INTERNATIONAL SCIENTIFIC
CONFERENCE
18-19 November 2022, GABROVO

APPLICATION OF SIC AND GAN TRANSISTORS IN HIGH-FREQUENCY INVERTER CIRCUITS FOR INDUCTION HEATING

Petko Stefchov Marinov
Department of Electronics, Faculty of Electrical Engineering and Electronics
Technical University of Gabrovo
4 Hadji Dimitar str., 5300 Gabrovo, Bulgaria
pepimarinov@abv.bg, p.marinov@tugab.bg

Abstract

This paper is about the power semiconductor devices which play a major role in efficient power conversion. As we have Silicon (Si), Silicon Carbide (SiC) and Gallium Nitride (GaN) based power devices. GaN technologies are ideal for working in high-frequency power electronic systems (in MHz). Since the GaN has superior electron mobility and bandgap than the SiC and Si, it has superior characteristics like low conduction losses, high switching rate so that there is better power efficiency than SiC and Si based inverters. This paper is devoted to the application of SiC and GaN transistors in high- frequency inverter circuits for induction heating.

Keywords: Power electronics transistors; Efficiency, SiC; GaN; Wide Bandgap.

I. INTRODUCTION

The majority of power electronic devices has been based on silicon for a number of decades. Silicon is a semiconductor that can be manufactured at a low cost and is practically defect free. The fact that silicon has almost entirely realized its theoretical capability highlights some of its limitations, such as its limited ability to block voltage and its limited potential for heat transfer, as well as its non-negligible conduction losses. Wide bandgap (WBG) semiconductors, including gallium nitride (GaN) and silicon carbide (SiC), outperform silicon in terms of switching frequency, efficiency, operating temperature, and operating voltage.

Gallium Nitride and Silicon Carbide has a bandgap from 3,4(eV) and 3,3(eV) respectively, which is nearly three times higher than that of Silicon, which is equal to 1,1(eV).

This means that more energy is required to excite a valence electron in the conductive band of the semiconductor. While this property limits the use of GaN and Sic in ultra-low voltage applications, it has the advantage of allowing larger breakdown voltages and greater thermal stability at higher temperatures. GaN and SiC greatly increases the efficiency of power conversion stages, serving as a valuable replacement for silicon in the production of high efficiency voltage converters, power MOSFETs and Schottky diodes.

Compared to Silicon, Gallium Nitride and Silicon Carbide allows to obtain important improvements, such as greater energy efficiency, smaller dimensions, lower weight, and lower overall cost.[1]

The purpose of this paper is to compare the losses in high frequency inverter schemes with the selected: Si (JD225005), SiC (SCT2280KE) and GaN (GAN063-650WSAQ) transistors.

TABLE 1. *OVERVIEW OF BANDGAP OF DIFFERRENT TYPE OF SEMICONDUCTORS.[2]*

Material	Chemical Symbol	Bandgap Energy (eV)
Germanium	Ge	0,7
Silicon	Si	1,1
Gallium arsenide	GaAs	1,4
Silicon Carbide	Sic	3,3
Gallium Nitride	GaN	3,4
Gallium Oxide	GaO	4,8
Diamond	C	5,5

WBG benefits include:

- 90% of the power losses that happen during power conversion are eliminated.
- Higher switching frequencies than Si-based devices by up to 10 times.
- Higher maximum operating temperature than Si-based devices.
- Systems with lower overall energy consumption.[1]

II. CASE STUDY

A. FUNCTIONAL DESCRIPTION OF SILICON CARBIDE:

In devices with rated breakdown voltages of 600 V and above, SiC serves as a semiconductor material.

Commercially available SiC Schottky diodes with 600- and 1200-V ratings are considered to be the best way to increase power converter efficiency.

Silicon Carbide (SiC) devices offer advantages in inverters, motor drives, and battery chargers including higher power density, lower cooling demands, and lower overall system costs.

The benefits at the system level, especially at 1,200V, more than cover the increased device cost of a SiC device, although it being more expensive than its silicon analog. The advantages over silicon are negligible at or below 600V. For a SiC die to benefit, highly specialised gate drivers and packaging are required.[2]

In high-power, high-voltage applications where better results, reliability, and power density are crucial factors, Silicon carbide (SiC) provides a number of advantages:

Solar inverters; Welding; Plasma cutters;

- Quick vehicle charges; Oil prospecting.

These are a few examples of industrial applications that benefit from the higher breakdown field strength and improved thermal conductivity that SiC offers over silicon (Si) material.

Advantages of designing in SiC include: SiC diodes have near-zero reverse recovery current; Improved efficiencies and decreased thermal dissipation; Smaller power electronics and system size; Higher power density; Higher operating frequency; Simple parallel operation; Reduced overall system cost.[3]

B. FUNCTIONAL DESCRIPTION OF GALLIUM NITRIDE:

A wide bandgap semiconductor called gallium nitride is quickly replacing silicon as the preferred material for power transistors.[3]

By growing a thin layer of aluminum gallium nitride (AlGaN) on top of a GaN crystal, a strain is created at the interface that induces a compensating two-dimensional electron gas (2DEG). This 2DEG is used to efficiently conduct electrons when an electric field is applied across it. This 2DEG is highly conductive, in part due to the confinement of the electrons to a very small region at the interface. This confinement increases the mobility of electrons from about 1000 cm2/V·s in unstrained GaN to between 1500 and 2000 cm2/V·s in the 2DEG region. This high mobility produces transistors and integrated circuits that feature higher breakdown strength, faster switching speed, higher thermal conductivity and lower on-resistance than comparable silicon solutions.

The leading candidate for taking electronic performance to the next level and a reactivation of positive momentum of Moore's Law is gallium nitride. GaN's ability to conduct electrons more than 1000 times more efficiently than silicon, while being able to be manufactured at a lower cost than silicon has now been well established. Silicon is out of gas, and a new, higher performing semiconductor material is emerging – GaN is on the rise.

Fortunately, the cost to produce a GaN device is inherently lower than the cost to produce a MOSFET device, since GaN devices are produced using standard silicon manufacturing procedures in the same factories that currently produce traditional silicon semiconductors, and the resulting devices are much smaller for the same functional performance. Since the individual devices are much smaller than silicon devices, many more GaN devices can be produced per wafer, thus forming a situation where GaN devices always cost less to manufacture than their silicon counterparts. As GaN technology improves, the cost gap gets even wider.[4]

GaN E-HEMTs* from Gan Systems enable designers to set new norms for efficiency, power density, size, and weight because to their outstanding material qualities and ease of use.

GaN are easy to use because:

- Voltage driven, like MOSFETs;
- True enhancement-mode, normally off;
- Easily driven by Si or GaN-specific gate driver;
- Conventional slew rate control using RG;
- Simple paralleling.

Advantages of designing in GaN include:

- ZERO reverse recovery – Low power loss, high efficiency;
- High switching frequency – Size reduction, high power density;
- Bi-directional conduction – New high efficiency topologies;
- Intrinsically stable paralleling – Broad power range.[3]

The power source is type LSS7.5/200 of the American company LEPEL, built on the basis of a three-phase rectifier, an input pulse regulator and a high-frequency series transistor inverter with self-excitation [6], as shown in the block diagram - fig.1. The input pulse regulator is used to set and change the output power.

In the rectifier, the AC voltage of the supply network is converted into DC, which is fed to the input of the pulse regulator. Through it, the magnitude of the input voltage of the bridge inverter is adjusted, thereby adjusting the output power.

Fig. 1 shows the power circuit of the inverter - implemented in a bridge circuit with four MOSFET transistors. A separating transformer is included in the diagonal of the inverter, which also serves to match the parameters of the load with those of the bridge inverter. Transformer TR1 has six secondary windings which are switched by the TAP SWITCH. In this way, the load impedance can be matched to the inverter output. In addition, there is the option of adding capacitors to the high-frequency capacitor bank in the secondary winding of the transformer.

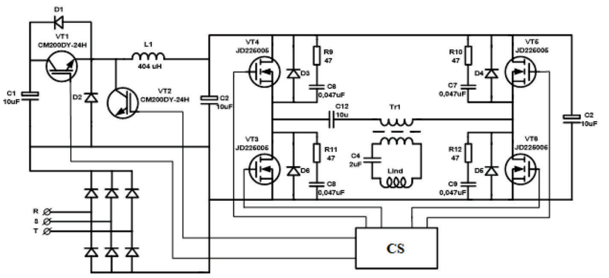

***Fig. 1.** Principle schematic of the transistor inverter of Lepel LSS7.5 with transistors JD225005*

- The maximum power of the scheme is 7.5kW.
- Maximum operating frequency 200kHz,
- Maximum output voltage on the primary side of the transformer – 450V.
- Maximum current on the primary side of the transformer – 37A.

For the correct setting, it is necessary to establish the range of variation of the equivalent parameters of the load.

According to the obtained simulation results and the done modeling of the inductor-detail system, according to the methodology described in [1], an inductor was constructed.

The results of the performed simulations are compared with the experimental data, reporting a coincidence of the results with an accuracy of 10%.

Experimental studies were carried out in the brazing of hard alloy plates with the largest part size. The operation of the inverter is reflected by oscillograms at several control points. The voltage of the circular capacitor C4 is shown in Fig. 2, with a load - a tool of the largest dimensions.

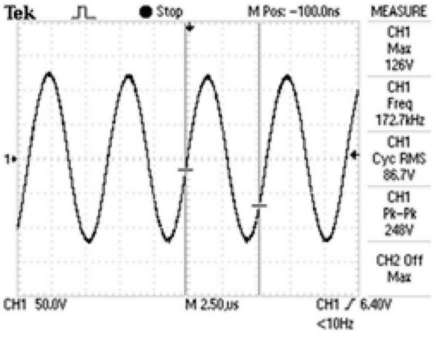

***Fig. 2.** Oscillogram of voltage UC4*

Figure. 2 shows the voltage of C4 obtained as a result of the simulations. It can be seen that in both cases its value does not exceed the maximum allowable effective capacitor voltage of 200V.

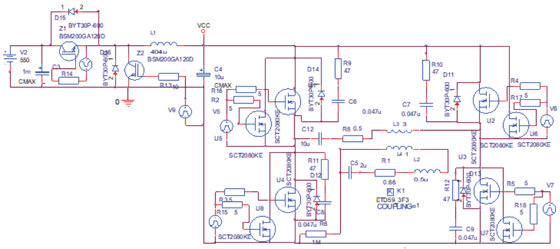

***Fig. 3.** Principle schematic of the transistor inverter of Lepel LSS7.5 with SiC transistors SCT2280KE*

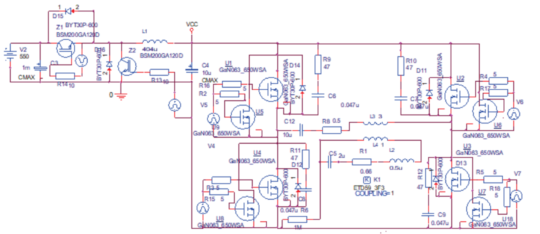

***Fig. 4.** Principle schematic of the transistor inverter of Lepel LSS7.5 with SiC transistors GAN063-650WSAQ*

III. NUMERICAL RESULTS

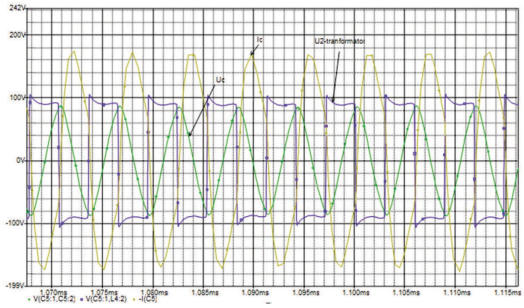

***Fig. 5.** Oscillogram of voltage Uc4, current Ic4 and secondary voltage of transformer Tr.2 with JD225005 transistors*

The comparison of the data from oscillograms 5, 6 and 7 show that after the change of the element base of the inverter - its characteristics have not changed.

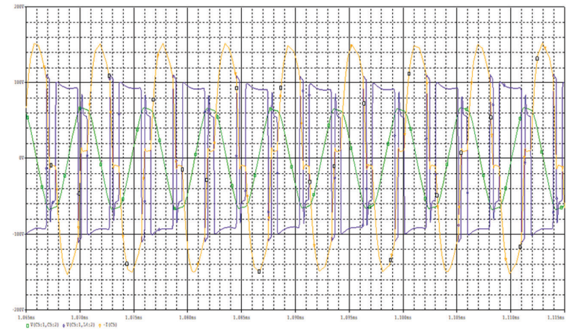

***Fig. 6.** Oscillogram of voltage Uc4, current Ic4 and secondary voltage of transformer Tr.2 with SCT2280KE transistors*

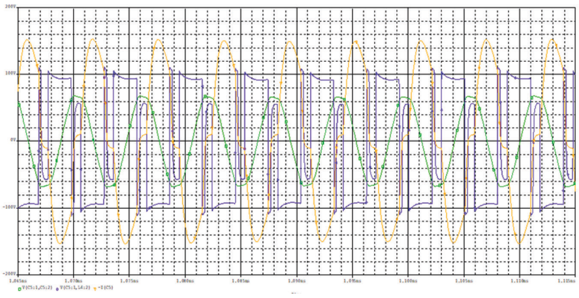

***Fig. 7.** Oscillogram of voltage Uc4, current Ic4 and secondary voltage of transformer Tr.2 with GAN063-650WSAQ transistors*

On fig. 8. the voltage oscillogram of transistor VT3 in the bridge series inverter is shown.

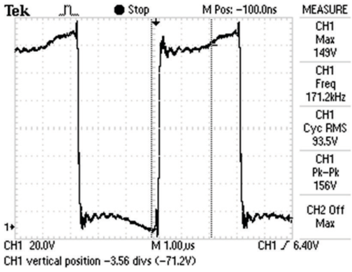

***Fig. 8.** Voltage on transistor VT3*

Fig. 8 matches with the shown of fig. 9. the results of the current and voltage simulation of the same transistor – VT3 are shown. The resonant nature of the current in the circuit can be seen, as well as the type of commutation. The transistor turns on at zero current and turns off at zero voltage. The cut-off voltage is determined by the voltage drop across the reverse-connected diode D4.

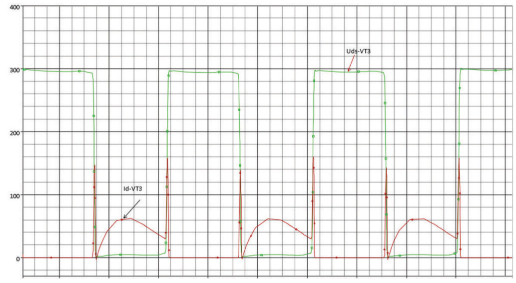

Fig. 9. *Current and voltage simulation of VT3 with JD225005 transistors*

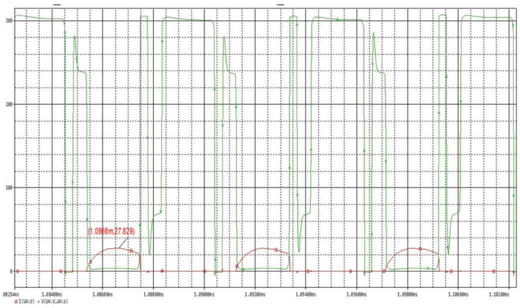

Fig.10. *Current and voltage simulation of VT3 with SCT2280KE transistors*

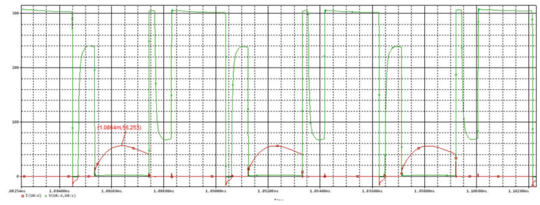

Fig.11. *Current and voltage simulation of VT3 with GAN063-650WSAQ transistors*

The obtained results described on fig. 9, 10 and 11 shows a coincidence of the voltage and current with those of the experimental operation of the generator. The power does not exceed the maximum permissible of 7.5kW. The operating frequency in the simulations also corresponds to the experimentally measured one with a value of 170kHz.

The agreement of the simulation results and the experimental work for the designed inductor shows the adequacy of the selected models.

The results of the simulations, at a translation ratio of the high-frequency transformer of 5:1, are shown on Fig. 12.

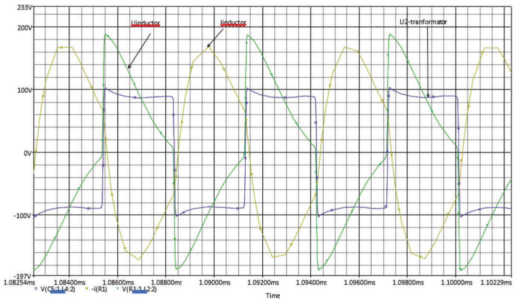

Fig. 12. *HF transformer voltage with 5:1 ratio with Si transistors type: (JD225005)/ixfk55n50/*

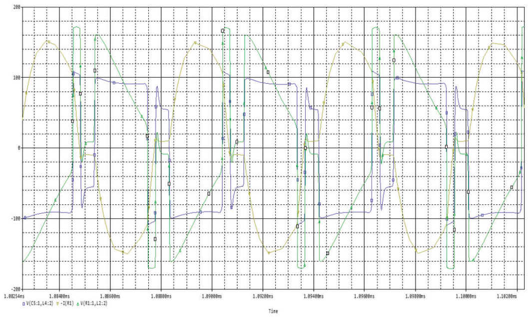

Fig. 13. *HF transformer voltage with 5:1 ratio with SiC transistors type: (SCT2280KE)/*

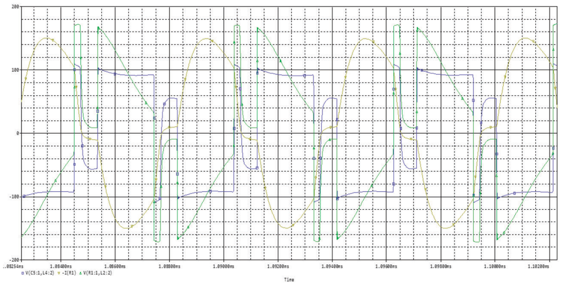

Fig. 14. *HF transformer voltage with 5:1 ratio with GaN transistors type: (GAN063-650WSAQ)*

Figures 12, 13, 14 summarize the simulation results of the 3 types of transistors. They have the same readings, regardless of the type of semiconductor used.

An experimental study of the performance of the different types of transistors has been made, and the major characteristics are described in the table below:

TABLE 2. CHARACTERISTICS OF THE USED TRANSISTORS

Semiconductor	**Si**	**SiC**	**GaN**
Characteristics	**JD225005**	**SCT2280KE**	**GAN063-650WSAQ**
Junction Temperature, Tj	-40 up to 150 °C	175 °C	-55 up to 175 °C
Storage Temperature, Tstg	-40 up to 150 °C	-55 up to 175 °C	-55 up to 175 °C
Drain Source Voltage, VDss	450/500 V	1200V	650 V
Gate-Source Voltage, VGss	± 20 V	-10 to 26 V	± 40 V
Continuous Drain Current, ID	50 A	35 A	34.5 A
RDs(on)	0.32Ω	280mΩ	60mΩ
Power Dissipation, Pt	310 W	108 W	143 W

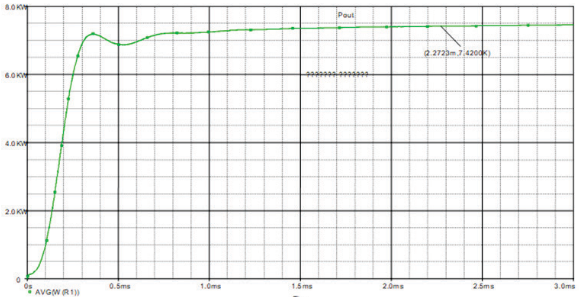

Fig. 15. *Output power simulation of LEPEL LSS7.5/200 with JD225005 transistors*

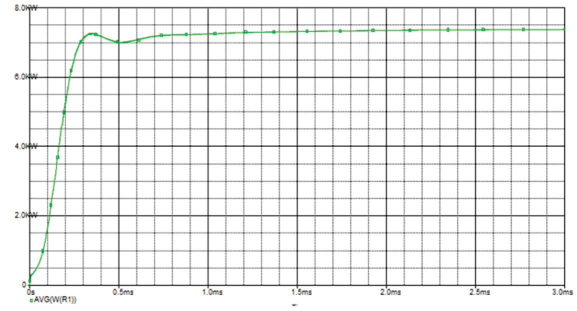

Fig. 16. *Output power simulation of LEPEL LSS7.5/200 with SCT2280KE transistors*

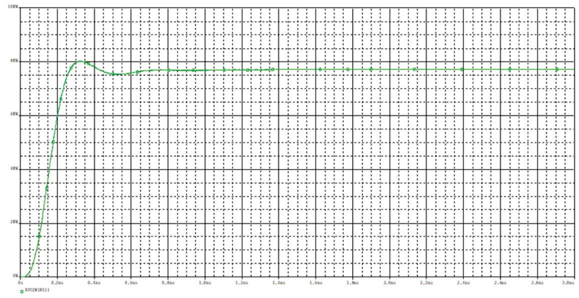

Fig. 17. *Output power simulation of LEPEL LSS7.5/200 with GAN063-650WSAQ transistor*

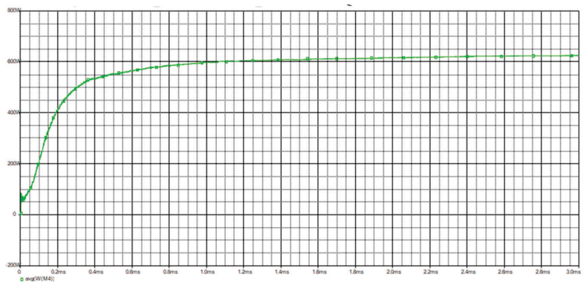

Fig.18. *Losses in the Si transistor type: JD225005*

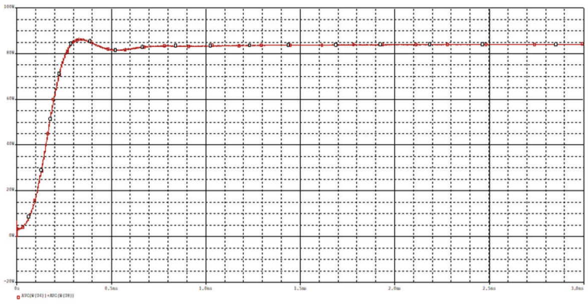

Fig.19. *Losses in the SiC transistor type: SCT2280KE*

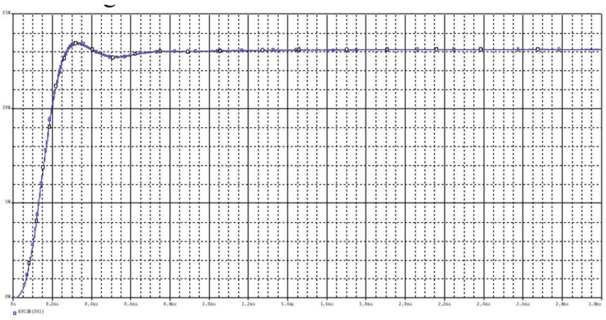

Fig. 20. *Losses in the GaN transistor type: GAN063-650WSAQ*

TABLE 3. LOSSES IN THE TRANSISTORS

	Type of the transistor	Losses of the transistor PVT [W]	Pdiss	Efficiency
1	Si	615	P_{diss} =4. P_{VT}	2460
2	SiC	86	P_{diss} =8. P_{VT}	688
3	GaN	14.5	P_{diss} =8. P_{VT}	116

Table 3 shows and summarizes the transistor losses and their efficiency.

The following formulas were used:

$$Pdiss = 4.\ PVT \tag{1}$$

$$Pdiss = 8.\ PVT \tag{2}$$

The inverter efficiency is calculated with the following equations:

$$Si = \frac{POUT}{(POUT+PDISS)} = \frac{7500}{(7500+2460)} = \frac{7500}{9960} = 0.753 \times 100 = 75.3\%$$

$$SiC = \frac{POUT}{(POUT+PDISS)} = \frac{7500}{(7500+688)} = \frac{7500}{8188} = 0.9159 \times 100 = 91.59\%$$

$$GaN = \frac{POUT}{(POUT+PDISS)} = \frac{7500}{(7500+166)} = \frac{7500}{7616} = 0.9847 \times 100 = 98.47\%$$

The following formulas were used:

$$Efficiency = P_{OUT}/(P_{OUT}+P_{DISS}) \tag{3}$$

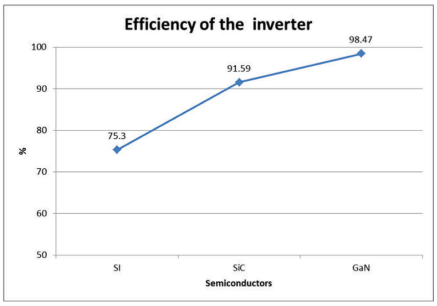

Fig. 21. *Efficiency graph of the three of inverters with the three types transistors*

Fig. 21 shows that the inverter with GAN transistors has the highest efficiency.

TABLE 4. MAXIMUM TRANSISTORS LOAD

Maximum transistor load				
	Type of the transistor	**Losses of the transistor PVT [W]**	**Power Dissipation by catalogue [W]**	**Results [%]**
1	Si	615	310	99.19
2	SiC	86	108	79.6
3	GaN	14.5	143	10.14

Table 4 shows and summarizes the maximum transistor load and the result in %.

The following formulas were used:

PVT/Pt (by catalogue) (4).

The maximum transistors load is calculated with the following equations:

$$\text{Si} = \frac{\textit{Losses in the transistor}}{\textit{Dissipated power by catalogue}} = \frac{615}{310*2} = \frac{615}{620} = 0.9919 * 100 = 99.19\ \%$$

$$\text{SiC} = \frac{\textit{Losses in the transistor}}{\textit{Dissipated power by catalogue}} = \frac{86}{108} = 0.796 * 100 = 79.6\%$$

$$\text{GaN} = \frac{\textit{Losses in the transistor}}{\textit{Dissipated power by catalogue}} = \frac{14.5}{143} = 0.10139 * 100 = 10.14\%$$

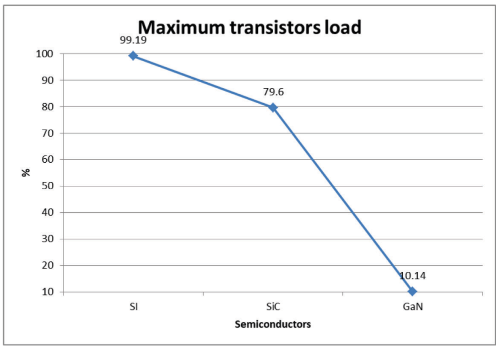

Fig. 22. *Efficiency graph of the three of inverters with the three types transistors*

Fig. 22 shows that Si transistor type: JD225005 has the largest maximum transistor load. This means that it will defect. This transistor cannot operate at maximum power for an extended period of time. The GaN transistor type: GAN063-650WSAQ is least loaded.

CONCLUSION

This paper has investigated a circuit that is simulated on PSpice TI and has used real models of the transistors in it.

A comparison of the output power, efficiency, operating points and maximum transistors load was made. What became clear is that the highest efficiency has been achieved with the transistors based on GaN.

The faster switching capability of the new generation of transistors on the basis of SiC and GaN has a significant effect on increasing the efficiency of the high frequency inverters.

As it is having been demonstrated in this paper, the efficiency of the inverter is improved with the same load.

Real experiments with this circuit and transistors based on GaN and SiC are forthcoming.

ACKNOWLEDGMENT

The authors would like to thank to all reviewers for their advices and suggestions on improving this paper.

The present paper has been prepared in connection with implementation of contract №2102У/21.03.2022, "Development of an electric car" of UCRT (University Center for Research and Technology) at Technical University of Gabrovo.

REFERENCES

[1] “10 Things to know about GaN”, https://www.powerelectronicsnews.com.

[2]“The great semi debate: SiC or GaN”, https://www.electronicdesign.com/power-management .

[3] GaN & SiC Technologies for Power Electronics, RichardsonRPFD, June 2021.

[4] “What is Gallium Nitride (GaN), epc-co.com.

[5] Dankov D., "Modeling and research of the inductor-part system in induction soldering", Unitech'09, Gabrovo, Bulgaria.

[6] Blau D., T. Hussey “Product Spotlight: LSS Series Power Supplies Offer Superior Performance in a Compact Pack-age”. Lepel Inc. – Hot topics in Newsletter, Vol. 1, No. 3, October 1995.