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Evaluation of GaN Power Transistor Switching Performance on Characteristics of Bidirectional DC-DC Converter

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***Abstract*—The paper deals with the experimental analysis of the switching performance of selected GaN (Galium Nitride) power transistor, whose use is then expected in bidirectional buck/boost DC-DC converter. The switching performance was evaluated through highly accurate and verified simulation models of GS61008P transistor from GaN systems. Experiments have been provided for a wide spectrum of switching frequency and load current in order to verify transistor performance. Then, based on the results, it was expected that high-frequency operation (above 500 kHz) should not distort the efficiency performance of the designed bidirectional converter. This was confirmed after laboratory measurements of the efficiency of the proposed DC-DC converter, while operation under very high switching frequency was more effective compared to low-frequency operation. Over 95 % of efficiency was achieved for both buck and boost mode (125 W), even switching frequency was above 500 kHz.**

***Index Terms*—GaN transistor; Switching performance; Simulation; Parametric; Bidirectional converter; Efficiency.**

I. INTRODUCTION

GaN (Galium Nitride) power transistors already settled within many practical applications considering wide scope of operational parameters of target system. It is discussed about small consumer power supplies, including portable chargers, or high-power density applications for industrial purpose. The performance of GaN transistors is markedly improved considering operational parameters, like voltage or current ratings. It is expected that these devices are suitable for high-performance power converter systems enabling improvements of efficiency and power density as well. Assuming the use of soft-switching and hard-switching modes of operation, the size and weight of target systems is expected to shrink continuously, thus saving materials. Together with this factor, it is expected, that operational life of GaN transistors shall be improved compared to conventional transistor types [1].

Therefore, it is required to provide detailed measurements and analysis experimentally or by simulation in order to estimate expected behavior for operational conditions of the system. Several approaches, where comparisons on conventional and GaN technology is provided, can be found, while it is being clearly shown, how perspective technology enables to improve specific operational and qualitative indicators of power semiconductor component in [2]–[5].

Currently, we also notice SiC (Silicone Carbide) and GaN as the materials advancing the performance of power electronic switches - SiC capable of several kilovolts, while GaN has just reached one-kilovolt ratings [6]. On the other side, many power supplies used in telecom or industrial segment convert AC line power to an isolated constant DC voltage, while 12 V for server PSUs (power supply unit), 48 V for telecom rectifiers, and 24 V for industrial PSUs are normative. The converter systems within these applications use low voltage MOSFETs (Metal Oxide Silicon Field Effect Transistor) as the power switches and now there is a natural process of the substitution of these devices by the new, perspective GaN transistors. One of the ways, how to effectively investigate MOSFET substitution by its GaN replacement, is proper analysis of switching losses. This can be done by precise experimental measurement, while for given transistor type, a special measuring circuit shall be developed to provide valuable results [7]–[10]. This process can be substituted by simulation analysis if manufacturer provides models with high level of accuracy and validity of the results [9]. Through this proposed approach, it is possible to save time by elimination of the need of testing device construction, as well as no needs for measuring equipment are given.

This paper presents the investigation of switching performance of the selected type of GaN transistor (GS61008P) for low voltage application (12Vdc/24Vdc). The target application of transistor is bidirectional buck/boost DC-DC converter. In order to check how switching frequency influences the switching losses of the given transistor type, parametric simulation was provided, while simulation models with high level of accuracy have been used. Experiments were provided under the change of load current and the value of switching frequency as well. Based on the received results, the bidirectional buck-boost DC-DC converter (12 V/24 V - 125 W) was designed for specified operational range considering power delivery, input/output parameters, as well as switching frequency. The converter was, then, evaluated from the efficiency point of

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view within the full operational range, whereby it is shown that high-frequency operation is more suitable for designed converter.

II. SELECTED GAN TECHNOLOGY AND TRANSISTOR TYPE

To examine commutation losses, we have selected GaN transistor structures from the GaN Systems Company. The basic parameters are characterized by breakdown voltage, current rating, static characteristics, and dynamic characteristics (Table I).

TABLE I. MAIN PARAMETERS OF SELECTED TRANSISTOR.

Material composition	**GaN**	
Type	**GS61008P**	
V_{DS}	100	V
$R_{DS(ON)}$	17.5	mΩ
	105 at 150 °C	mΩ
I_D	90	A
V_{GS}	-10 to +7	V
$V_{GS(th)}$	1.3	V
R_G	0.77	Ω
V_{PLAT}	3	V
C_{ISS}	590	pF
C_{OSS}	280	pF
$Q_{G(tot)}$	12	nC
Q_{RR}	0	nC

GS61008P is an enhancement mode GaN-on-silicon power transistor. It has better efficiency than a Si MOSFET because it has a smaller gate charge and a smaller recovery charge. The properties of GaN allow for high current, high voltage breakdown, and high switching frequency. GaN Systems implements patented Island Technology® cell layout for high-current die performance & yield. GaNPX® packaging enables low inductance & low thermal resistance in a small package. The GS61008P is a bottom-side cooled transistor that offers very low junction-to-case thermal resistance for demanding high power applications. These features combine to provide very high efficiency power switching [11]. The transistor is expected for use within high power density/high efficiency power conversion systems. For these reasons, we initially provide analysis of the commutation losses, within the hard-switching mode of operation, while the value of RMS transistor current and switching frequency are parameters, which vary during experimentations.

III. TRANSISTOR'S SWITCHING PERFORMANCE ANALYSIS THROUGH PSPICE SIMULATION

As a development aid to ensure first-pass design success, GaN Systems® provides PSpice and LTspice models for simulation. Because typical switching frequencies achievable with GaN Systems' transistors are comparable with the response times associated with thermal phenomena, a complete electro-thermal model has been developed [10]. This approach ensures reliable and accurate behavior compared to the physical sample (Fig. 1). The thermal modeling is implemented with a separate thermal network, which allows self-heating simulations to take place. A package-level model is provided and the thermal impedance of the package is included in the model.

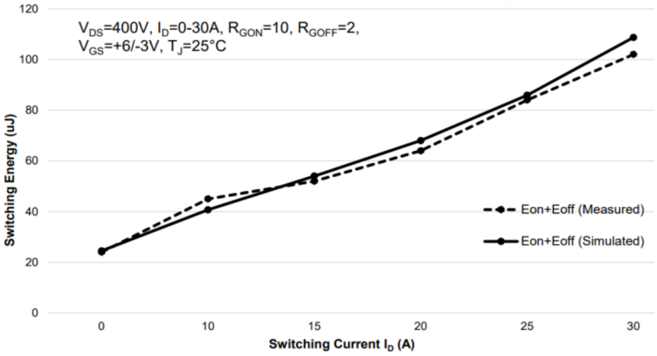

Fig. 1. Example of comparison between switching loss simulation and experimental measurement [11].

As a simulation software, OrCAD PSpice 16.6 was used. For the model to better converge, it is recommended to adjust the PSpice parameters VNTOL to 10 uV and ABSTOL to 1.0 nA. Depending on the specific application, some other parameters may need to be changed as well. "Auto Converge" should be enabled to improve convergence. The maximum time step can be modified if needed [12], [13].

The power loss of selected GaN through simulation was analyzed for the steady-state operation, i.e., when the circuit passed initial transient related to circuit start-up. The total evaluated power loss is then comprised from conduction loss and switching losses (ON/OFF). Figure 2 describes the principle of generation of power loss during operation of the transistor structure.

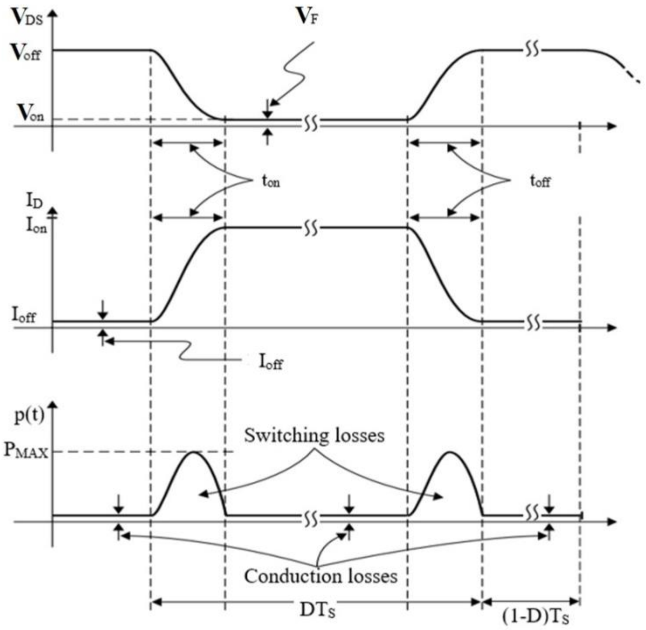

Fig. 2. Voltage, current waveforms and loss rate during hard-switching.

Even with the use of the simulation model (Fig. 3), these waveforms are obtained for steady-state. Both parts of losses (conduction and switching) are, then, evaluated using OrCAD-PSpice analysis tools. The mathematical background behind loss evaluation is given by (1) and (2).

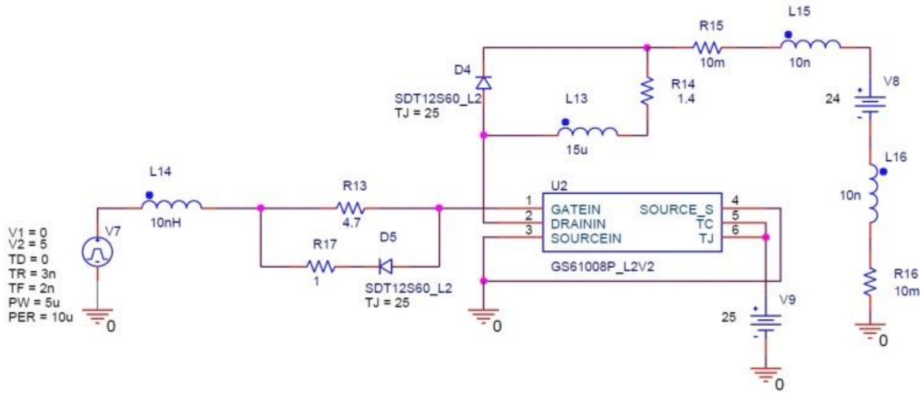

Fig. 3. Simulation circuit of switching performance analysis under hard-switching.

Mean power loss representing total transistor losses during one period is given as

$$P_{AV} = \frac{1}{T_S}\int_{0}^{T_S} i_{SW} u_{SW}\, dt = P_{AVswitching} + P_{AVconduction}, \tag{1}$$

where i_{sw} is the instant value of transistor current and u_{sw} is instant voltage on the transistor.

The total loss is then defined as

$$P_{tot} = \frac{1}{T}\left[W_{sw\_on} + W_{con} + W_{sw\_off} + W_{OFF}\right], \tag{2}$$

where W_{con} is energy generated by device during conduction state, W_{sw_on} is energy generated by device during turn-on transient, W_{sw_off} is energy generated during turn-of transient, W_{OFF} is energy received by the device in a steady turn-off state, and T is operational period.

A. *Parametric Evaluation of Switching Losses*

The simulation analysis of switching performance of GaN GS61008P was provided under two supply voltages, i.e., 12 Vdc and 24 Vdc, what reflects the operational parameters of proposed bidirectional buck-boost DC/DC converter, which will be described within further part of the paper. Instead of supply voltage, these circuit parameters varied:

- V_{IN} = 12 Vdc, V_{IN} = 24 Vdc;
- $I_{D(RMS)}$ = 2 A, 4 A, etc.;
- f_{SW} = 100 kHz, 300 kHz, etc.;
- D_{NULL} = SDT12S60.

The simulation circuit (Fig. 3) was adapted to drive components that are also used within the proposed DC/DC converter. Also, recommended setting for simulation run has been used.

The current I_D and the voltage V_{DS} were recorded for steady-state mode, for each value of current and frequency (Fig. 4). The power was then calculated from these variables independently for turn-on, conduction, and turn-off process of the transistor.

Figure 5 and Figure 6, respectively, show one switching cycle with detail of turn-on and turn-off during a steady state of operation. The total loss for each of the setting listed above was evaluated from these waveforms and is listed in Table II for 12 Vdc of supply voltage and in Table III for 24 Vdc of the supply voltage.

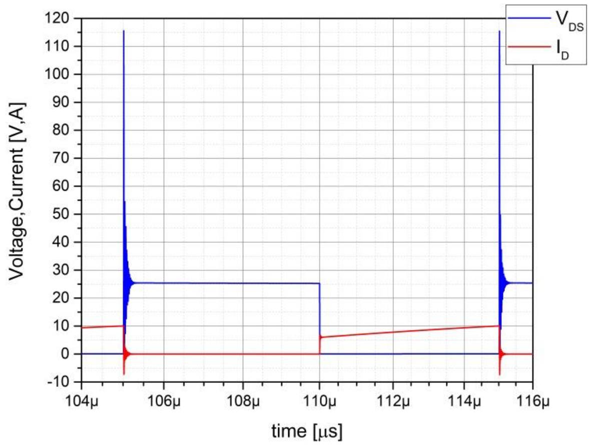

Fig. 4. Switching waveforms of GS61008P during steady-state operation.

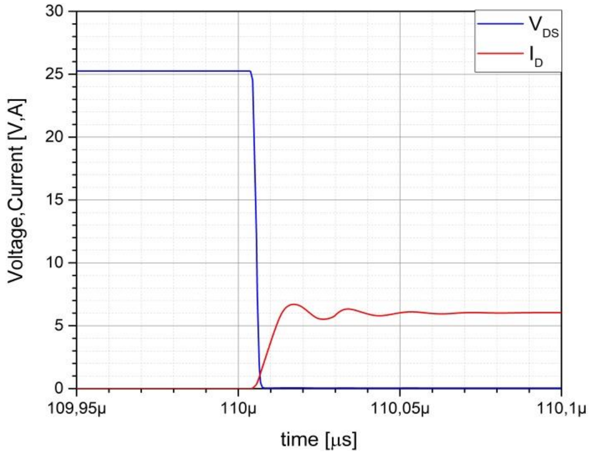

Fig. 5. Detail of GS61008P turn-on process.

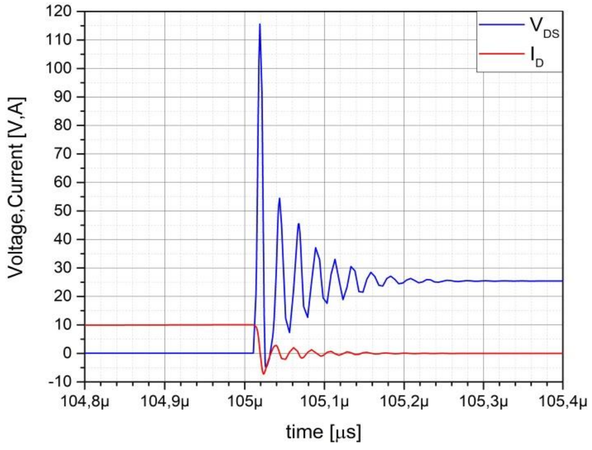

Fig. 6. Detail of GS61008P turn-off process.

TABLE II. HARD-SWITCHING SIMULATION RESULTS FOR TRANSISTOR GS61008P (V_{IN} = 12 V).

V_{DS} [V]	12 V				
I_D [A]	2	4	6	8	10
f_{sw} [kHz]	100				
P_{sw_on} [mW]	0,0666	0,136	0,354	0,475	1,09
P_{sw_off} [mW]	7,663	37,97	95,82	187	304
P_{con} [mW]	10,67	13	40,7	70,2	91
P_{tot} [mW]	18,3996	51,106	136,874	257,675	396,09
f_{sw} [kHz]	300				
P_{sw_on} [mW]	0,375	0,882	1,362	2,295	2,805
P_{sw_off} [mW]	11,28	52,704	122,4	220,5	348
P_{con} [mW]	28,05	42,84	109,8	200,4	211,2
P_{tot} [mW]	39,705	96,426	233,562	423,195	562,005
f_{sw} [kHz]	500				
P_{sw_on} [mW]	0,674	1,71	3,13	5,125	5
P_{sw_off} [mW]	13,845	56,265	129,5	230,25	354,65
P_{con} [mW]	48,87	69,075	302	272,25	388,9
P_{tot} [mW]	63,389	127,05	434,63	507,625	748,55
f_{sw} [kHz]	700				
P_{sw_on} [mW]	0,82	1,375	4,5	7,5	12,885
P_{sw_off} [mW]	10,39	41,565	94,25	167,09	257,75
P_{con} [mW]	46	97,06	190,95	282,17	458,675
P_{tot} [mW]	57,21	140	289,7	456,76	729,31

The data from Table II are graphically interpreted in Fig. 7, where total power loss of GS61008P is evaluated in dependency on switching frequency and transistor current. Figure 8 shows similar dependency separately for turn-on and turn-off loss. These interpretations provide more detailed overview on the contribution of switching losses to total power loss of the transistor.

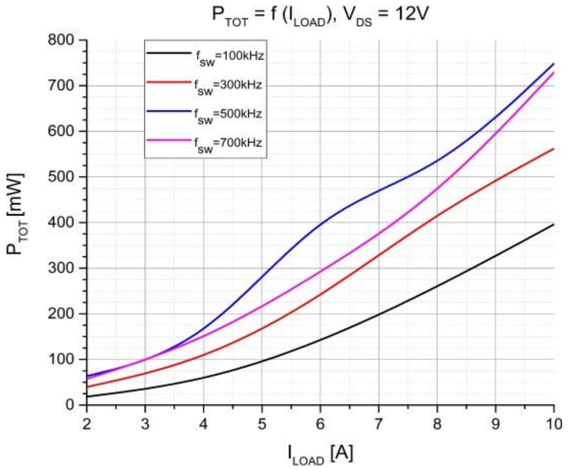

Fig. 7. Total switching losses in dependency on current and switching frequency for 12 Vdc.

From Fig. 7 and Fig. 8, is can be seen that for each value of the switching frequency all the parts of losses are almost exponentially rising considering dependency on the transistor’s current. For 500 kHz and 700 kHz, the switching performance of the transistor is basically the same. This trend is expected also for the higher values of operational frequency, while GaN transistors are suited for high switching. The difference between total loss for 100 kHz and 700 kHz is approximately 100 % if P_{TOT} (100 kHz) is taken as reference.

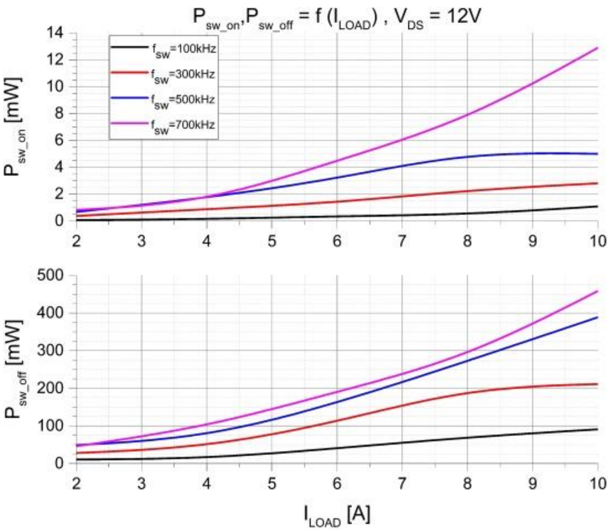

Fig. 8. Turn-on and turn-off switching losses in dependency on transistor current and switching frequency for 12 Vdc.

The graphical interpretation of power losses based on the results listed in Table III. are shown in Fig. 9 and Fig. 10, respectively. From Fig. 10, is seen, that both switching and conduction parts of the losses are comparable from the magnitude point of view to those from Fig. 8. Then, regarding overall switching performance (Fig. 9) for 24 Vdc is like 12 Vdc. These results have confirmed that the switching performance is linearly dependent on the switching frequency, exponentially on transistor current. The main part of total losses is comprised mostly from turn-off and conduction loss, which are the same regarding their values. Turn-on performance of GaN is superior as it achieves lower than 12 mW even for 10 A and simultaneously 700 kHz.

TABLE III. HARD-SWITCHING SIMULATION RESULTS FOR TRANSISTOR GS61008P (V_{IN} = 24 V).

V_{DS} [V]	24 V				
I_D [A]	2	4	6	8	10
f_{sw} [kHz]	100				
P_{sw_on} [mW]	0,55	0,61	0,86	1,08	1,5
P_{sw_off} [mW]	10,05	32,64	77,3	150	250
P_{con} [mW]	18,5	28,3	61	74,1	110
P_{tot} [mW]	29,1	61,55	139,16	225,18	361,5
f_{sw} [kHz]	300				
P_{sw_on} [mW]	1,92	2,52	3,75	4,74	6,18
P_{sw_off} [mW]	11,91	44,1	108,78	215,4	330
P_{con} [mW]	58,2	45,9	123	228,3	345
P_{tot} [mW]	72,03	92,52	235,53	448,44	681,18
f_{sw} [kHz]	500				
P_{sw_on} [mW]	Pzap	3,5	4,7	7,2	9,25
P_{sw_off} [mW]	Pvod	13,7	52,5	125,5	224,5
P_{con} [mW]	Pvyp	103	118	265	304
P_{tot} [mW]	Ptot	120,2	175,2	397,7	537,75
f_{sw} [kHz]	700				
P_{sw_on} [mW]	3,5	5,25	7,4	9,6	11,5
P_{sw_off} [mW]	12	41,05	91	165	265
P_{con} [mW]	90	167,5	221,8	326,5	436,9
P_{tot} [mW]	105,5	213,8	320,2	501,1	713,4

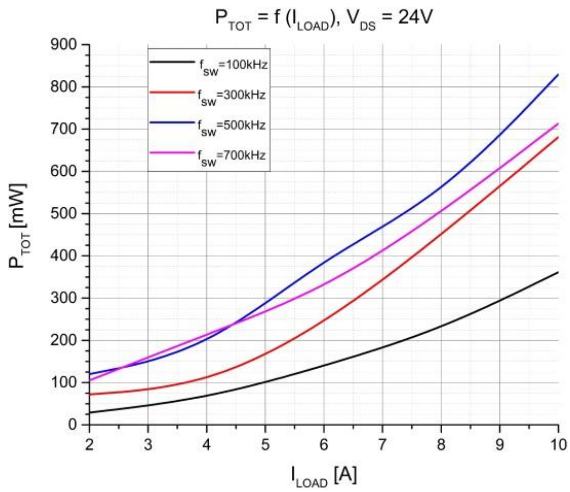

Fig. 9. Total switching losses in dependency on current and switching frequency for 24 Vdc

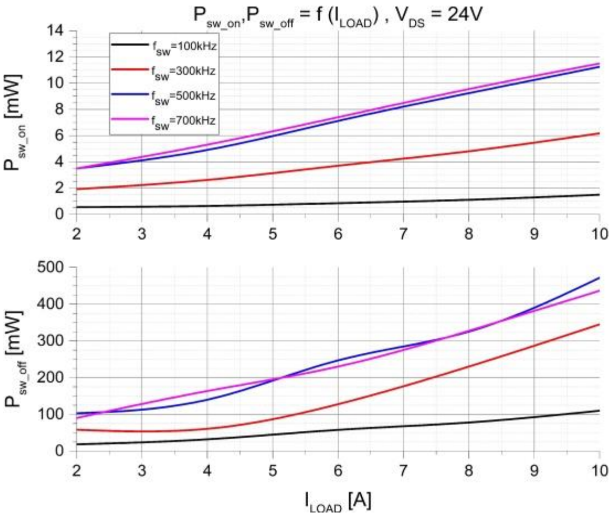

Fig. 10. Turn-on and turn-off switching losses in dependency on transistor current and switching frequency for 24 Vdc.

At this point, we found that switching losses of selected GaN transistor are not visibly influenced if very high switching frequency is required (above 500 kHz). On the other side, such operation enables a reduction of system size components, what can be valuable for the reduction of other parts of converter losses (capacitor loss, inductor loss, PCB trays loss, etc.). In the next Section, the evaluation of switching performance of GS61008P will be realized within the proposed bidirectional buck/boost DC/DC converter, whose efficiency is the main evaluation parameter.

IV. GaN Transistor Implementation within Proposed Bidirectional DC/DC Converter Power Stage

Figure 11 shows the circuit schematic of proposed bidirectional DC-DC buck/boost converter, which is based on synchronous topology. It operates as a synchronous buck converter from the right side to the left side. From the left side to right side, it works as a synchronous boost converter. Switching transistors T_1 and T_2 are presented by tested GaN types GS61008P. Other circuit components (power inductors or capacitors) are small because of the use of very high-frequency operation. This approach results in a decrease of overall volume and costs [14].

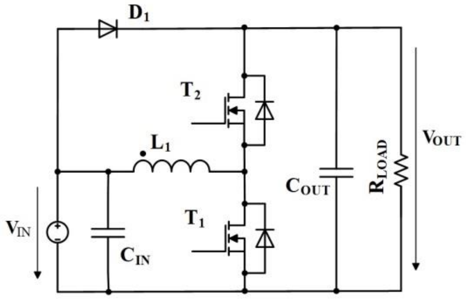

Fig. 11. Electrical diagram of one converter of modular topology.

The input and output parameters for the converter design are listed in Table IV. If the 8-module solution is considered, the output power of the modular system is the same as for the non-modular system.

TABLE IV. INPUT/OUTPUT PARAMETERS OF BIDIRECTIONAL BUCK/BOOST CONVERTER.

Parameter	Value
Input voltage	10 Vdc – 14 Vdc
Input current	10 ADC
Output voltage	25 VDC
Output current	5 ADC
Switching frequency	500 kHz (nominal)
Output power	125 W

A. *Laboratory Prototype of Proposed Converter*

Figure 12 shows the laboratory prototype of a designed converter based on data given in Table IV. The proposed module consists of 2 boards. The horizontal motherboard is composed mostly of filtering components like electrolytic capacitors with MLCC (Multi-Layer Chip Capacitor) capacitors and power inductors. The vertical board consists from GaN transistors with gate drivers, DC/DC isolated module, optical isolator, and connector sockets. The vertical board is connected to motherboard trough socket for better serviceability of measured parameters and for more suitable electronic components changing.

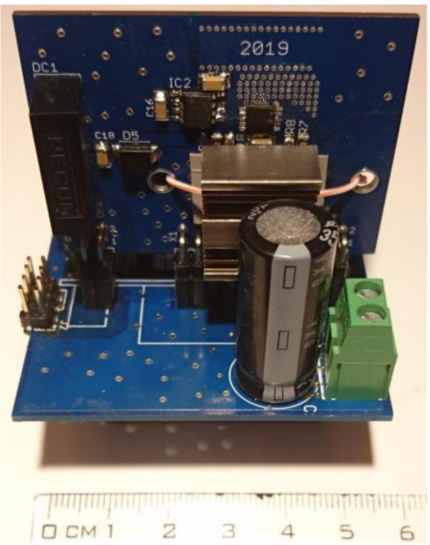

Fig. 12. Laboratory prototype of designed DC/DC converter with tested GaN transistors.

The main electronic components used within the converter are listed in Table V.

TABLE V. LIST OF ELECTRONIC COMPONENTS OF THE CONVERTER'S POWER STAGE.

Electronic part	**Value**
Inductor cores	Bourns 15 µH automotive inductor
Switching transistors	Gan systems GS61008T
Capacitors (one module)	8 × MLCC 4.7 µF/100 V, 2 × Nichicon 1500 µF/35 V electrolytic capacitors
Gate driver	LM5113 WSON10

B. Parametric Evaluation of Transistor Switching Performance on Efficiency of the Proposed Converter

As was mentioned in the introduction of this paper, the aim of this research is to evaluate the impact of switching performance of selected transistor type on the overall efficiency of power semiconductor converter. Therefore, the designed converter undergone testing (Fig. 13), while its switching frequency was changed and efficiency was evaluated within full operational range of output power. The efficiency was evaluated for boost as well as for buck operation mode [15].

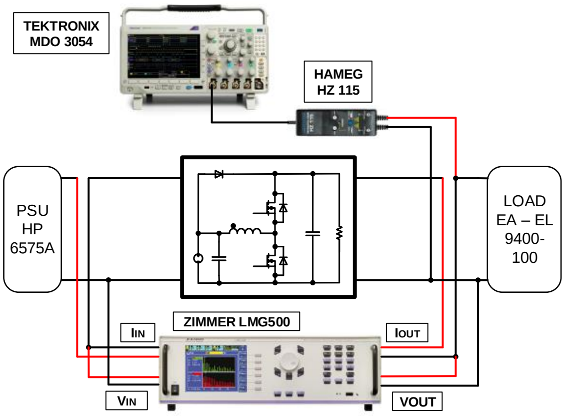

Fig. 13. Experimental laboratory set-up for evaluation of efficiency performance of designed bidirectional converter.

Figure 14 is showing the dependency of efficiency for the boost mode of operation. Figure 15 shows similar dependency for buck mode of operation. For both cases, the maximum of almost 98 % of efficiency is reached, while it is located within 40 %–50 % of nominal power delivery.

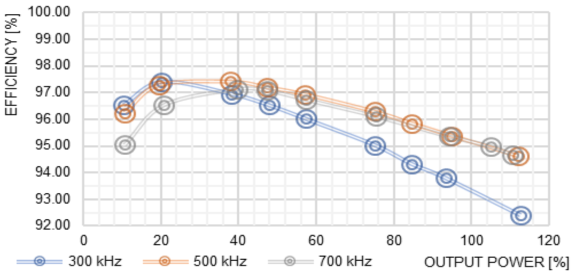

Fig. 14. Efficiency performance of proposed DC-DC converter in dependency on switching frequency and power for boost mode.

From both figures, is also seen, that above 20 % of converter's nominal power the efficiency for 300 kHz of switching frequency is decreasing. Comparing to 500 kHz and 700 kHz situation for 100 % of power, the efficiency difference in constraint to 300 kHz is over 3 %. For higher operational frequencies, the efficiency characteristic is almost the same.

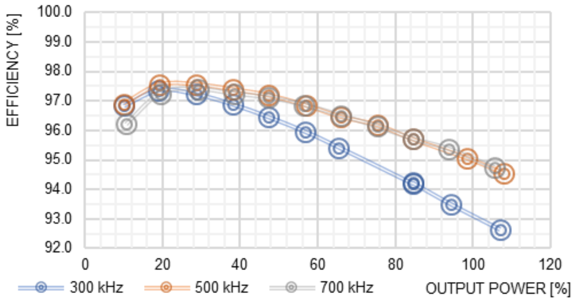

Fig. 15. Efficiency performance of proposed DC-DC converter in dependency on switching frequency and power for buck mode.

V. CONCLUSIONS

From the results of efficiency measurements of the designed converter, it can be concluded that very high switching frequency of GaN power transistors are not affecting the efficiency performance of the power converter stage. The maximum achieved efficiency was above 97,5 % at the 40 % of power delivery, while this result is valid for 500 kHz and 700 kHz of operation. Lower frequency compared to mentioned causes visible drop of efficiency of converter for both modes of operation. Here, it must also be said that initial simulation experiments of switching performance can be accepted as reference merit if converter performance comes into account. These simulations had shown that the difference between low and high frequency operations is not huge, and instead of that, over 300 kHz the results are comparable. Also, it was confirmed, that the supply voltage does not affect switching losses visibly. This confirmation is valid for low voltages, which were investigated here (12 Vdc and 24 Vdc), while it is expected that this behavior can be achieved up to 100 V, while the miller capacitance dependency is not harsh for this region. The different situation can be expected if higher supply voltages (i.e., 400 Vdc) are considered. To overcome transistors, supply voltage influence on efficiency performance, it could be advised to use a modular connection of small modules operated at very high switching frequencies in order to minimize volume requirements.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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