Design, Analysis and Comparison of Si- and GaN-Based DC-DC Wide-Input-Voltage-Range Buck-Boost Converters

Mikołaj Koszel, Piotr Grzejszczak, Bartosz Nowatkiewicz, and Kornel Wolski

Abstract—The purpose of the article is a comparison between DC/DC topologies with a wide input voltage range. The research also explains how the implementation of GaN E-HEMT transistors influences the overall efficiency of the converter. The article presents a process of selection of the most efficient topology for stabilization of the battery storage voltage (9 V – 36 V) at the level of 24 V, which enables the usage of ultracapacitor energy storage in a wide range of applications, e.g., in automated electric vehicles. In order to choose the most suitable topology, simulation and laboratory research were conducted. The two most promising topologies were selected for verification in the experimental model. Each of the converters was constructed in two versions: with Si and with GaN E-HEMT transistors. The paper presents experimental research results that consist of precise power loss measurements and thermal analysis. The performance with an increased switching frequency of converters was also examined.

Keywords—buck-boost, synchronous DC/DC converter, GaN, high efficiency, ultracapacitor, power losses, SEPIC, Ćuk

I. Introduction

PLENTY of DC-DC applications require a possibility to obtain output voltage that is higher or lower than the input voltage. Some energy storage devices characterized by a wide range of operating voltage create a need for a DC-DC converter that stabilizes voltage at the desired level. This condition is necessary when we consider highly efficient energy storage systems based on supercapacitors. Wide-input-voltage-range DC-DC converters provide batteries with the optimal operating conditions and allow them to use their full available capacity. Supercapacitors can be discharged to 0 V, which challenges power converters to use energy in the entire working range efficiently. Allowing operation at a low voltage level increases energy storage capacitance significantly (Fig. 1). Cut-off voltage level should be a trade-off between available capacitance, power converter boost capabilities, and efficiency. A wide choice of buck-boost topologies is described in the literature [1]. The most popular of them are: inverting buck-boost, SEPIC, Ćuk converter, and cascaded

buck-boost. They are also the least complex, therefore, easy to implement in industrial conditions. Proposed topologies differ in the quantity of necessary semiconductor or passive devices and the control characteristics. Selection of the appropriate topology for the desired application seems to be a nontrivial task.
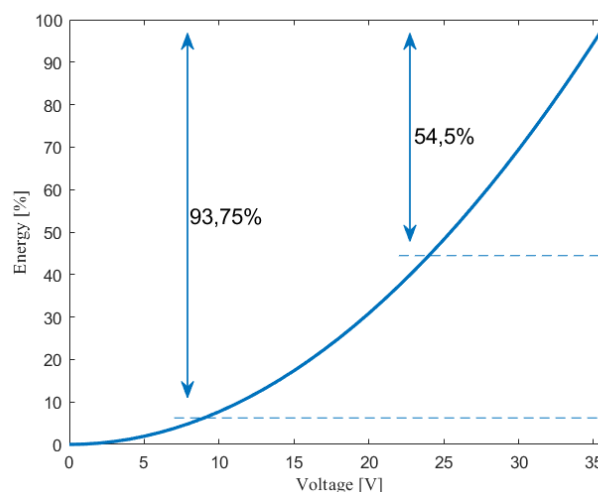

Fig. 1. Energy stored in a supercapacitor related to its voltage

Some simulation results show that non-inverting cascaded buck-boost can be more efficient than inverting buck-boost due to better working conditions of the semiconductor devices [5]. The discussed topologies are also widely used in photovoltaics systems 0[6]. Ćuk converter can be successfully applied, especially in designs where non-pulsed input currents are required [7][8]. It should be noted that key design factors in energy storage systems are specific and in some areas different from other applications, e.g. photovoltaics. Another examined issue is the possible application of wide-bandgap transistors to improve well-known topologies regarding operating frequency and overall efficiency [9]. GaN transistors designed to operate at low voltage values (100 V nominally) are a cutting-edge but also verified technology. The possibility of increasing the switching frequency while maintaining high-efficiency level is desirable and will result in decreasing the size of power converters. GaN E-HEMT transistors can be compared with silicon MOSFET power devices. However, some differences in structure, operation, and application have to be noted [10].

M. Koszel, P. Grzejszczak and K. Wolski is with Warsaw University of Technology, Institute of Control and Industrial Electronics, Poland (e-mail: mikolaj.koszel@pw.edu.pl, piotr.grzejszczak@ee.pw.edu.pl, kornel.wolski@pw.edu.pl).

Bartosz Nowatkiewicz is with the Wibar Technology Ltd., Poland (e-mail: bartosz.nowatkiewicz@wibar.pl).

II. RESEARCH CRITERIA

The analyzed buck-boost converter is projected to stabilize voltage provided by supercapacitor energy storage, enabling such storage device to power various types of electric vehicles. Principle design parameters (TABLE I) assume operation with constant output voltage and switching frequency and variable input voltage and output power.

TABLE I
POWER CONVERTER DESIGN PARAMETERS

Parameter	Unit	Value
V_{IN}	V	9 – 36
V_{OUT}	V	24
$P_{OUT\ AVG}$	W	250
P_{MAX}	W	1000
f_{SW}	kHz	100
t_{dead}	ns	100
η	%	98
$I_{IN\ max}$	A	50

III. TOPOLOGY SELECTION

During the topology selection process, several factors were taken into consideration. Firstly, a topology must have the possibility to step up and step down the voltage in the defined range without any reconfiguration. Furthermore, efficiency should be as high as possible. Lastly, power density and material costs must be held at the appropriate levels to facilitate future industrial implementation of the converter.

A. Topology overview

Step-up / step-down converters can be divided into two main groups: galvanically isolated and non-isolated (Fig. 2). The assumed voltage ratio (TABLE I) does not require a transformer; therefore, in the solution, the selection of the topology is limited to converters without galvanic isolation. Furthermore, resignation from the transformer will allow the maximization of the power density factor.
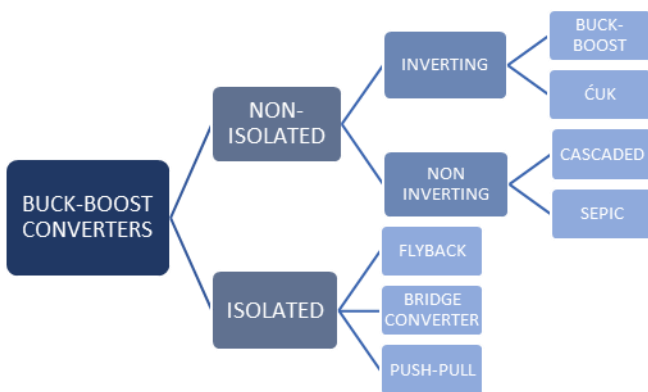
Fig. 2 Buck-boost topology overview

Different topologies result in diverse working conditions of semiconductors and passive components, which causes differences in power losses [11]. Each of the presented topologies (Fig. 3) has pros and cons presented in TABLE II. The higher number of transistors results in a more complex control structure, the discontinuous input or output currents increase EMI filter dimensions, and the reverse output voltage polarity makes it challenging to implement a converter in a complex system.
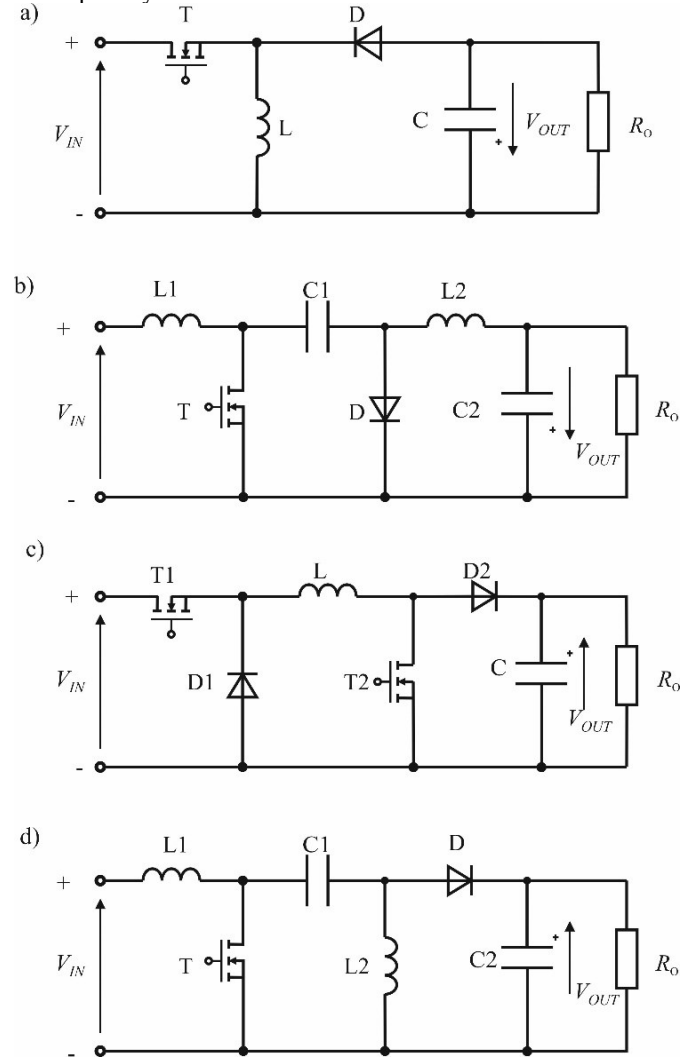
Fig. 3 Converter topologies: (a) Inverting buck-boost converter; (b) Ćuk converter; (c) Cascaded buck-boost DC/DC converter; (d) SEPIC converter

Four non-isolated topologies (Fig. 3) were chosen for simulation verification.

TABLE II
Comparison of non-isolated buck-boost DC/DC topologies

	Buck-boost	Ćuk	Cascaded	SEPIC
Switches no.	1	1	2	1
Capacitors no.	1	2	1	2
Inductors no.	1	2	1	2
Input current	DC[a]	CC[b]	DC	CC
Output current	DC	CC	DC	DC

[a] DC - discontinuous current
[b] CC - continuous current

B. Simulation analysis

Simulation research aimed to observe the efficiency of different topologies in key operating points. However, the simulation model was somewhat simplified so that the core and AC conduction losses of inductors as well as snubber losses were not included. As for the transistors, realistic models prepared by the manufacturer were used (Fig. 4). Synchronous versions of converters were used in order to minimize conduction losses [12].
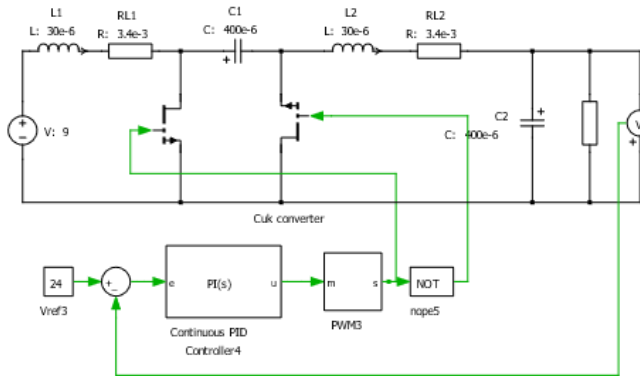

Fig. 4 Simulation model of Ćuk converter

The cascaded converter achieved the highest efficiency at all operating points, whereas classic inverting buck-boost had the most losses (TABLE III). The results for Ćuk and SEPIC converter were similar, so the non-inverting SEPIC topology was chosen as the more desirable because of the non-inverting characteristic.

TABLE III
SIMULATION POWER EFFICIENCY RESULTS
($V_{OUT} = 24$ V, $P_{OUT} = 250$ W, $f_{SW} = 100$ kHz)

Input voltage	Buck-boost	Ćuk	Cascaded	SEPIC
9 V	92.8%	94%	94.8%	94%
15 V	97%	97%	98.2%	97%
24 V	98.3%	98.3%	99.4%	98.3%
32 V	98.6%	98.6%	99.3%	98.7%

Based on simulation results, two topologies, the cascaded buck-boost and SEPIC, were chosen for further experimental research.

IV. EXPERIMENTAL MODELS

Prototypes of the two selected topologies were constructed for experimental analysis (Fig. 5). Converters in each topology were designed using two technologies: Si and GaN E-HEMT. Each of the resulting four prototypes was built with similar passive components (TABLE IV) in order to achieve comparable results.

In converters using GaN E-HEMT devices (Fig. 6c, Fig. 6d), each switch consists of two paralleled discrete transistors. This solution stems from high $R_{ds(on)}$ of selected GaN E-HEMT GS61008T [13] transistors (7 mΩ at $T_j = 20$ °C) in comparison to $R_{ds(on)}$ of the used Si IPP030N10N5 [14] devices (3 mΩ at $T_j = 20$ °C). What is more, GaN E-HEMT transistors have a high positive temperature coefficient. Using the

increased number of GaN E-HEMT transistors can even lead to the higher overall efficiency of the converter despite increased switching losses because of low parasitic capacitance and gate charge values. Limiting conduction losses seemed to be the priority because of relatively high currents flowing in the circuit (up to 50 A).
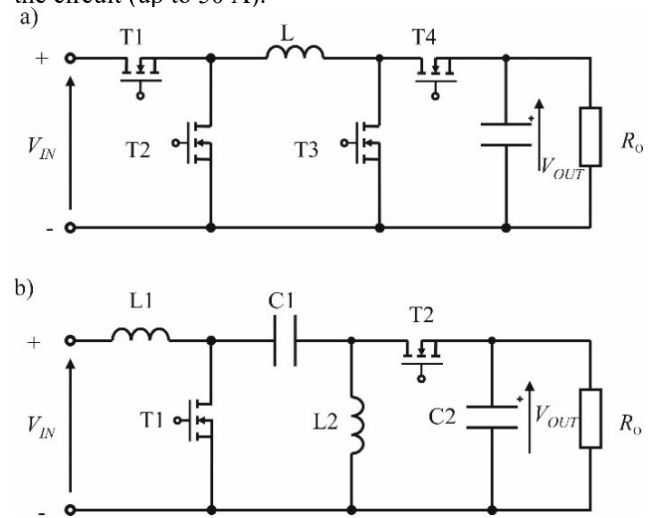

Fig. 5 Selected topologies: (a) Synchronous cascaded buck-boost DC/DC converter; (b) Synchronous SEPIC converter

TABLE IV
EXPERIMENTAL MODEL PARAMETERS

	Cascaded	SEPIC
C_{IN}	3300 µF, 20 mΩ	22 µF, 10 mΩ
C2	-	260 µF, 8.3 mΩ
C_{OUT}	3300 µF, 20 mΩ	10800 µF, 2.3 mΩ
L1	15 µH, 51.6 A	30 µH, 51.6 A
L2	-	30 µH, 51.6 A

An RC snubber circuit paralleled each transistor in order to minimize V_{DS} overshoot and oscillations. Specific R and C values were selected based on simulations and experimental tests (10 nF and 3.3 Ω for Si transistors and 2.2 nF and 1 Ω for GaN semiconductors) [15].
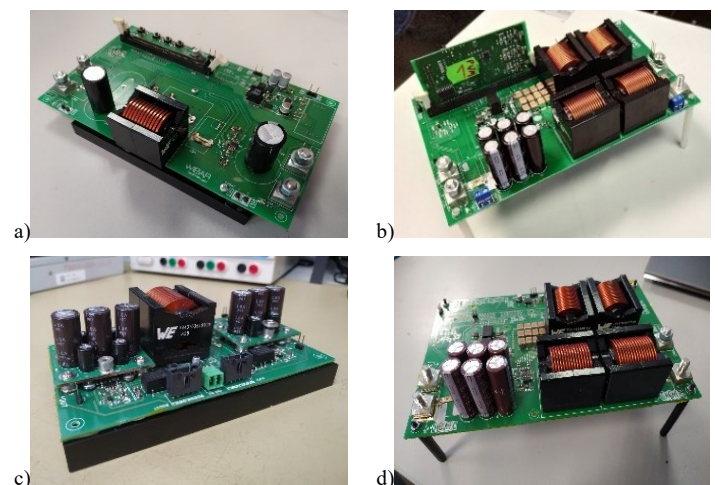

Fig. 6 Experimental models: (a) Cascaded, Si; (b) SEPIC, Si; (c) Cascaded, GaN; (d) SEPIC, GaN

In each design, isolated Si8271 gate drivers were used. V_{GS} of Si-based converters was set to 12 V / 0 V with external 6.8Ω / 3.3Ω gate resistors, whereas for GaN-based converter, V_{GS} was set to 5.6 V / -3.4 V and external gate resistance values were equal to 3.3 Ω / 1 Ω. Bipolar V_{GS} improves noise immunity; however, it results in higher switching losses. Robustness is crucial in application with GaN E-HEMTs because of low gate threshold voltage [16].

V. EXPERIMENTAL ANALYSIS

The purpose of experimental research was to verify preliminary simulation tests and compare power losses in Si- and GaN-based transistors. All four converters were tested with regards to power losses through electrical (Fig. 7), (Fig. 9) and thermal (Fig. 11) measurements.
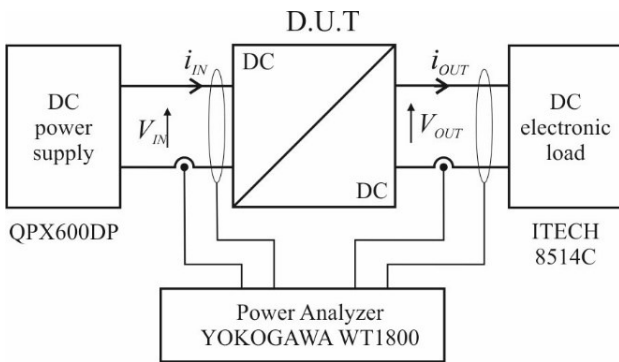
a)
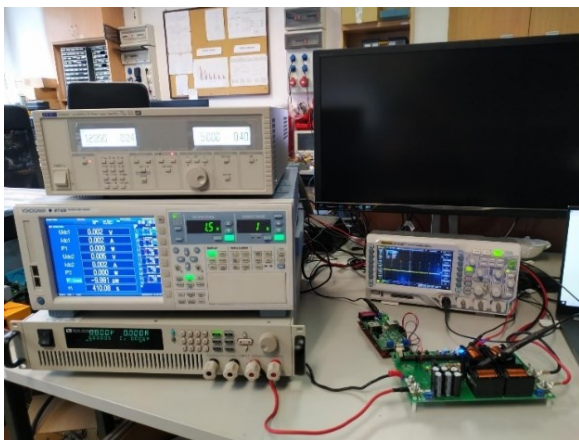
b)

Fig. 7 Power loss measurements: a) Photograph of the laboratory setup; b) Scheme of the setup

The results showed that the buck-boost converters work with the highest efficiency when input and output voltage values are similar. Operating in boost mode is significantly less efficient because of increased currents, assuming constant power and output voltage.

Results of power analyzer measurements presented in TABLE V and in the chart (Fig. 8) highlight the difference in efficiency between the cascaded buck-boost and SEPIC converter, which was first observed in simulation research (TABLE III).
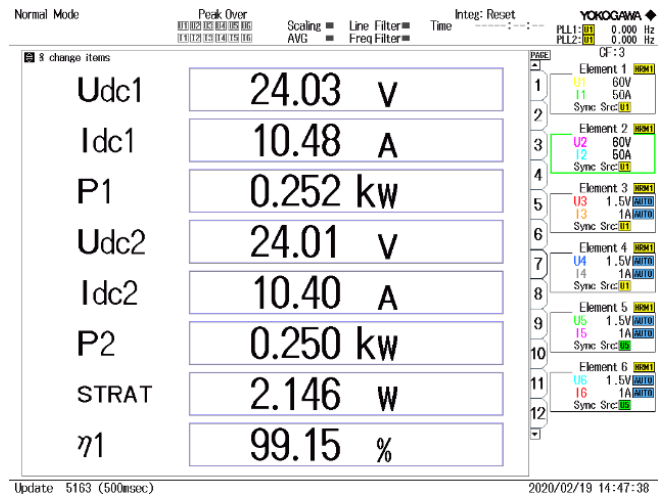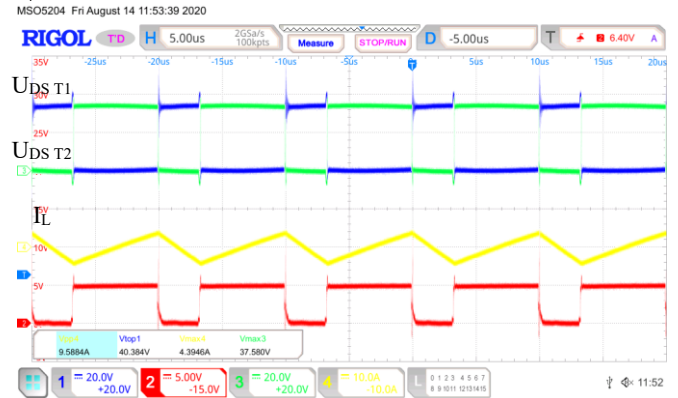
Fig. 8 Power analyzer Yokogawa WT1800 screenshot – Cascaded GaN converter in optimal operating point
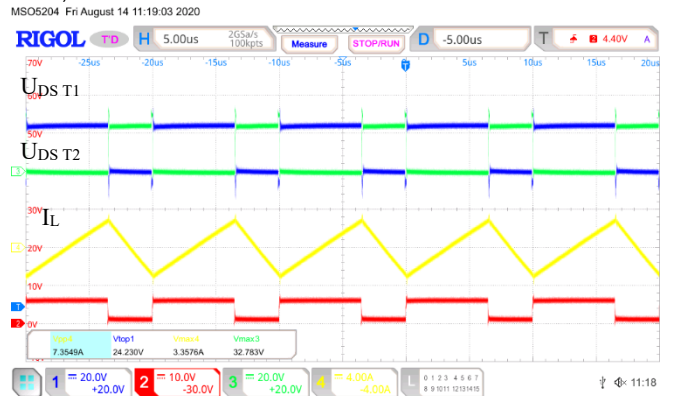
a)

b)

Fig. 9 Cascaded GaN converter waveforms in steady-state operation, boost mode: Logic signal (red), V_{DST1}(blue), V_{DST2} (green), and I_L (yellow): (a) 36 V / 24 V; (b) 9 V / 24 V

The second remark is that SEPIC characteristics are flatter than cascaded converter ones. At the range limits (especially at minimum voltage), SEPIC and cascaded converter losses are similar, but in the middle of the range, cascaded buck-boost has significant superiority.

TABLE V.
MEASURED EFFICIENCY
($V_{OUT} = 24$ V, $P_{OUT} = 250$ W, $f_{SW} = 100$ kHz)

Input voltage	Cascaded Si	Cascaded GaN	SEPIC Si	SEPIC GaN
9 V	89.6%	91.2%	90%	87.7%
16 V	96.3%	97.1%	94.5%	93.9%
24 V	98.7%	99.2%	95.1%	99.2%
36 V	96.6%	98.2%	94.9%	94.9%

Cascaded buck-boost GaN-based converter has lower losses than the Si-based one in the whole analyzed range of input voltage. On the other hand, the SEPIC converter with Si semiconductors in the majority of the operating range is more efficient than its GaN-based version (Fig. 10). Losses of the SEPIC GaN converter increase significantly when the input voltage is low. It mainly stems from the operation principle of the SEPIC topology and higher RMS values of currents flowing through transistors. Higher $R_{ds(on)}$ of the GaN transistors and their positive temperature coefficient also have an impact on losses in this case.
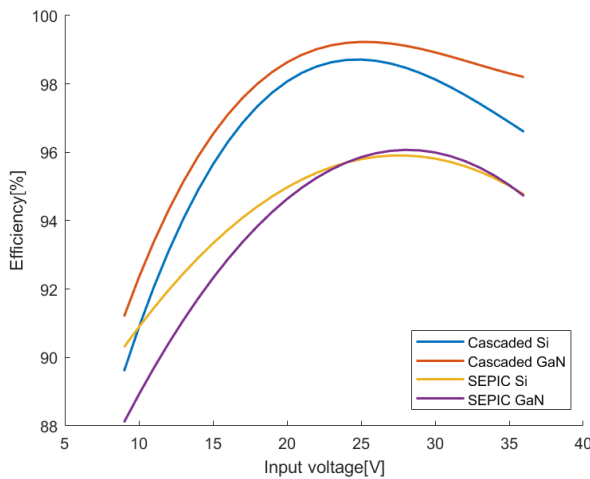

Fig. 10 Measured efficiency of the designed converters

In order to confirm the achieved results, long-term-operation tests were performed (Fig. 12). All the tested converters were passively cooled with a 2.2-K/W heatsink.

Fig. 11 Experimental setup – thermal analysis

Heating curves, in general, confirm the power analyzer measurements. However, the power efficiency of SEPIC Si was slightly higher than that of the cascaded Si at the analyzed operation point ($V_{IN} = 9$ V, $V_{OUT} = 24$ V, $P_{OUT} = 250$ W) (Fig. 10).
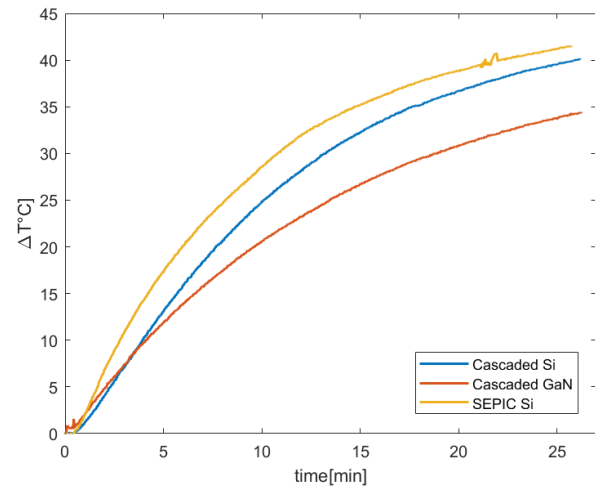

Fig. 12 Heating curves. ΔT – heatsink temperature increase ($V_{IN} = 9$ V, $V_{OUT} = 24$ V, $P_{OUT} = 250$ W, $f_{SW} = 100$ kHz)

VI.   HIGH SWITCHING FREQUENCY PERFORMANCE

In the research, power losses with different switching frequencies were also examined. GaN E-HEMT transistors are predestined to operate at high switching frequency because of their small parasitic capacitance and charge values [13][17]. These theoretical values were checked in simulation and experimental research in comparison with the Si power transistors. Simulation results that covered losses of the transistor, inductor, and PCB traces (Fig. 12) were compared with total converter losses measured according to Section III. Transistor switching losses were estimated by approximation of switching energy as a triangle as per formulas (1) and (2). Switching period duration ($t_1 - t_4$) was calculated based on datasheet parameters and the applied V_{GS} level.

$$E_{ON} = \frac{1}{2} * U * I * (t_1 + t_2) + E_{OSS} \qquad (1)$$

$$E_{OFF} = \frac{1}{2} * U * I * (t_3 + t_4) \qquad (2)$$

To calculate inductor losses, the manufacturer's RED EXPERT software was used. The software uses experimental data in order to estimate inductor losses correctly at various duty cycle levels. PCB trace resistances were precisely measured and also included in simulation models.

Simulation and experimental 3D profiles of losses in Si and GaN transistors are concurrent. However, values of losses estimated in simulation underestimate actual losses. This relationship is evident in GaN-based converters, which can result from GaN transistors' structure. GaN E-HEMT does not include a body diode as in Si MOSFETs, which next to numerous advantages, provides the drawback of higher dead-time losses [18]. Underestimated are especially the losses in boost mode of the converter (Fig. 13b, Fig. 14b).
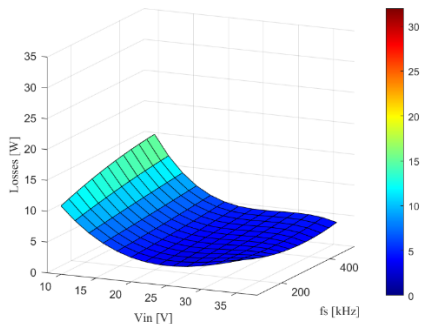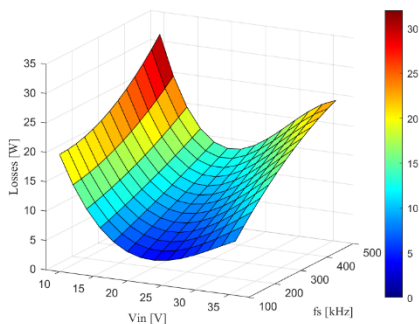
a)
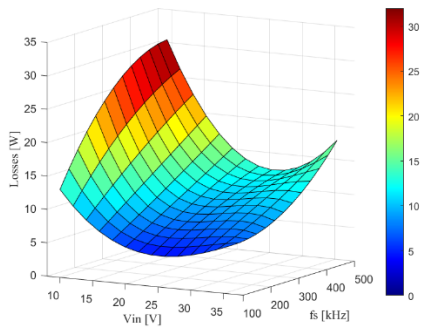
b)

Fig. 13 Simulation results. Power losses depending on input voltage level and switching frequency: a) Cascaded Si converter b) Cascaded GaN converter
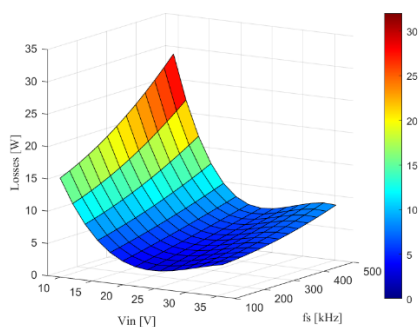
a)

b)

Fig. 14 Experimental results. Power losses vs. input voltage and switching frequency: a) Cascaded Si converter; b) Cascaded GaN converter

The superiority of GaN E-HEMT can be observed in buck mode, whereas in boost mode, minimization of transistor switching losses is compensated by other phenomena, like higher dead-time losses and high-temperature coefficient.

VII. CONCLUSIONS

The research focused on two main issues: selecting the most efficient topology of non-isolated buck-boost converter for low-voltage supercapacitor energy storage and comparing Si and GaN E-HEMT transistor losses in the solution. Initial simulation research has helped to identify two topologies with the highest efficiency (SEPIC and cascaded converter) for further experimental investigation. This research showed that buck-boost converter working with supercapacitor energy storage should be explicitly used for the application to improve the overall performance. Both simulation and experimental studies showed that the cascaded buck-boost converter has the highest efficiency despite the increased number of transistors. Converters with Si and GaN semiconductor devices reached a similar level of efficiency. However, it should be noted that GaN solution can be superior at high switching frequency (up to 1 MHz), at which they are intended to operate. High switching frequency will result in the possibility of decreasing inductance values and lead to an increased power density factor of the converter. A small package of GaN E-HEMT devices reduces parasitic inductances and, as a result, limits overshoot and oscillations during the switching process. This allows designing converters more effortlessly. On the other hand, to get the full benefit of the devices, an appropriate cooling system should be included. Heat dissipation from small chips is constricted and will demand more sophisticated cooling solutions, especially in devices operating at increased frequencies in high power density applications.

References

[1] M. Nowak and R. Barlik, „Poradnik inżyniera energoelektronika," in WNT, Warszawa, pp.161-194, 1998. (in Polish)

[2] N. Mohan, W. P. Robbins, T. M. Undeland, and N. Mohan, "Solutions manual: power electronics: converters, applications, and design," New York: Wiley, 1989.

[3] L. Wuidart, "Topologies For Switched Mode Power Supplies," STMicroelectronics, 1999.

[4] M. Zehendner and M. Ulmann, "Power Topologies Handbook," Texas Instrument, pp.23-171, 2016.

[5] X. Weng, X. Xiao, W. He, Y. Zhou, Y. Shen, W. Zhao, and Z. Zhao, "Comprehensive comparison and analysis of non-inverting buck boost and conventional buck boost converters" The Journal of Engineering, vol. 2019, no. 16, pp. 3030–3034, 2019.
DOI: https://doi.org/10.1049/joe.2018.8373

M. Luthfansyah, S. Suyanto, and A. Bakarr Momodu Bangura, "Evaluation and Comparison of DC-DC Power Converter Variations in Solar Panel Systems Using Maximum Power Point Tracking (MPPT) Flower Pollination Algorithm (FPA) Control" E3S Web of Conferences, vol. 190, p. 00026, 2020.
DOI: https://doi.org/10.1051/e3sconf/202019000026

[6] B. Amri and M. Ashari, "The comparative study of Buck-boost, Cuk, Sepic and Zeta converters for maximum power point tracking photovoltaic using P&O method" 2015 2nd International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE), pp. 327-332, 2015. DOI: https://doi.org/10.1109/ICITACEE.2015.7437823

[7] M. V. D. de Sá and R. L. Andersen, "Dynamic modeling and design of a Cúk converter applied to energy storage systems" 2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), 2015, pp. 1-6. DOI: https://doi.org/10.1109/COBEP.2015.7420080

[8] B. M. M. Mwinyiwiwa and J. Dunia, "Performance Comparison between ĆUK and SEPIC Converters for Maximum Power Point Tracking Using Incremental Conductance Technique in Solar Power Applications," World Academy of Science, Engineering and Technology International

Journal of Computer and Systems Engineering, 2013. vol. 7, no. 12. DOI: https://doi.org/10.5281/zenodo.1089293

[9] Y. Attia and M. Youssef, "GaN on silicon E-HEMT and pure silicon MOSFET in high frequency switching of EV DC/DC converter: A comparative study in a nissan leaf," 2016 IEEE International Telecommunications Energy Conference (INTELEC), pp. 1-6, 2016. DOI: https://doi.org/10.1109/INTLEC.2016.7749112

[10] S. K. Pullabhatla, P. B. Bobba, and S. Yadlapalli, "Comparison of GAN, SIC, SI Technology for High Frequency and High Efficiency Inverters," E3S Web of Conferences, vol. 184, p. 01012, 2020. DOI: https://doi.org/10.1051/e3sconf/202018401012

[11] A. Deihimi and M. E. Mahmoodieh, "Analysis and control of battery-integrated dc/dc converters for renewable energy applications" IET Power Electronics, vol. 10, no. 14, pp. 1819–1831, 2017. DOI: https://doi.org/10.1049/iet-pel.2016.0832

[12] R. Nowakowski and N. Tang, "Efficiency of synchronous versus nonsynchronous buck converters, " Texas Instruments, 2009.

[13] Gan Systems, "GS61008T datasheet, ", 2021 online: www.gansystems.com (2021).

[14] Infineon, "IPP030N10N5 datasheet", Rev.2.3,2016-10-03, 2021. online: www.infineon.com

[15] P. Grzejszczak , A. Czaplicki , M. Szymczak , R. Barlik „The impact of snubber circuits on switching energy losses in high frequency converters" Przeglad Elektrotechniczny, vol. 96, no. 06, pp 93-97, 2020, (in Polish). DOI: https://doi.org/10.15199/48.2020.06.17

[16] GN012 Application Guide Design with GaN Enhancement Mode HEMT, , 2021 online: www.gansystems.com (2021).

[17] M. Koszel and P. Grzejszczak, "Power loss estimating in GaN E-HEMT based synchronous buck-boost converter," 2020 Progress in Applied Electrical Engineering (PAEE), 2020, pp. 1-6. DOI: https://doi.org/10.1109/PAEE50669.2020.9158576

[18] D. Craig, "Common misconceptions about the MOSFET body diode," GaN Systems, 23-Oct-2019. online: https://gansystems.com/newsroom/common-misconceptions-about-the-mosfet-body-diode/ (2021)