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PAPERS

Comparison of the performance of Si, SiC, and GaN based switching elements in high gain DC-DC boost converter

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In this study, Si, SiC, and GaN based semiconductor switching elements to be used in the design of new generation high gain DC-DC converters are compared. Each switching element is tested at different frequencies and different pulse period ratios. The efficiency and output voltage of the high gain boost converter are analyzed in detail according to the switching element used. The amplifiers have been investigated at 50 kHz and 5 MHz switching frequencies. The results show that the converter using GaN-based MOSFET is more efficient than converters using other MOSFETs and reaches the highest efficiency at 200 kHz switching frequency. The proposed converter achieves 91.68% efficiency and 2.66 voltage gain at 0.3 pulse period rate, 94% efficiency and 3.78 voltage gain at 0.5 pulse period rate and 93.94% efficiency, and 6.33 voltage gain at 0.7 pulse period rate. Thus, it is understood that when GaN based MOSFETs are used in high gain DC-DC converters, higher gain and higher efficiency are achieved.

Keywords: high gain DC-DC boost converter, Si MOSFET, SiC MOSFET, GaN MOSFET

1 Introduction

Today, energy efficiency has become a critical factor in the design of electronic power conversion systems. High gain boost DC-DC converters have a wide range of applications to improve energy efficiency and utilize power supplies more efficiently [1]. The switching elements determine the performance of these converters. In addition to the traditional Silicon (Si) material, Silicon Carbide (SiC) and Gallium Nitride (GaN) based switching elements have recently become the focus of designers [2]. The limitations of silicon-based switching elements can limit energy efficiency, especially in applications with high power density and fast switching requirements. SiC and GaN based switching elements are notable for their high frequency operation and low switching losses. These switching elements improve energy efficiency due to their low conductor resistance. Therefore, the selection of switching elements plays a significant role in determining the performance of DC-DC converters. Electric vehicle (EV) technologies are becoming increasingly important as an environmentally friendly and sustainable transportation alternative. An important component for these vehicles to be more efficient and more performant is a high gain converter [3]. High gain converters increase the efficiency of the energy storage system in an EV. Offering a constant voltage level, the energy storage system allows the EV to reach the power level it needs thanks to a high gain converter. In addition, bi-directional converters provide regenerative braking for EVs [4].

Recently, there have been many studies on the design of high gain converters for EVs with semiconductor switching elements such as Si, SiC, and GaN. Aaron et al. have tested GaN based switching elements on a buck DC-DC converter [5]. Zhang et al. tested SiC MOSFET elements on different converter topologies. They discussed the advantages and disadvantages of SiC MOSFET in the study [6]. Chou et al. investigated the losses of SiC MOSFET and IGBT switching elements used in the drive circuit of an EV [7]. Nelson et al. analyzed the static behaviour of SiC MOSFET using the finite element method [8]. In other studies, Si and SiC based switching elements have been tested and analyzed in different circuit topologies [9-11]. Chen et al. tested GaN and SiC-based switching elements on AC-DC converters [12]. K. Kavin et al. designed a DC-DC converter for the drive system of an EV with a brushless DC motor. The proposed converter was found to be about 2-3% more efficient than other converters [13]. H. Khalid et al. designed a high gain DC-DC converter for EV applications. The designed converter was found to operate in the efficiency range of 88% to 96% at different pulse period ratios [14]. S. Devi et al. compared the performance of quasi-impedance source inverters (qZSI) using Si, SiC, and GaN semiconductor materials. In the study, these three different semiconductors have been evaluated according to performance criteria such as efficiency, switch losses, voltage, and current stress. According to the results, GaN-based qZSI has the highest efficiency of 95.05%, while Si-based qZSI has the lowest efficiency of 90.34% [15].

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The increasing demand for sustainable and efficient energy systems drives the need for advanced high gain converters, which in turn necessitates the evaluation and optimization of various semiconductor materials. This study aims to address these needs by comparing the performance of Si, SiC and GaN MOSFETs in high gain DC-DC converters, providing insights that can guide future design and development in this critical area.

In this study, the performance of the widely used Si MOSFET and the newer technology SiC and GaN MOSFETs are compared on the high efficiency and high gain new generation boost converter topology. The effect of each switching element on the efficiency and output voltage of the boost converter has been analyzed. All analyses have been performed in the range from 50 kHz to 5 MHz and in the base temperature condition. The results show that Si MOSFETs are less efficient at high frequencies, while SiC and GaN MOSFETs are more efficient at high frequencies. The boost converter operates at 200 kHz and 0.7 pulse period ratio with 93.94% efficiency and 6.33 voltage gain. The study reveals that GaN based MOSFETs operate with higher efficiency than Si and SiC MOSFETs at all frequencies.

2 The design of a high gain boost converter

Nowadays, increasing energy demand and limited energy resources encourage more efficient use of energy. High gain boost converters offer an important solution for electrical energy conversion [16]. These converters provide the required level of voltage by converting energy from low voltage sources to high voltages with high efficiency. This situation not only increases the efficiency of energy systems but also promotes sustainable energy use. In this study, a high gain high efficiency DC-DC converter topology has been used [17]. This high gain topology is particularly useful for the different speed levels of light electric vehicles, charging systems with fast charging, and regenerative braking.

2.1 Topology of high gain boost converter

The circuit structure of the high gain boost converter is shown in Fig. 1. As can be seen from Fig. 1, the proposed converter includes a switching element, transformer, inductance, capacitance, diode, and load resistor. The specifications of the elements used in the circuit are shown in Table 1.

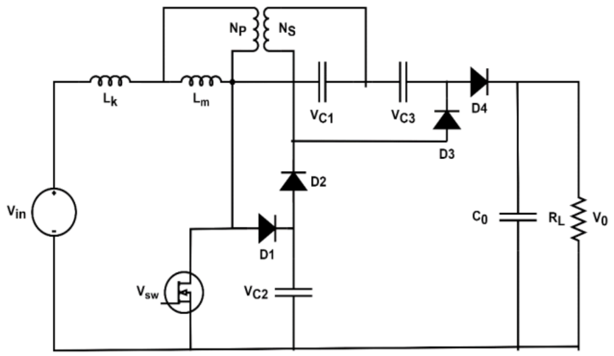

Fig. 1. High gain boost converter equivalent circuit

Table 1. Specifications of the high gain boost converter

Parameter	Value
Input voltage (V)	20
Output voltage (V)	126.5
Frequency (kHz)	200
Input power (W)	193.6
Output power (W)	181.86
Efficiency (%)	93.94

All the components shown in Fig. 1 are ideal and the parameters generating parasitic effects have been neglected. In the first stage ($t_0 < t < t_1$), D3 and S switch are on. V_{in}, magnetization L_m, and leakage L_k inductances have been charged. Capacitor C3 is also charged from the secondary side of the transformer N_s. Capacitor C0 transfers energy to the output load. Then ($t_1 < t < t_2$), D2 and switch S are on. Capacitor C1 is charged by N_s, and C2. Capacitor C0 transfers energy to the output load. Then ($t_2 < t < t_3$), switch S is closed. Diodes D1, D2 and D4 are open. Capacitor C2 is charged. Capacitors C1 and C3 transfer energy to the output load. Then ($t_3 < t < t_4$), switch S is closed. Diodes D1, D3 and D4 are open. Capacitors C1 and C3 transfer energy to the output load. At the final ($t_4 < t < t_5$), switch S is closed. Diodes D3 and D4 are in the open state. Capacitor C3 transfers energy to the output load. The S switch is turned on. Figure 2 shows the operating state of the proposed converter consisting of five stages. When the leakage inductance is neglected and depending on the operating stage, these equations are shown in Eqns. (1 to 7). Here, n and D represent the transformer conversion ratio and pulse period ratio, respectively.

$$V_{lm} = V_{in} \quad \text{for } \{t_1 < t < t_2\} \quad (1)$$

$$V_{C1} = V_{C2} + n \cdot V_{lm} \quad \text{for } \{t_1 < t < t_2\} \quad (2)$$

$$V_{lm} = -\frac{V_{C3}}{n} = V_{in} - V_{C2} \quad \text{for } \{t_3 < t < t_5\} \quad (3)$$

$$V_o = V_{C1} + V_{C2} + V_{C3} \quad \text{for } \{t_3 < t < t_4\} \quad (4)$$

$$V_o = V_{C1} + V_{in} + V_{C3} - V_{lm} \quad \text{for } \{t_4 < t < t_5\} \quad (5)$$

$$V_{C1} = \frac{(1 + n - nD)V_{in}}{1 - D} \qquad V_{C2} = \frac{V_{in}}{1 - D} \quad (6)$$

$$V_{C3} = \frac{nDV_{in}}{1 - D} \qquad V_0 = \frac{(n + 2)V_{in}}{1 - D} \quad (7)$$

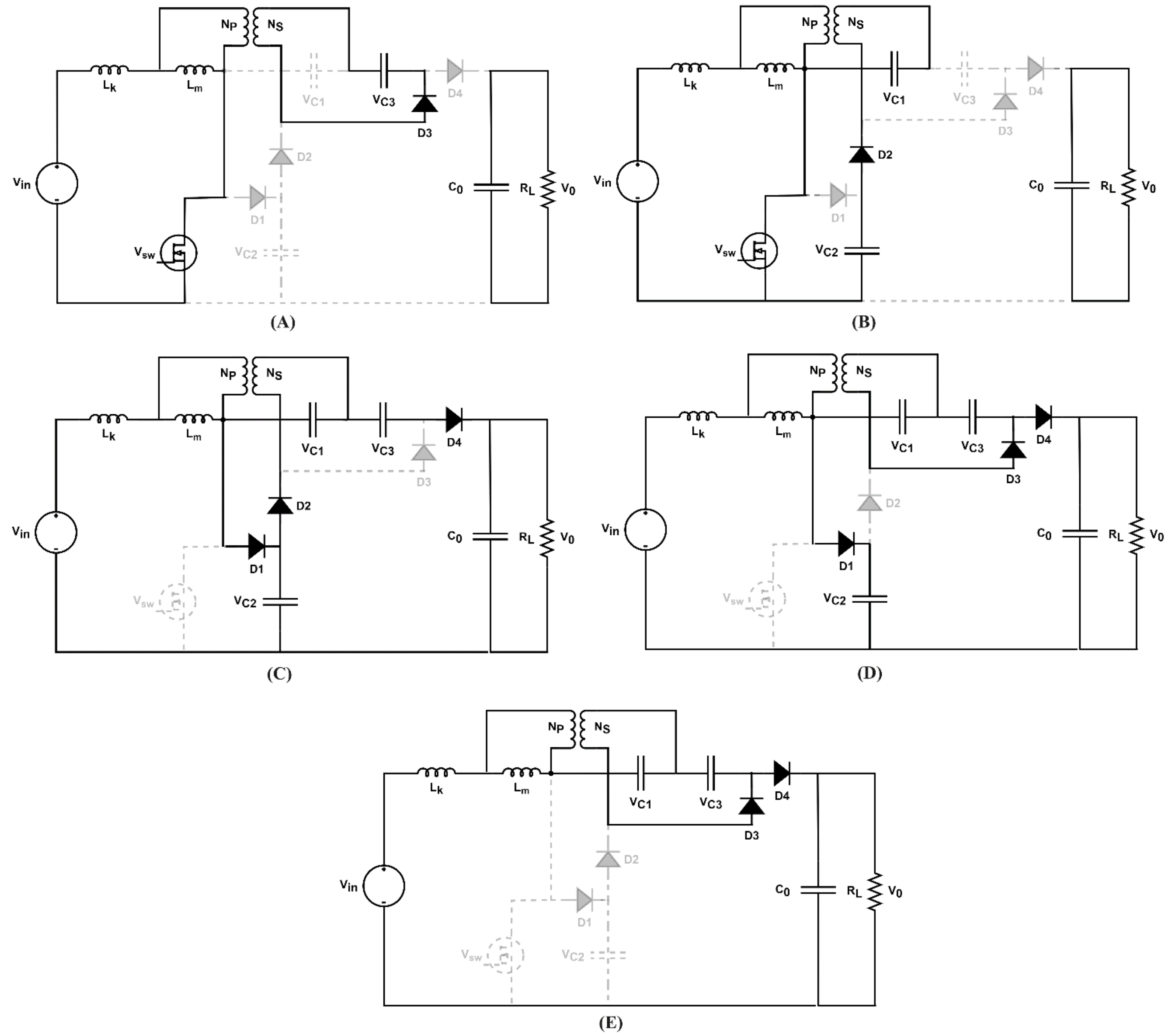

Fig. 2. Typical three-shunt sensing inverter operation stages of a high gain boost converter in sequential time ranges: (A) $t_0 < t < t_1$, (B) $t_1 < t < t_2$, (C) $t_2 < t < t_3$, (D) $t_3 < t < t_4$, (E) $t_4 < t < t_5$

2.2 Structures of Si, SiC, and GaN based switching elements

In power electronics applications, switching elements have great importance. Si based switching elements have been used for many years. Nowadays, wide bandgap materials such as SiC and GaN have been developed to achieve high performance and energy efficiency targets [18]. Si has the disadvantage of energy losses and temperature resistance [19]. SiC has a wide band gap and high electron mobility. Thus, it has the potential to operate at high temperatures and efficiently [20]. GaN has high electron mobility and high carrier density. This ensures that GaN based switching elements operate with high efficiency at high frequencies [21]. In Fig. 3, Si, SiC, and GaN materials have been compared.

As seen in Fig. 3, GaN based MOSFETs appear to be superior in all parameters except thermal conductivity. The highest thermal conductivity has been observed in SiC based MOSFETs [22].

While determining the Si, SiC, and GaN based MOSFETs to be used in the study, their output currents and current production status in the market have been taken into consideration. In these criteria, three different MOSFET structures have been selected. Table 2 shows the properties of the selected MOSFETs.

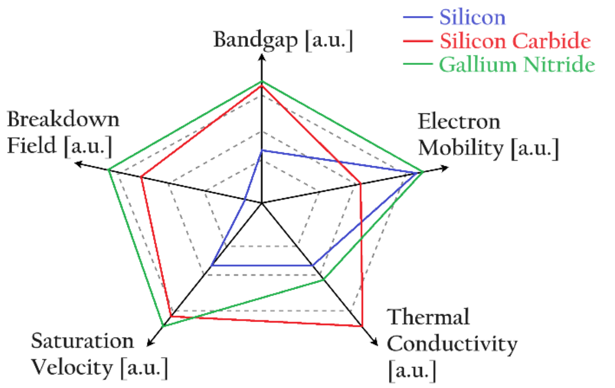

Fig. 3. Comparison of Si, SiC, and GaN material properties [22]

Table 2. Characteristics of the selected MOSFETs

Specifications	IRFP460	SCT20N120AG	GNP1070TC-Z
Material	Si	SiC	GaN
Highest V_{DS} voltage (V)	500	1200	650
I_D current (A)	20	20	20
Highest I_D current (A)	80	45	66
Statik drain resistor $R_{DS(on)}$ (Ω)	0.27	0.189	0.07
Input capacitance C_{iss} (pF)	4200	650	200
Output capacitance C_{oss} (pF)	500	65	70
Reverse transfer capacitance C_{rss} (pF)	50	14	0.6

3 Performance of Si, SiC, and GaN MOSFETs in boost converter

The proposed converter is analyzed using three different switching elements with characteristics shown in Table 2. In the first stage, the pulse period ratio D of the converter has been selected as 0.5 and the effect of frequency on the converter efficiency has been analyzed. In the next stage, the frequency value at which the highest efficiency has been obtained is kept constant and the effect of the pulse period ratio on the converter is observed. The boost converter circuit used in the study is shown in Fig. 4.

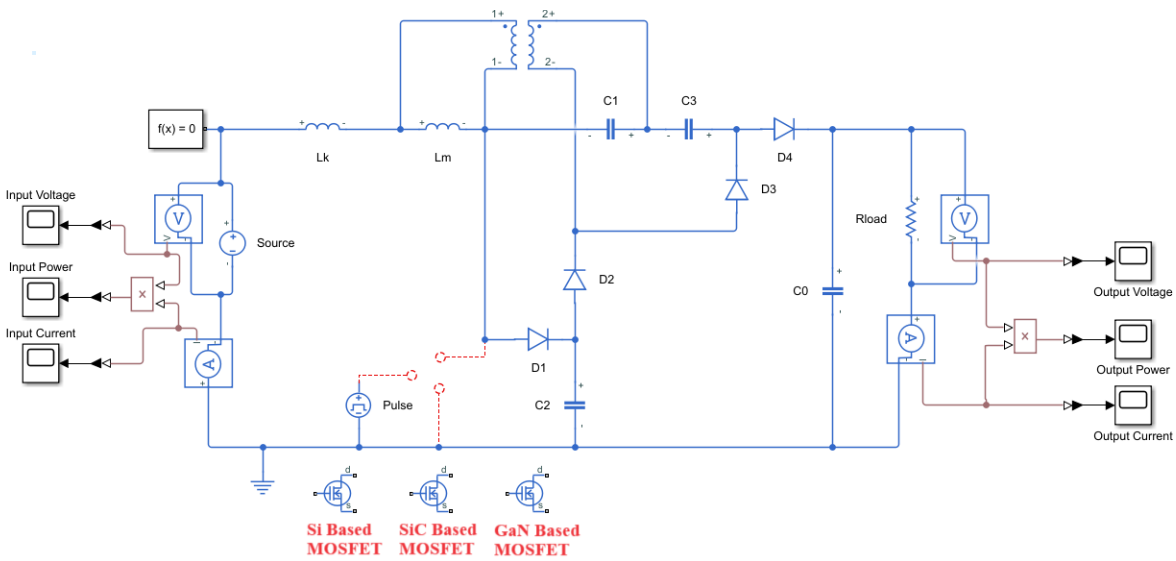

Fig. 4. Simulation circuit observing the effect of Si, SiC, and GaN MOSFETs on the performance of the converter

Si, SiC, and GaN-based MOSFETs are used as switching elements of the circuit. The efficiency and output voltage of the system have been analyzed by varying the frequency and pulse period ratio. The results obtained are shown in Figs. 5 to 7. Figure 5 shows how Si, SiC, and GaN MOSFETs affect the efficiency of the converter in the frequency range from 50 kHz to 5Mhz. The graph is shown logarithmically. As seen in Fig. 5, the converter efficiency is highest at 200 kHz. At this frequency, the efficiency of the GaN-based MOSFET is 94%, while the efficiency of the Si and SiC-based MOSFETs are 93.54% and 93.67%, respectively. In addition, the highest efficiency has been obtained at all frequencies when GaN MOSFETs are used. In the next step, the effect of Si, SiC, and GaN MOSFETs on the efficiency of the converter according to the pulse period ratio has been analyzed by keeping 200 kHz. Figures (6,7) show the efficiency and output voltage of the converter according to the pulse period ratio. All MOSFET types have been reached the highest efficiency at 0.5 pulse period ratio.

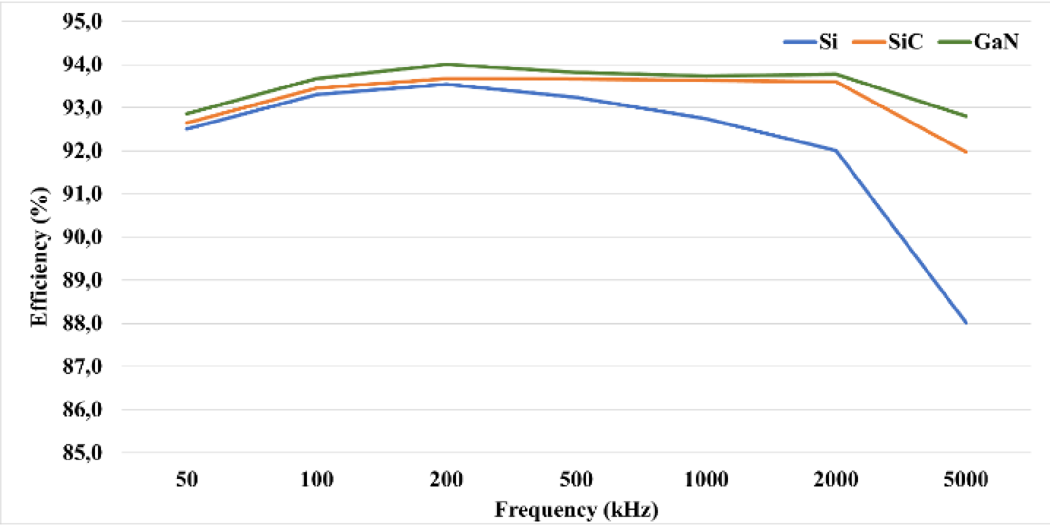

Fig. 5. Effect of Si, SiC, and GaN MOSFETs on converter efficiency according to frequency

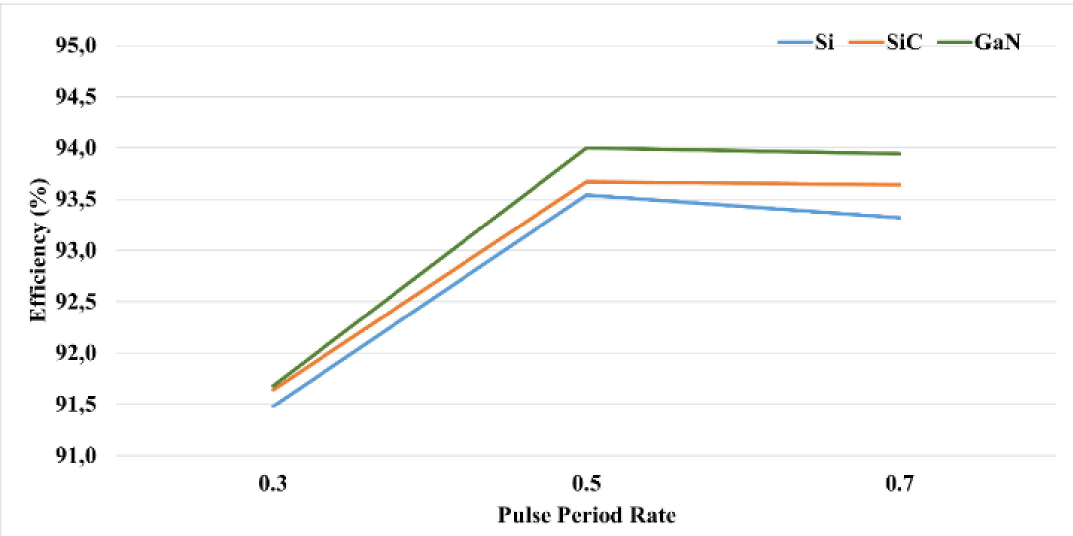

Fig. 6. Effect of Si, SiC and GaN MOSFETs on converter efficiency according to pulse period rate

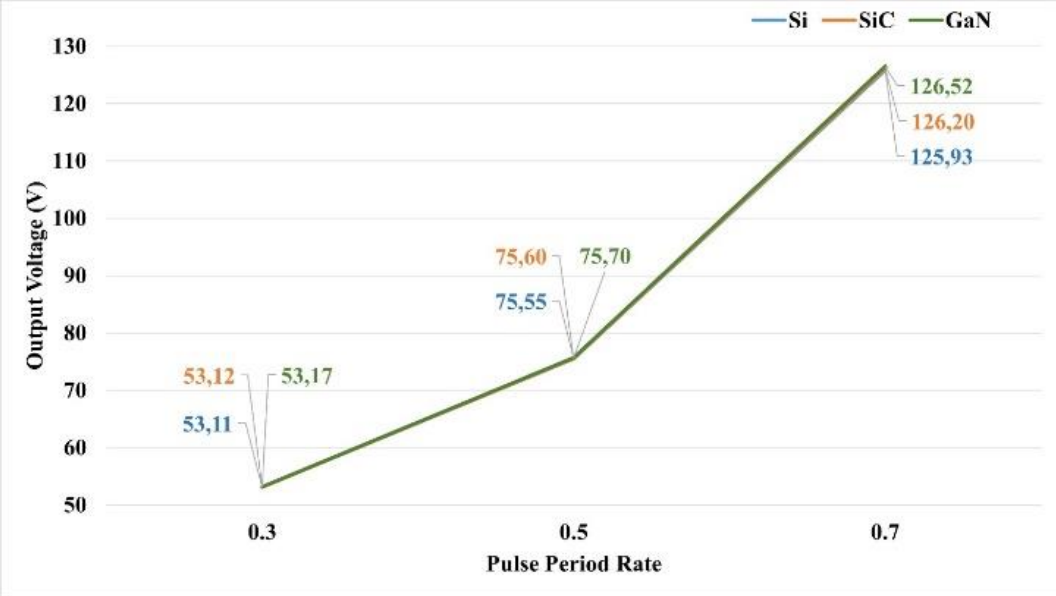

Fig. 7. Effect of Si, SiC and GaN MOSFETs on the output voltage of the converter according to pulse period rate

When Figs. 6 and 7 are evaluated, it is seen that better results are achieved in both converter efficiency and converter output voltage with GaN based MOSFETs. The fact that GaN-based MOSFETs have lower internal resistance and operate in a higher bandwidth compared to other MOSFET types provides high efficiency and relatively high output voltage.

4 Conclusion

In this study, the effects of three different switching elements used in high gain boost converters on converter performance are compared. Si MOSFETs, which are widely used in power electronics applications, and SiC and GaN MOSFETs, which are recent technologies, are chosen as the switching elements to be compared. The selected MOSFETs are tested in a high gain boost converter. For this purpose, the switching frequency of each MOSFET has been varied in the range of 50 kHz-5MHz and the efficiency of the converter has been observed. According to the results, the highest efficiency has been obtained at 200 kHz for all MOSFET types. In the next step, the switching frequency for the converter has been fixed at 200 kHz and the effect of the pulse period ratio on the converter efficiency and output voltage has been investigated. In the designed converter, 94% efficiency and 3.79% voltage gain have been reached by using a GaN based MOSFET with a pulse period ratio of 0.5. For Si and SiC MOSFETs, the efficiency is 93.54% and 93.67%, respectively, and the voltage gain is 3.77 and 3.78, respectively. When the pulse period ratio is 0.7, the efficiency of the converter using GaN based MOSFETs is 93.94% and the voltage gain is 6.33. These values are 93.32 and 6.3% for Si, 93.64 and 6.31% for SiC, respectively. The results revealed that GaN based MOSFETs have higher efficiency and voltage gain than Si and SiC based MOSFETs at all frequencies and pulse period ratios.

References

[1] P. Rajesh, F. H. Shajin, B.N. Kommula, “An efficient integration and control approach to increase the conversion efficiency of high-current low-voltage DC/DC converter”, *Energy Systems,* vol. 13, no. 2, pp. 939–958, 2022.

[2] G. J. Su, “Comparison of Si, SiC, and GaN based Isolation Converters for Onboard Charger Applications”, *2018 IEEE Energy Conversion Congress and Exposition*, vol. 3, pp. 1233–1239, Dec 2018.

[3] S. Naresh, S. Peddapati, M. L. Alghaythi, “A Novel High Quadratic Gain Boost Converter for Fuel Cell Electric Vehicle Applications”, *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 4, no. 2, pp. 637–647, Feb 2023.

[4] A. Dolara, S. Leva, G. Moretti, M. Mussetta, Y. R. Novaes, “Design of a Resonant Converter for a Regenerative Braking System Based on Ultracap Storage for Application in a Formula SAE Single-Seater Electric Racing Car”, *Electronics*, vol. 10, no. 2, pp. 161-166, 2021.

[5] A. Wadsworth, M. G. S. Pearce, D. J. Thrimawithana, “A Cryogenic 3-kW GaN E-HEMT Synchronous Buck Converter”, *IEEE Transactions on Industrial Electronics,* vol. 71, no. 7, pp. 7075-7084, 2023.

[6] W. Zhang, L. Zhang, P. Mao, X Chan, “Analysis of SiC MOSFET Switching Performance and Driving Circuit”, *2018 IEEE International Power Electronics and Application Conference and Exposition*, Dec 2018.

[7] W. Chou, A. Kempitiya, O. Vodyakho, “Reduction of Power Losses of SiC MOSFET Based Power Modules in Automotive Traction Inverter Applications”, *IEEE Transportation and Electrification Conference and Expo*, vol. 28, pp. 1035–1038, Aug 2018.

[8] B. W. Nelson, A. N. Lemmon, B. T. Deboi, M. M. Hossain, H. A. Mantooth, C. D. New, "Computational Efficiency Analysis of SiC MOSFET Models in SPICE: Static Behavior", *IEEE Open Journal of Power Electronics*, vol. 1, pp. 499–512, 2020.

[9] B. Gutierrez, S. S. Kwak, "Cost-effective matrix rectifier operating with hybrid bidirectional switch configuration based on Si IGBTs and SiC MOSFETs", *IEEE Access*, vol. 8, pp. 136828–13684, 2020.

[10] X. K. Li, W. J. Li, B. Liang, G. R. Zhu, M. Xie, X. S. Li, "Research on Performance Comparisons of SiC MOSFET, CoolMOS, and Si MOSFET Based on H-Bridge Double-Sided LCC Resonant Network" *2015 International Conference on Industrial Informatics - Computing Technology, Intelligent Technology, Industrial Information Integration*, vol. 6 pp. 276–280, Jan 2016.

[11] J. Qi, K. Tian, Z. Mao, S Yang, W. Song, M. Yang, "Dynamic performance of 4H-SiC power MOSFETs and Si IGBTs over wide temperature range", *IEEE Applied Power Electronics Conference and Exposition - APEC*, vol. 18, pp. 2712–2716, Apr 2018.

[12] J. Chen, H. Peng, Z. Feng, Y. Kang, "A GaN BCM AC-DC Converter for Sub-1 V Electromagnetic Energy Harvesting with Enhanced Output Power", *IEEE Transactions on Power Electronics,* vol. 36, no. 8, pp. 9285–9299, Aug 2021.

[13] K. S. Kavin, P. Karuvelam, "PV-based Grid Interactive PMBLDC Electric Vehicle with High Gain Interleaved DC-DC SEPIC Converter", *IETE Journal of Research*, vol. 69, no. 7, pp. 4791–4805, Feb 2023.

[14] H. Khalid, S. Mekhilef, M. B. Mubin, M. Seyedmahmoudian, A. Stojcevski, M. Rawa, B. Horan, "Analysis and Design of Series-LC-Switch Capacitor Multistage High Gain DC-DC Boost Converter for Electric Vehicle Applications", *Sustainability*, vol. 14, no. 8, pp. 4495-4519, Apr 2022.

[15] S. Devi and R. Seyezhai, "Comparative analysis of Si, SiC and GaN based quasi impedance source inverter", *Materials Today Proceedings*, vol. 62, pp. 787–792, Jan 2022,

[16] A. A. A. Freitas, F. L. Tofoli, E. M. Sá Júnior, S. Daher, F. L. M. Antunes, "High-voltage gain dc–dc boost converter with coupled inductors for photovoltaic systems", *IET Power Electronics*, vol. 8, no. 10, pp. 1885–1892, 2015.

[17] A. Farakhor, H. Ardi, M. Abapour, "Analysis and design procedure of a novel high voltage gain DC/DC boost converter", *8th Power Electronics, Drive Systems and Technologies Conference*, vol. 24, pp. 454–459, Apr 2017.

[18] F. Roccaforte, P. Fiorenza, G. Greco, R. Lo Nigro, F. Giannazzo, F. Iucolano, M. Saggio, "Emerging trends in wide band gap semiconductors (SiC and GaN) technology for power devices", *Microelectronic Engineering*, vol. 187, pp. 66–77, Feb 2018.

[19] W. Ma, H. Li, S. Yin, X. Pang, D. Chu, "Design of hybrid SiC/Si based T-type three-level LLC resonant converter with wide-input range and low conduction loss for automotive auxiliary power module", *IET Power Electronics*, vol. 16, no. 2, pp. 209–226, Feb 2023.

[20] S. S. Ahmad, C. Urabinahatti, K. N. V. Prasad, G. Narayanan, "High-Switching-Frequency SiC Power Converter for High-Speed Switched Reluctance Machine", *IEEE Transactions on Industry Applications,* vol. 57, no. 6, pp. 6069–6082, Feb 2021.

[21] S. Jr, H. Pereira, A. Cupertino, E. O. Prado, P. C. Bolsi, H. C. Sartori, J. Pinheiro, "An Overview about Si, Super-junction, SiC and GaN Power MOSFET Technologies in Power Electronics Applications", *Energies*, vol. 15, no. 14, pp. 5254, 2022.

[22] M. F. Fatahilah, K. Strempel, F. Yu, S. Vodapally, A. Waag, H. S. Wasisto, "3D GaN nanoarchitecture for field-effect transistors" *Micro and Nano Engineering*, vol. 1, no. 3, pp. 59–81, May 2019.

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