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SPECIAL SECTION

Resonant step-down DC-DC converter based on GaN power integrated circuits and SiC diodes

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Abstract. In the paper results of the operation and efficiency of a DC-DC resonant converter with a switched capacitor topology, equipped with GaN transistors and SiC diodes are presented. Investigated problems are related to the optimization of the DC-DC power electronic converter in order to achieve miniaturization, a simplified design, and high efficiency. The proposed system operates at a high frequency with low switching losses. The proposed design helps to achieve uniform heating of the transistors and diodes, as demonstrated by the results of the thermal imaging measurements. The GaN transistors are integrated into one package with dedicated gate drivers and used to simplify the circuitry of drivers and increase the power density factor of the proposed device. In the high-frequency design presented in the paper, the converter is implemented without electrolytic capacitors. The results included in the paper contain waveforms recorded in the power circuit at ZVS operation when switching on the transistors. It occurs when the system operates above the frequency of current oscillations in the resonant circuit of the switched capacitor. Efficiency characteristics and a voltage gain curve of the converter versus its output power are presented as well. The results of efficiency and quality of waveforms are important because they facilitate characterizing the tested system for implementation using WBG devices. The use of integrated GaN modules to minimize elements in the physical system is also unique to this model and it allows for very short dead-time use, and operation in ZVS mode at low reverse-conduction losses.

Keywords: Gallium nitride transistor (GaN); GaN power IC; silicon carbide diode (SiC diode); DC-DC buck converter; high frequency; high efficiency.

1. INTRODUCTION

DC-DC converters are used in many types of power supply and energy harvesting systems, such as DC-power supply in telecommunications and data centers [1], battery-powered electric vehicles [2], fuel-cell electric vehicles [2, 3], photovoltaic systems [4], and various types of battery chargers and switched-mode power supply systems. The optimization of DC-DC converters is significant and is made possible by current developments in the field of GaN transistors and the concept of their modular implementation.

GaN transistors integrated with gate drivers within one package enable the miniaturization of the converter, and a reduction in the number of required components [5]. The gate circuit is a significant part of the total cost of the converter. Moreover, in GaN-based converters, the correct implementation of the gate circuit is crucial to ensure proper operation of the power circuit without increased switching losses and electromagnetic interference. The gate circuit design is especially important for the operation of the converter, and the inductances have a significant effect on the oscillations of the gate circuit. The results of such studies are presented in [6] for a buck circuit based on cascode GaN transistors.

Another particularly important aspect of the implementation of gate circuits in converters equipped with GaN transistors is their power supply. Gate circuits of GaN devices require voltages lower than voltages suitable for IGBT or MOSFET switches (e.g. 6 V). Additionally, the way in which energy is delivered to the particular drivers strongly depends on the main circuit topology, and often a bootstrap approach may be adopted, such as in the case of the proposed converter. Ensuring these specific requirements and reducing the problems associated with the parasitic parameters of a gate circuit can be achieved by integrated GaN transistor modules.

The converter investigated in this paper operates on the principle of switched capacitor (SC) circuits. This technique is frequently proposed for step-down converters, especially with a high-voltage ratio [7–18]. The presented concept of a step-down converter was demonstrated in [18], but in this article, it is implemented using specialized, large-scale integration system GaN transistors, which combine a switching power device along with a gate driver in one package ($5 \times 6 \times 1$ mm).

The analyzed converter uses GaN transistors along with SiC diodes to operate efficiently at a high frequency. The converter, in the demonstrated design, does not use electrolytic capacitors and insulated voltage converters. A low volume 1 μH resonant choke is implemented in the power circuit to avoid inrush current in the switched capacitor circuit and operate in the ZVS turn-on mode.

The operation of the system at a switching frequency of 400 kHz and a maximum power of 700 W is demonstrated in this paper. Peak efficiency of 98.83% was achieved at $P_{\text{out}} = 500$ W. The efficiency achieved by this device can be considered high, and competitive to other DC-DC converters.

The advantage of the system is a small number of elements, uncomplicated design, control, and high reliability. The system is not a synchronous DC-DC converter and works in a configura-

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tion with diodes to achieve a reduction in the manufacturing cost of the overall device. Since the converter uses 650 V components, such a design is correct and ensures an even temperature distribution of the power components.

For conversions at lower voltages, more complex topologies of switched capacitor-based converters are proposed in the literature. In [7–14] the concepts of SC circuits are presented, with an indication for the implementation of the power supply from the voltage of 48 or 54 V. In [15] the concept of an SC-based stack of capacitors balancing system for powering four microprocessor receivers is presented.

The effective implementation of voltage reduction from e.g. 400 V is also a critical issue for the power supply of low-voltage devices. In [16] and [19] the step-down layouts for higher input voltages are presented, namely 300 V in [16] and 400 V in [19]. This can be implemented in switched-mode or hybrid DC-DC circuits using SC modules.

In the research literature, there is a growing interest in converter optimization using monolithic integrated GaN modules [20, 21]. In [20] the implementation of the GaN module in the flyback converter topology for auxiliary supply from 400 V battery is demonstrated, and while [21] described the synchronous buck converter circuits using the half-bridge monolithic power stage with 100 V of breakdown voltage GaN transistors. However, this article presents a novel and unique GaN module implementation in the SC circuit with a resonant inductor that steps down the voltage from 400 V. The converter operates at a constant voltage gain which is typical for SC converters. Yet, this type of circuit exhibits attenuation when reducing the transistor duty cycle, but this is not investigated in this article. Such methods are described in the literature, as in [19] which presents the concept of full-range regulation in a multilevel resonant switched-capacitor converter.

In this paper, the original and modern concept of DC-DC converter implementation, its measurement results in the form of waveforms, efficiency characteristics, and voltage gain are demonstrated. The converter achieves high efficiency, low and even heating of the power elements, stable gain with power changes, and high-quality waveforms of currents and voltages. The advantage is that the system is based on a small number of elements. Only two GaN modules are used in the system, which works with SiC diodes. The ability to operate at a high frequency (400 kHz) with low switching losses was achieved. Q_{rr} losses are eliminated and E_{oss} losses are reduced, as ZVS mode operation is used when switching on transistors.

The converter can be used in DC power distribution systems as a unit of high step-down multistage converter, e.g. 400 V DC to point of load (PoL) in telecommunication systems.

2. THE CONVERTER TOPOLOGY AND PRINCIPLE OF OPERATION

2.1. The converter topology

The tested system is a resonant step-down converter with a genesis based on the technique of switched capacitors. The diagram of the system is shown in Fig. 1. The circuit contains two transistors and two diodes, as well as a switched capacitor circuit with a resonant choke. The diagram shown in Fig. 1 contains a supply concept of the transistor gate circuits, through abootstrap capacitor. The transistor branch is a typical power electronics module and, in the presented concept, the circuit does not require the implementation of isolated voltage sources for gate circuits. The control signals are isolated in both channels to ensure equal signal propagation delays.

Figure 2 shows the individual operating states of the converter and explains how the converter should be controlled. It uses a

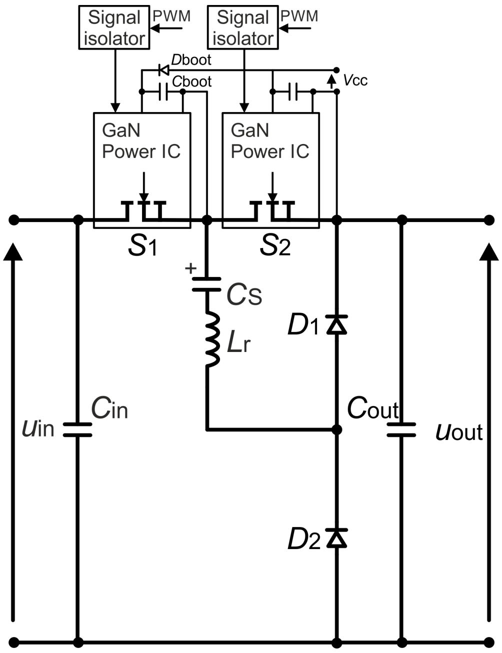

Fig. 1. The DC-DC step-down resonant converter with GaN ICs and simplified electronic circuits

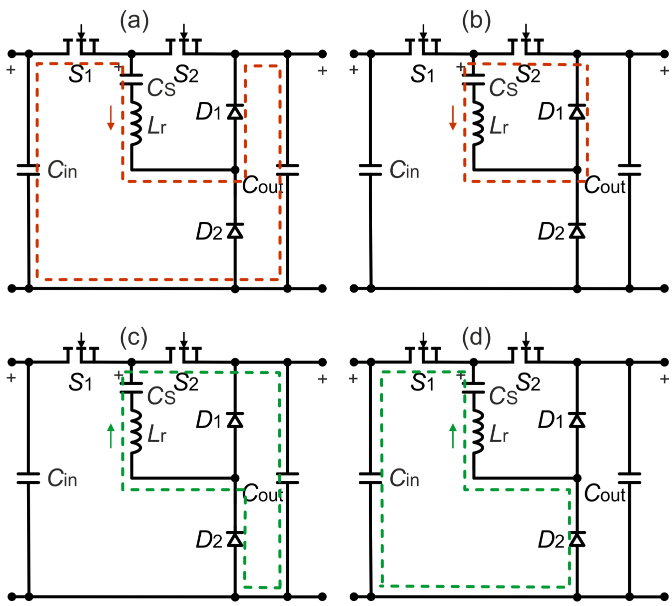

Fig. 2. Stages of operation: (a) and (c): operation with one transistor turned-on, (b) and (d): current passing during the dead-time and reverse conduction of a transistor

control signal with a 0.5-duty cycle and an implemented dead time. The logic signal for transistor control is mutually inverted.

2.2. Operation at a frequency above resonance

The use of a resonant choke makes the charging and discharging current of the switched capacitor oscillate. In this case, the choke with low inductance and dimensions (here 1 µH, $25.2 \times 22 \times 4.1$ mm) was implemented on the PCB. The element transferring energy in this system is a switched capacitor C_s. Despite the small size of the choke, the volume of the switched capacitor is much smaller, however, according to the general principle, a capacitor can accumulate several dozen times more energy than a choke with a comparable volume [22].

The use of the choke also allows it to work with zero voltage switching ZVS during transistor turn-on and operate with remarkably high switching frequencies. In the proposed system, the output capacitance of the switched-off transistor is charged to (U_{in} - U_{out}) voltage; or if both transistors are switched off then $(U_{\text{in}} - U_{\text{out}})/2$. However, if the transistor is switched on at reverse conduction, it does not dissipate the charge of the output capacitance at each switch-on. To achieve this, the switching frequency is set higher than the frequency of the current oscillations. During the dead time (Fig. 2b and 2d) the current flows in reverse directions through the transistor, which is turned on in the next pulse cycle. The operation above resonant frequency will be visible on the experimental waveforms shown later in the article.

3. IMPLEMENTATION CONCEPT

Figure 3 presents the laboratory converter implementation. The main components were mounted on the top layer of the PCB and heatsinks were attached to the bottom layer by thermal vias.

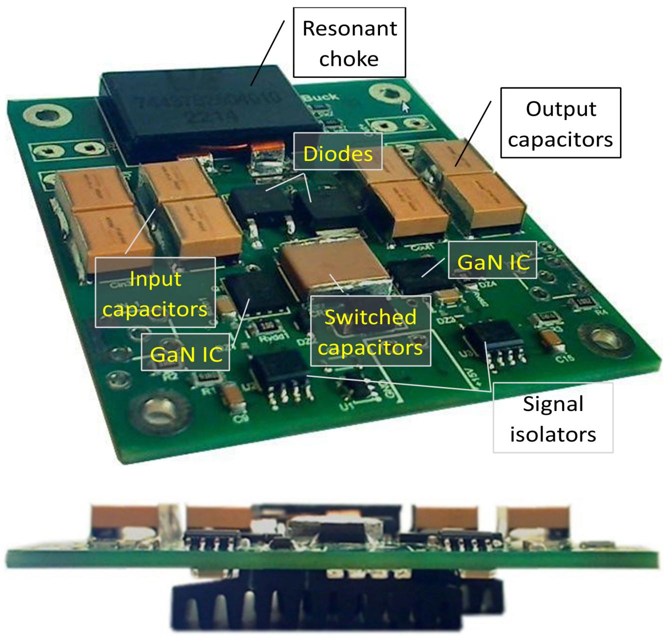

Fig. 3. The laboratory converter implementation: top view on components and side view with heatsink

The PCB board was designed for laboratory testing purposes, however a small complication of the system, a small number of components and potentially high-power density of the converter, is visible. The converter was made on a four-layer PCB with 35 µm copper thickness. In addition to the power circuit, the system uses digital signal isolators and power supply components for the GaN integrated circuits. One type of switching pattern was used (Fig. 2), which gives a voltage gain of 0.5. By changing the transistor control scheme, no change in the gain of this system is achieved. However, voltage regulation can be introduced by variation of the switching frequency in some range [18] or by shortening the switching time of a transistor.

The converter was powered by Delta Elektronika SM1500-CP-30 power supply. The same unit was configured as a load for the examined circuit since the employed power supplies are capable of bidirectional energy transfer. All the presented scope captures were recorded using the Tektronix MSO68B oscilloscope with the Tektronix TCP0030A current probe and two Tektronix THDP0200 differential voltage probes. Efficiency and converter output voltage curves vs. output power were delivered based on measurements performed with the Yokogawa WT1800 power analyzer. Table 1 contains the basic parameters of the examined device.

4. EXPERIMENTAL RESULTS

Table 1 presents the parameters of the converter power circuit elements. The converter steps down the voltage twice from 400 V to 200 V and operates at a frequency of 400 kHz.

Table 1
Power circuit components

Component	Type
Transistors and gate drivers	NV6117 GaNFast Power IC [23]
Diodes	SiC Schottky GE10MPS06E
Switched capacitors	3×220 nF KCLink
DC capacitors	4×1 µF, B58031U5105M062 CeraLink
Resonant inductor	1 µH (7443762504010)
Input voltage	400 V
Output voltage	200 V
Switching frequency	400 kHz

Figure 4 presents the waveforms of the switched capacitor voltage (u_{Cs}), inductor current (i_L), input voltage (u_{in}), output voltage (u_{out}), and the drain source of the voltages of transistors ($u_{ds(1,2)}$). The waveforms show that the system operates correctly and lowers the voltage. The waveforms of the input and output voltage (u_{in}, u_{out}) contain negligible small ripples at the rated power P_{out} = 500 W. Voltage stress across the switches, presented as waveforms u_{dsS1}, u_{dsS2}, is on the level of $U_{\text{in}} - U_{\text{out}} = 200$ V, which corresponds to the modulation principle shown in Fig. 2. The system operates in ZVS when the transistor is switched on. From the waveform of the resonant choke current (i_L) it can be seen that the transistor turn-off in the system occurs earlier than the current reaches zero. As a result, a transistor that will be switched on conducts the reverse current beforehand, and its switching on takes place with negligibly small u_{ds} voltage. To achieve ZVS mode, the frequency of the current oscillation should be lower than the switching frequency. In the presented design concept, this was achieved by using a switched capacitor with a capacitance of $C_S = 4$ μF and a resonant choke with an inductance of $L_r = 1$ μH. With such values of passive components, the ripples of the switched capacitor voltage are also insignificant, as can be seen in the u_{CS} waveforms in Fig. 4.

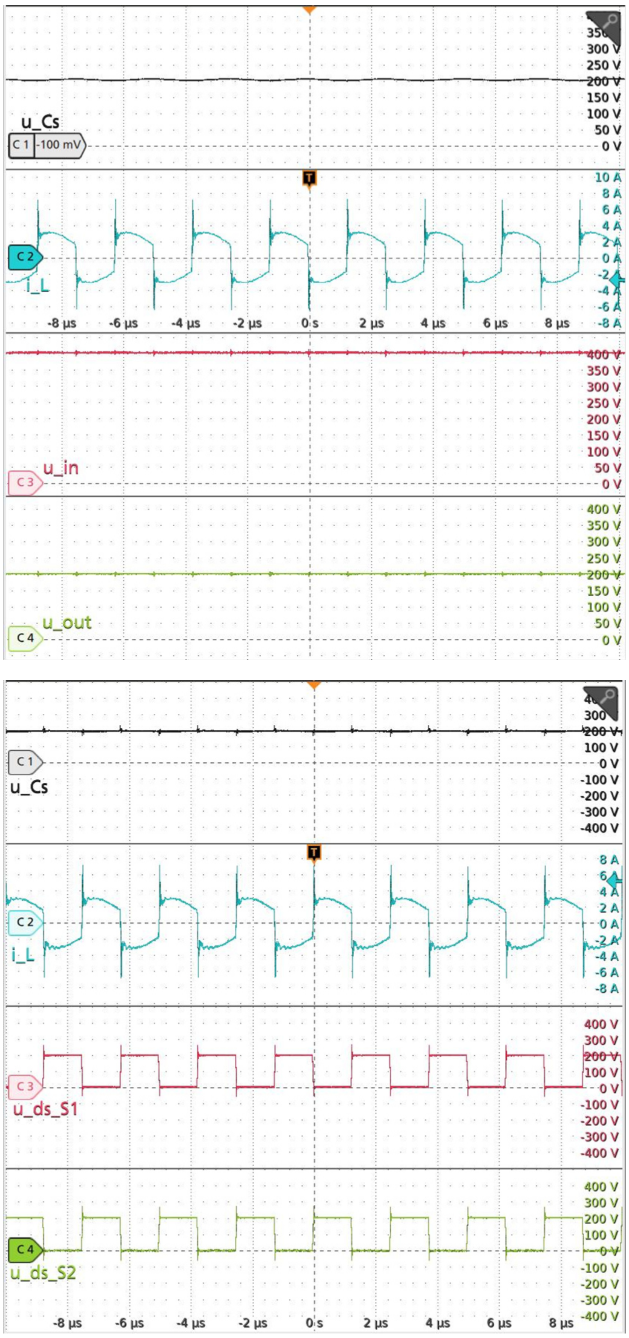

Fig. 4. Results of operation for $P_{out} = 500$ W

Figures 5 and 6 present the efficiency curve of the converter and its voltage gain characteristic as a function of the output power. Efficiency measurements were performed only for the power circuit. Power consumption of the control circuit and the primary side of the drivers was at the level of 2 W, so there is no significant impact on the obtained results. The converter achieves a maximum efficiency of 98.83% at $P_{out} = 500$ W and the efficiency characteristics for higher powers show a slight drop. The switching losses at the switching frequency of 400 kHz are small, as evidenced by the efficiency of 88.7% measured at low load, $P_{out} = 50$ W. The voltage gain is maintained close to 0.5 value over a large load range. This is beneficial for a converter that operates without a closed feedback control loop with known voltage gain. If the load is completely disconnected, the gain of the system increases due to small recharges of the output capacitor. The analyzed converter was configured with high-voltage GaN transistors with resistance $R_{ds(\mathrm{on})} = 120$ mΩ and SiC diodes with a minimum forward voltage of $V_F = 1.25$ V at 25 degrees. Based on the efficiency characteristics of the converter, it can be concluded that in the power range from 400 W to 600 W, the system is characterized by efficiency close to the maximum. In this power range, the conduction losses in diodes are not significantly higher than those in transistors. Both types of components used are also characterized by a low level of switching losses. This is confirmed by the thermal imaging measurements shown in Fig. 6, obtained at an output power of 400 W and a switching frequency of 400 kHz.

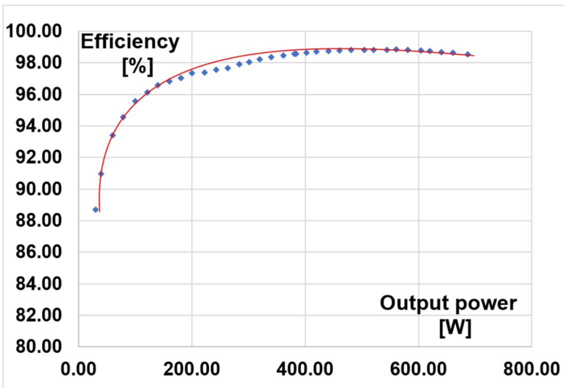

Fig. 5. Results of the efficiency of the converter

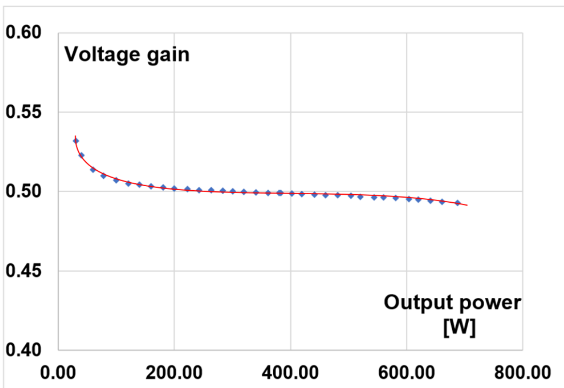

Fig. 6. Results of the voltage gain of the converter

The analyzed converter was configured with high-voltage GaN transistors with resistance $R_{ds(\mathrm{on})} = 120$ mΩ and SiC diodes with a minimum forward voltage of $V_F = 1.25$ V at 25 degrees. Based on the efficiency characteristics of the converter, it can be concluded that in the power range from 400 W to 600 W, the system is characterized by efficiency close to the maximum.

In this power range, the conduction losses in diodes are not significantly higher than those in transistors. Both types of components used are also characterized by a low level of switching losses. This is confirmed by the thermal imaging measurements shown in Fig. 6, obtained at an output power of 400 W and a switching frequency of 400 kHz. From the measurement results shown in Fig. 7, it can be seen that the temperature of the power components (diodes and transistors) is comparable.

Fig. 7. Results of the thermal imaging measurements of the converter at $P_{\mathrm{out}} = 400$ W, $f_s = 400$ kHz, and forced airflow with an ambient temperature of 20 degrees Celsius (measurement points Sp1, Sp2 indicate transistors, and Sp3, Sp4 indicate diodes)

5. CONCLUSIONS

The paper presents a DC-DC step-down resonant converter based on integrated circuits with the GaN transistor (GaNFast Power IC) and SiC diodes.

The presented approach to the implementation of the DC-DC converter results in both important conclusions regarding the design and the results of the converter's operation. The advantageous features of the presented design, which allow for further optimization of its volume and costs, are as follows:

- The system operates at high frequency and the use of electrolytic capacitors is avoided.
- No external gate drivers are used.
- No isolated voltage converters are required.
- The experimental circuit uses a resonant choke with an inductance of 1 µH mounted on the PCB.
- With the 4 µF capacitor banks used, there are no significant values of voltage ripples at the input and output voltage waveforms.

The obtained results allow us to characterize this non-typical DC-DC converter based on a resonant SC circuit. In the presented concept of its implementation and control, the results demonstrate beneficial features of the converter, including:

- Peak efficiency of 98.83% at $P_{\mathrm{out}} = 500$ W and a switching frequency of 400 kHz.
- An even temperature distribution in the diodes and transistors of the system.
- The measured voltage gain of the converter exhibits a slight change over a broad range of power changes.
- Current and voltage waveforms recorded in the power circuit indicate slight disturbances and the high quality of the waveforms indicates the feasibility of a high-frequency converter with high efficiency, durability, and low interference.
- Fast switching GaN transistors allow to operate in ZVS mode during switch-on. The modulation takes place with a noticeably short dead time, which, given the duration of the current oscillation in the SC circuit (1500 ns), allows for the commutation before the current reaches zero. In addition, the reverse conduction of the GaN transistor occurs at a current lower than the oscillation amplitude and lasts for a brief time, which does not cause significant power losses.

The applied concept of the system allows us to obtain a converter with exceptionally good electrical parameters and a small number of elements. The previously mentioned features demonstrate that the proposed converter can be considered optimized in terms of its volume, cost, and reliability.

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