating points of VHF converters (for efficiency purposes) are highly dependent on temperature [19], [20]. Adaptive mechanisms for ensuring optimal operation over industry standard temperature ranges are yet to come.

IV. CONCLUSION

The merge of techniques used in radio communication electronics and power electronics was pointed out. The development through the previous decades has been revisited and recent developments were summarized. Remaining challenges and the latest advances were described. The implementations of numerous VHF converters were presented. Among them are low-power, high-step-down converters with a switching frequency of 70 MHz and an efficiency beyond 70 % as well as a 120 MHz, 9 W LED driver with an efficiency up to 89 %. Both converters maintain high efficiencies over a wide load range.

The remaining challenges, that require solutions before VHF converters can be implemented in numerous industrial applications were found to be within the categorizes components, circuit architectures and reliability testing.

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