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Analysis of GaNbased BLDC Motor Drive for Automotive Application

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***Abstract*— Automotive industry is quickly changing from IC engine to electrification. High torque to weight ratio and simple control are characteristics of BLDC motor making it popular in the field of e-vehicle. In this paper switching loss calculation of three kilowatt GaN based BLDC drive for electric vehicle is in focus. Gallium-nitride based power transistor is used to reduce switching losses in BLDC drive inverter.**

Design of inverter at higher frequencies with improved power density and efficiency as compared to traditional Si devices is become possible due to gallium nitride semiconductor-based device. In this paper description ofGaN based BLDC drive introduce, then commercially available GaN devices compared with Si MOSFET of same rating followed by selection of proper GaN device for BLDC inverter. Closed loop PSIM simulation of BLDC has been carried out in this paper. Switching losses analytically calculated and then compared with SPICE simulation losses.

Keywords— ***BLDC drive, three phase inverter, GaN devices, Switching losses, Si MOSFET.***

I. INTRODUCTION

Nowadays, Electric vehicles (EVs) are in focus because of its capabilities of avoiding pollution and fuel resource crunch. India consist of 14 of the world's 20 most polluted cities, it's in the greatest interests of the India to move towards electrification. The government of India set a goal of having 32% electric vehicle on its roads by 2030. If India achieve this then, we might just save the country from its pollution problem. Energy consumption increment leads to efforts from government and user to reduce losses in power converters.

Wide band gap semiconductor devices have higher blocking voltage and high switching frequencies. These devices have low on state resistance and output capacitance thus conduction and switching losses will be less.

Rapid development in wide band gap devices support use of GaN devices as the main switch in the high power (>10kW) converters. A 10kW GaN-Based inverter is developed with 98.8% peak efficiency and 0.7-liter box volume. High efficiency achievement is depending on proper selection of critical component [1]. There are vertical and lateral GaN devices available commercially. characteristics and commercial status of both vertical and lateral GaN power devices must be studied for selection of suitable power switch during converter design [2]. Increasing switching frequency in converter leads to reduction of size of overall system. Double pulse test on Half bridge structure is useful for dynamic characterization of GaN power devices [3]. There are many advantages of high frequency PWM in motor drive application. Fast control response, high efficiency, lower motor torque ripple are few advantages [4]. for fast speed electrical drive applications where the more switching frequencies permitted using GaN decreases the rotor losses inof high-speed permanent-magnet electric machines [10].

GaN devices will help many applications such as electric vehicles,aerospace, power inverters and industrial motor drives. The losses of power inverter reduced using GaN devices which further helps in thermal management aspects [5]. Using GaN-based Gate Injection Transistors, 99.3% efficiency of Three-Phase Inverter for Motor Drive achieved in [6].

GaN devices that are likely to be used in automotive applications are required to work at high temperatures and run withlarge current. The simulation of drive circuitry must be done when they are used in high-power circuits along with GaN transistor[7]. Due to the high dvDS/dt and small gate source capacitances in grouping with modest drain-gate feed-back capacitances cross conduction in GaN HFETs is naturally critical. Switching frequency is limited due to cross conduction phenomenon in converters, cross conduction can be avoided by, lower turn-off gate driver voltage level which also minimize the total device losses [8]. Due to improvements in switching frequencies and low parasitic packaging like Line grid array (LGA) package provided by eGaN FETs, layout of the printed circuit board (PCB) becomes critical to converter performance [9].

Wide band gap semiconductor devices have higher blocking voltage and high switching frequencies. These devices have low on state resistance and output capacitance thus conduction and switching losses will be less. The gallium nitride (GaN) semiconductor is one of the best replacements for the existing silicon technology due to its excellent material properties. Gallium Nitride (GaN) has a future in a wide area of power electronic applications.

As GaN is recently developed technology research done in area of GaN is limited in the literature. There is need of more research in this area. The objective of this paper is to analyze the performance of GaN devices as switch in BLDC drive application. Comparison between traditional Si device-based drive and GaN devices-based drive has been done in this work. Gallium Nitride (GaN) innovation is being received in an assortment of energy electronic applications because of their high efficiency even at high switching speeds. In the last few years, gallium nitride (GaN) and silicon carbide (SiC) have been receiving much attention. Also, SiC and GaN semiconductors are commonly attributed as compound semiconductors because they are comprised of multiple elements from different groups in the periodic table. These materials have challenged the long-held dominance of silicon. GaN and SiC have a wide band gap as compared to Si. The critical electric field or breakdown field of GaN and SiC is an order of magnitude higher than that of Si. These WBG materials can withstand high operating temperatures, high frequencies, and higher voltages leading to much efficient power conversion systems. Because of these characteristics, the electronic devices can be made with low power losses and are smaller in size as compared to the present-day technology.

GaN devices, the best alternative to Si, can switch at high frequencies with low power losses and as a result can achieve high efficiency. High frequency operation to achieve high bandwidth reduces the size. of passive components making it far easier to make compact electronic circuits. With the excellent properties such as wider band gap, high breakdown voltage, higher breakdown electric field, and higher electron mobility, GaN devices can operate at higher voltages and high switching frequencies. In addition, GaN material has high electron saturation velocity. This property allows the GaN based devices to operate at much higher speeds. Also, GaN power transistors help lessen the losses due to conduction and switching, hence operating a higher efficiency. The foremost application area of GaN power devices are power electronic converters and radio-frequency power amplifiers

In this paper section II will provide details of component selection. In section III we will discuss analytical switching power loss calculation of GaN devices. Simulation and comparison of switching loss of GaN devices and Si Mosfet will be carried out in section IV. In section V, brief conclusion is drawn.

II. Power Device Selections for Comparison

In this section commercially available GaN devices compared with Si MOSFETs. The power devices, which are selected for the performance comparison, are EPC2022 GaN by EPC, GS61008P GaN by GaN System and SiDR668DP Si MOSFET by Vishay. The datasheet comparison of power transistors shown in Table 1.

TABLE I. THE DATASHEET COMPARISON OF POWER TRANSISTORS

TYPE	**GaN**	**GaN**	**MOSFET**
Part number	EPC2022	GS61008	BSC047N08NS3 G
Voltage rating VDS	100V	100V	80V
Current rating ID (Continuous)	90 A	90A	100A
On-state resistance RDSon (Max)	3.2mΩ	7mΩ	4.5 mΩ
Total gate charge Qg (Max)	13nC	12nC	51nC

From datasheet comparison it is found that on state resistance is minimum for EPC2022 GaN device. As conduction losses depends on on-state resistance EPC2022 have less losses. Whereas total gate charge of EPC2022 and GS61008 is nearly equal. It observed that Si MOSFET have four time more total gate charge as compared to GaN devices.

Primarily, like silicon transistors, the GaN devices can also be categorized into (a) depletion mode (d-mode) and (b) enhancement mode (e-mode). While, the basic functions of the two modes remain the same, few critical differences exist in terms of the channel formation, reverse currents, and the electrical characteristics. In the case of Si transistors, the channel required for the flow of electrons between the source and the drain terminals is created by application of electric field at the gate terminal. Consequently, by applying a positive charge at the drain terminal, the electrons are attracted towards the drain, while the holes (or actual current) move towards the source terminal. In short, the width of the channel as well as its length is determined by the applied electric field. The main reason for such transistors to be termed as field-effect transistors. In GaN devices, the channel is formed in the form of a 2-dimensional electron gas (2DEG) layer. The 2DEG conduction layer is created due to the structural abnormalities, which results in the charge generation. The hexagonal structure of gallium nitride leads to high conductivity. Strain is caused at the interface, when a thin layer of aluminum-gallium nitride (AlGaN) is grown on the GaN crystal. Application of electrical field at the interface induces a dense electron gas. This is called 2-dimensional electron gas (2DEG). The strain at the GaN/AlGaN junction decides the number of electrons in the gas. Large number of electrons collect near the interface of the GaN and AlGaN because of which the electron mobility is very high near the interface. This is the basis of high conductivity of GaN.

III. Switching Loss Calculation of GaN Devices

In this work we calculated switching losses for EPC2022 used in 48 volt 3 kilowatt three phase inverter for BLDC drive. In drive operating condition for single device is bus voltage (VDS) equals to 48 volt, drain to source current (IDS) equals to 21.7 amperes, switching frequency (fsw) equals to 7.27 kilohertz’s and on state gate resistances are (Rgon) equals to 7 ohm , off state gate resistances (Rgoff) equals to 4ohm.

TABLE II. DEFINITIONS OF TERMS USED IN SWITCHING LOSS ANALYSIS

Terms	**Definitions**
Vth	Gate threshold voltage (at QGS1)
V_{DR}	Gate driver on-state output voltage
Vpl	Gate plateau voltage (at QGD)
Vpl(op)	Plateau voltage at the operating condition current
Pon	Power losses during turn-on switching transition
Poff	Power losses during the turn-off switching transition
P_{SW}	Total power losses due to switching transitions
Q_{GS}	Charge required to increase gate voltage to the plateau voltage

Q_{GD}	Charge required into the gate to change the drain voltage down from the blocking state to near zero.
Q_G	Total gate charge required to drive a device from zero to rated gate voltage (fully enhanced)

The switching power loss calculated graphically from Fig.1, by summing the voltage transition power losses (PVt) and the current transition power losses (PCt) using the following equation.

$$\mathrm{Psw} = \mathrm{PVt} + \mathrm{PCt} \quad (1)$$

$$\mathrm{Psw} = 1/2 * VBUS * \mathrm{IL} * (\mathrm{txR} + \mathrm{txF}) * \mathrm{fsw} \quad (2)$$

Where txR and txF are the switching transition times as shown in Fig. 1.

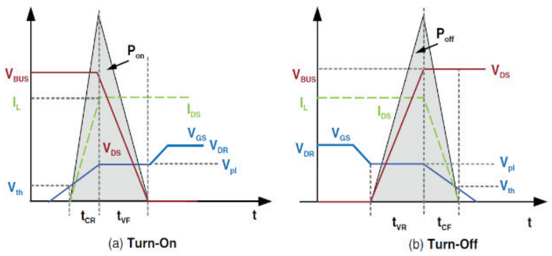

Fig. 1. Idealized switching waveforms used for calculating switching loss (a) turn-on (b) turn-off [12].

In general, QGS1 can be calculated using Equation

$$\mathrm{QGS1} = (\mathrm{QGS} \div \mathrm{Vpl}) \times \mathrm{Vth} \quad (3)$$

$$\mathrm{QGS1} = (3.4 \div 2.3) \times 1.4 = 2.069\ \mathrm{nC}$$

Where QGS1 is charge required to increase gate voltage from zero to the stated threshold voltage of the device. QGS and Vth is given in datasheet and Vpl can be found from curve given in datasheet.

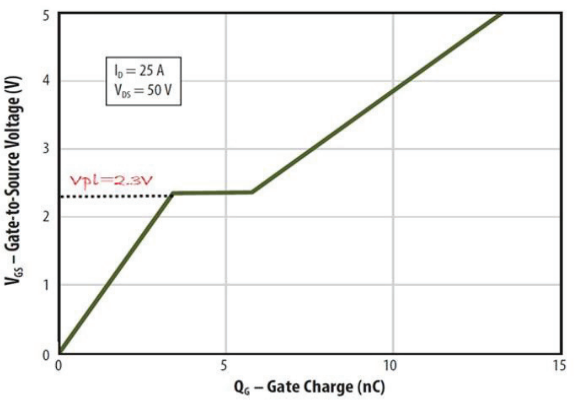

Fig. 2. Impact of gate charge on the gate plateau voltage for EPC2022 [11]

The QGS(op), which is the QGS at the operating value of I_{DS}, can also be calculated for the operating conditions by reading off the plateau voltage Vpl(op) from the transfer characteristic given in datasheet of device.

$$\mathrm{QGS(op)} = (\mathrm{QGS} \,/\, \mathrm{Vpl}) \times \mathrm{Vpl(op)} \quad (4)$$

$$\mathrm{QGS(op)} = (3.4 \div 2.3) \times 2.4 = 3.547\ \mathrm{nC}$$

With QGS(op) and QGS1 determined, QSG2 can be calculated using (5),

$$\mathrm{QGS2} = \mathrm{QGS(op)} - (\mathrm{QGS1}) \quad (5)$$

$$\mathrm{QGS2} = 3.574 - 2.069 = 1.4788\ \mathrm{nC}$$

Where QGS2 is Charge required to increase gate voltage from the stated threshold voltage of the device to the plateau voltage

The total device turn-on loss then can be determined using (6).

$$\mathrm{Pon} = \mathrm{PVt} + \mathrm{PCt} \quad (6)$$

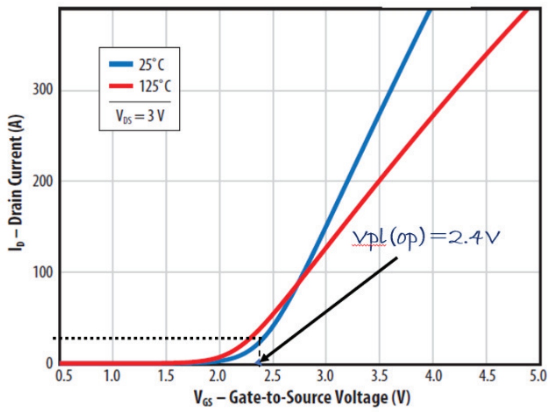

Fig. 3. Impact of drain current vs Gate to Source voltage [11]

$$\mathrm{Pon} = 0.5 \times \mathrm{VBUS} \times \mathrm{IDS} \times \mathrm{fsw} \times \mathrm{RGon} \times \{[(QGD/(VDR - Vpl))] + [(QGS2 \,/\, (VDR - (0.5(Vpl + Vth))]\}$$

$$\mathrm{Pon} = 0.5 \times 48 \times 21.7 \times 7.27 \times 15 \times \{[(2.4/(5 - 2.4))] + [(1.4788 \,/\, (5 - (0.5(2.4 + 1.4))] = 26503.512 \times (0.9230 + 0.4770) = 79.5\ mW \quad (7)$$

The total turn-off power loss (Poff) can be determined using Equation

$$\mathrm{Poff} = 0.5 \times \mathrm{VBUS} \times \mathrm{IDS} \times \mathrm{fsw} \times \mathrm{RGoff} \times \{[(QGD/(Vpl))] + [(QGS2 \,/\, (0.5(Vpl + Vth))]\}$$

$$\mathrm{Poff} = 0.5 \times 48 \times 21.7 \times 7.27 \times 4 \times \{[(2.4/(2.4)) + [(1.4788 \,/\, (0.5(2.3 + 1.4))]\}{=}15144.86{\times}\ (1 + 0.7993) = 27.25\ \mathrm{mW} \quad (8)$$

The total switching losses can now be summarized as the sum of Pon and Poff:

$$\mathrm{Psw} = \mathrm{Pon} + \mathrm{Poff} = 79.5 + 27.25 = 107\mathrm{mw} \quad (9)$$

Total power losses for epc2022 device calculated in (9) using analytical loss calculation method. Separation between switching losses shown in Fig.4.

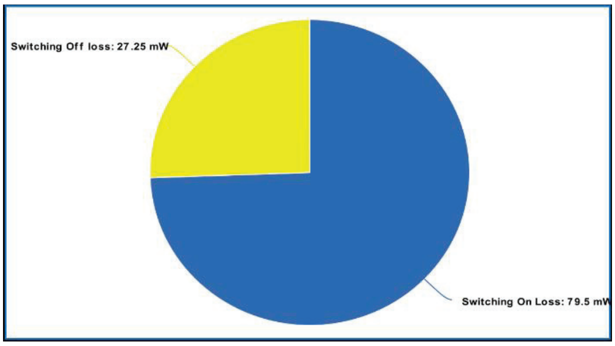

Fig.4. Total switching losses division

IV. Simulation and Comparison of Switching Losses

In this work we used half bridge topology to perform the double pulse test. To find out switching losses of different GaNFET and MOSFET devices double pulse test suggested in literature [3].

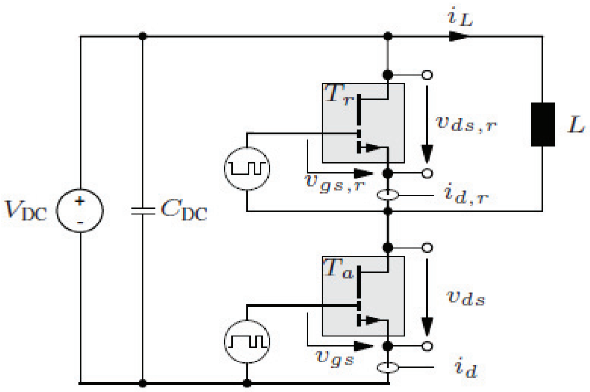

Fig. 5. Double Pulse Test Setup [10]

A half bridge double pulse test circuit in LtSpice is introduced and switching losses were simulated and compared for three devices. In this test we create same operating condition of bridge as in BLDC drive. In simulation drain to source voltage is 48volt, drain current through device is equals to 21.7 amperes and switching frequency is 7.27kilohertz. Gate resistances used are RGON=10ohm, RGOFF=20ohm. Conceptual circuit of double pulse test is shown Fig. 5. Results of double pulse test for EPC2022, GS61008 and BSC047N08NS3G is shown in Fig. 6-11.

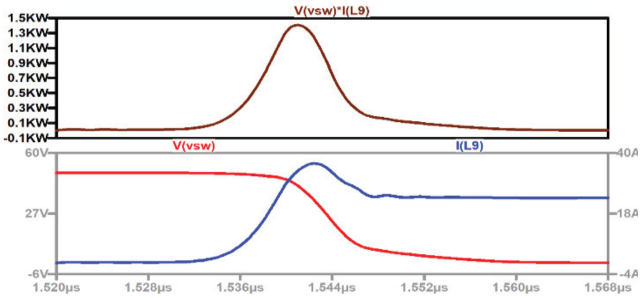

Fig. 6. Turn on losses of EPC2022 equals to 10.4 microjoules

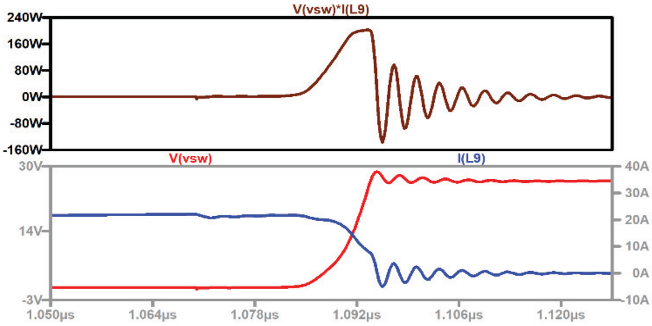

Fig. 7. Turn off losses of EPC2022 equals to 3.09 microjoules

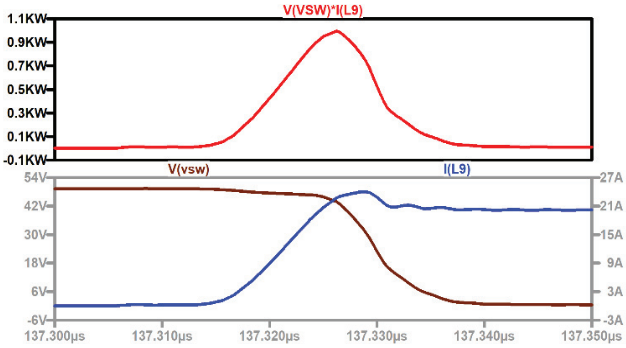

Fig. 8. Turn on losses of GS61008 equals to 10.7 microjoules

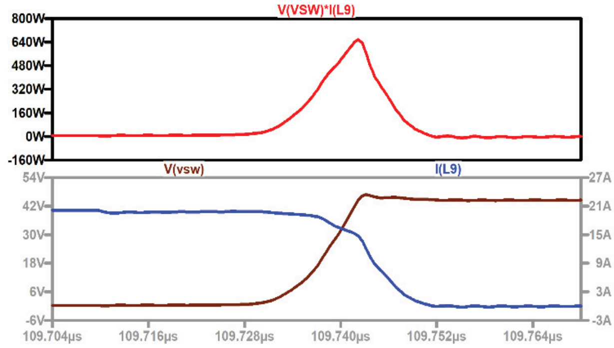

Fig. 9. Turn off losses of GS61008 equals to 5.9 microjoules

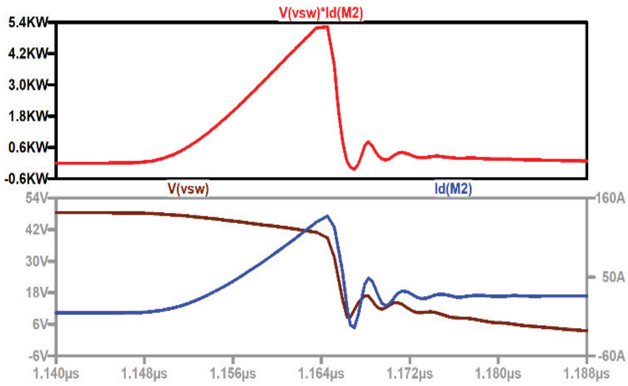

Fig. 10. Turn on losses of BSC047N08 equals to 47.7 microjoules

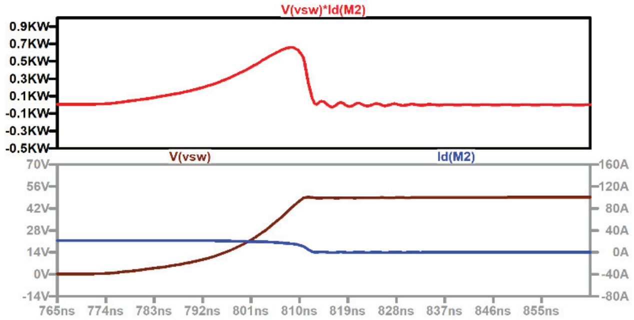

Fig. 11. Turn on losses of BSC047N08 equals to 10.6 microjoule.

Comparison of switching losses in ltspice table shows that total switching losses near about three times less in GaN FET. Less losses means less heat generation hence reduction in cooling requirement which reduce size and cost of system. Also, it is found that from Comparison of analytical and simulation losses that for low gate resistance analytical and simulation losses are nearly equal. With increase in gate resistances analytical losses increase linearly proportional but in simulation there is no significant effect of increasing gate resistances because nonlinear properties of SPICE model.

TABLE III. COMPARISON OF SWITCHING LOSSES IN LTSPICE

TYPE	**GANFET**	**GANFET**	**MOSFET**
PART NUMBER	EPC2022	GS61008	BSC047N08NS3 G
SWITCH ON LOSSES	10.49 uJ	10.7 uJ	39 uJ
SWITCH OFF LOSSES	3.08 uJ	5.9 uJ	7.5 uJ
TOTAL SWITCHING LOSSES	13.57 uJ	16.6 uJ	46.2 uJ

Material properties like carrier concentration, mobility, specific on resistance compared with silicon (Si) and silicon carbide (SiC). Comparison of switching speeds with Silicon, Silicon carbide and Gallium Nitride. In the Silicon MOSFET channel formed between source and drain due to electron hole pair but in Gallium nitride (GaN) channel formation occur due to 2-dimensional electron gas which is controlled by gate potential. GaN FETs are also called as High Electron mobility transistor due to their high electron density. GaNFET also operates in enhancement and depletion mode. Gallium Nitride devices used for energy efficiency and low power loss. Nowadays in all sector Gallium Nitride FET are widely used.

V. Conclusion

In this work analysis and comparison of switching characteristics of GaNFETs and Si MOSFETs has been done for BLDC drive application in automobile sector. Datasheet based switching loss calculation performed in this paper. The analysis of switching characteristics of shows that switching losses of GaNFETs are less than Si MOSFET. Double pulse test method for switching characterization is used in the SPICE simulation. This work shows that there is bright future of GaN devices in high frequency motor drive for automotive application.

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