SiC and Silicon MOSFET solution for high frequency DC-AC converters

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Abstract

In this paper, electrical and thermal comparison analyses are performed in Multichannel Voltage Source DC/AC converter in charge of supplying several loads with AC sinusoidal waveforms, as required by oncoming latest power applications. A comparison with silicon device’s state of art is made: electrical and thermal performances of main 650V transistors families (2nd Generation 650V SiC MOSFET devices and MDmesh M5 650V Silicon MOSFETs) are evaluated where the new 650V SiC MOSFET device is in used as switch in the inverter high frequency leg and the 650V silicon MOSFETs are used as switches in the inverter line frequency leg.

The right combination of SiC and Silicon MOSFETs switches will be proposed increasing the system efficiency giving to the market a super green energy saving solution

1. Introduction

SiC is a semiconductor permitting devices to operate at much higher voltages, frequencies and temperature than conventional semiconductor materials. From the past years using silicon MOSFETs in the 600V range in hard-switching DC-AC converters is quite uncommon, as a consequence of the intrinsic diode poor performance, which is integral part of the MOSFET structure. In the 600V range IGBTs are massively used in inverter applications, even if with some big limitations inherent to the switching frequency. Hence SiC MOSFET is the first device facing the challenge to switch in very high voltage, very high frequency and high power DC-AC converters, irrespectively of the final application ranging from Motor Drive to UPS and PV systems. In fact wide-bandgap semiconductors have almost ideal behavior in terms of reverse recovery and allows bidirectional current flow differently than IGBTs, even if the static drop exhibited when current direction is inverted during OFF time can be much higher than silicon based devices. Thus DC voltage levels up to 950V in a frequency range extended up to 200kHz make critical dead time choice and some special care must be taken in order to minimize the impact of the SiC MOSFET intrinsic diode static performance.

At the same time silicon MOSFETs technologies allow to achieve in a cost-effective way very low $R_{DS(on)}$ values in a single package, thus making highly appealing “hybrid” solutions tailored to properly mix silicon and SiC devices. In fact, thanks to appropriate modulating strategies based on not unique switching frequency and/or soohisticated PWM pattern, a combination of standard silicon and latest advanced SiC MOSFET families can offer the best trade-off among efficiency, cost, compactness and reliability.

Fig. 1. SiC MOSFET structure
2. Multi-output mixed frequency DC-AC voltage fed converter

2.1. Mixed technology approach

In some modern applications several AC loads must be supplied, in some cases even with several line frequency values, so increasing the need for DC-AC converter solutions with tunable output characteristics. A DC-AC converter able to work up to more than 100kHz PWM frequency, offers the right flexibility to cover a wide range of output frequency (from few tens of Hz up to few kHz). The suggested topology is a Full-Bridge featured by a high frequency leg switching with sinusoidal PWM and low frequency leg switching at the desired output frequency. The adoption of this modulating strategy allows optimizing the efficiency of the converter especially in the low load part of the operating profile since a sensible reduction in switching losses is achieved. The selection of the power devices is also crucial for the correct operation of the topology in terms of efficiency and reliability. Two SiC MOSFETs are included in the high-frequency leg in order to exploit the exceptional reverse recovery performance of WBG materials. Two silicon Super-Junction MOSFETs are applied in the second leg in order to switch at the output frequency (up to few kHz). An LCL filter is connected to the mid-point of each inverter leg and is used to interface the system to the load. On the DC side a bank of four electrolytic capacitors is used to store and deliver energy whenever this is required during normal operation. The basic scheme of the DC-AC converter topology is depicted in Figure 3.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Si</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Structure</td>
<td>Diamond</td>
<td>Hexagonal</td>
<td>Zirc-blende</td>
<td>Hexgonal</td>
<td>Diamond</td>
</tr>
<tr>
<td>Energy Gap (Eg(eV))</td>
<td>1.12</td>
<td>3.26</td>
<td>1.43</td>
<td>3.5</td>
<td>5.45</td>
</tr>
<tr>
<td>Electron Mobility (μe(cm^2/Vs))</td>
<td>1400</td>
<td>900</td>
<td>8500</td>
<td>1250</td>
<td>2200</td>
</tr>
<tr>
<td>Hole Mobility (μh(cm^2/Vs))</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Breakdown Field (E_b(V/cm) X10^6)</td>
<td>0.3</td>
<td>3</td>
<td>0.4</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm°C)</td>
<td>1.5</td>
<td>4.9</td>
<td>0.5</td>
<td>1.3</td>
<td>22</td>
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<tr>
<td>Saturation Drift Velocity (v_s(cm/s)X10^7)</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2.2</td>
<td>2.7</td>
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<tr>
<td>Relative Dielectric Constant (ε_r)</td>
<td>11.8</td>
<td>9.7</td>
<td>12.8</td>
<td>9.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Fig. 2. WBG materials properties Vs Silicon

2.2. Test vehicle description

The developed DC/AC converter stage consists of two or more PCBs to be connected in order to implement a multi-output inverter. The system is extremely modular and allows measurements to be contemporarily performed at different output load and voltage conditions thanks to the presence of several outputs. Both the voltage and current can be independently modulated for each output of the load. The boards containing the half-bridge legs are connected to the motherboard through connectors optimized in terms of parasitic stray inductance. The system can overall achieve 8kW of output power. The low frequency leg uses MOSFET MDmesh M5, the high frequency legs (up to a maximum of three) take advantage of 2nd generation ST SiC MOSFETs. The efficiency is increased by the excellent static performances of ST MOSFETs, whether they are in silicon or in silicon carbide. Switching losses are quite small up to 100kHz thanks to SiC superior speed capability, as it will be shown in the next sections. Below is a brief list of the characteristics of the board:

- Input Nominal Voltage: 380Vdc [350Vdc to 450Vdc];
- Switching frequency (Fsw): up to 200kHz
- Output Voltage: 20Vac to 300Vac;
- Output Power per channel: up to 2kW @ 16A_{max};
- Output Line Frequency (F_{line}): 40Hz to 1kHz;
- Capability to drive up to 3 AC loads;

The current ratings of the silicon MOSFETs are identified so as to manage the total power of the system while the SiC specifications are related to the maximum power that can be delivered to a single output.
2.3. ST MOSFETs proposal

ST’s 550 V and 650 V MDmesh M5 power MOSFETs are optimized for high-power PFC and PWM topologies in hard switching applications such as solar-power converters, power supplies for consumer products, electronic lighting controls and EV/HEV. They enable new generations of energy-conscious, compact and reliable electronic products thanks to low on-state losses per silicon area combined with low gate charge (Qg) in a wide range of packages. The main feature exploited in the current work is the extremely low $R_{DS(on)}$ for increased efficiency, since Si MOSFETs are used in the LF leg. Two part-numbers (STW88N65M5 and STY145N65M5) have been tested aiming to investigate different cost-performance trade-off levels.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_D$</td>
<td>$T_c = 100^\circ C$</td>
<td>87 A</td>
</tr>
<tr>
<td>$R_{DS(on)}$</td>
<td>$V_{G,S} = 10 V$, $I_D = 69 A$</td>
<td>12 mΩ (typ)</td>
</tr>
<tr>
<td>$Q_g$</td>
<td>$V_{G,S}=520 V$, $V_{C,D}=10 V$, $L=69 A$</td>
<td>414 nC</td>
</tr>
<tr>
<td>$V_{SD}$</td>
<td>Pulsed: pulse duration=300 μs, duty cycle 1.0%</td>
<td>1.5 V</td>
</tr>
<tr>
<td>$t_{rr}$</td>
<td>$V_{G}=100 V$, $L=138 A$, di/dt=100 A/μs</td>
<td>568 ns</td>
</tr>
<tr>
<td>$Q_{rr}$</td>
<td>$V_{G}=100 V$, $L=138 A$, di/dt=100 A/μs</td>
<td>14.5 μC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_D$</td>
<td>$T_c = 100^\circ C$</td>
<td>35 A</td>
</tr>
<tr>
<td>$R_{DS(on)}$</td>
<td>$V_{G,S} = 191 V$, $I_D = 20 A$</td>
<td>45 mΩ (typ)</td>
</tr>
<tr>
<td>$Q_g$</td>
<td>$V_{G,S}=400 V$, $V_{C,D}=20 V$, $L=30 A$</td>
<td>70 nC</td>
</tr>
<tr>
<td>$V_{SD}$</td>
<td>$L=10 A$, $V_{G,S}=50 V$</td>
<td>3 V</td>
</tr>
<tr>
<td>$t_{rr}$</td>
<td>$V_{G}=400 V$, $L=20 A$, di/dt=100 A/μs, $V_{G,S}=5 V$</td>
<td>18 ns</td>
</tr>
<tr>
<td>$Q_{rr}$</td>
<td>$V_{G}=100 V$, $L=64 A$, di/dt=100 A/μs</td>
<td>85 nC</td>
</tr>
</tbody>
</table>

ST is pursuing the development of wide bandgap transistors with silicon carbide (SiC) MOSFETs being the first members of this family of high-efficiency products. Some features of SiC MOSFETs include:

- Industry’s highest temperature rating of 200 °C;
- Superior switching performance in all temperature ranges compared to the best-in-class IGBTs;
- Very low $R_{DS(on)}$ * area values even at high temperatures as compared to silicon super junction MOSFETs;
- Ideal reverse recovery behavior in all the temperature range.

The main electrical characteristics of the first ST SiC MOSFET developed in the 650V range are listed in the table below.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_D$</td>
<td>$T_c = 100^\circ C$</td>
<td>50.5 A</td>
</tr>
<tr>
<td>$R_{DS(on)}$</td>
<td>$V_{G,S} = 10 V$, $I_D = 42 A$</td>
<td>24 mΩ (typ)</td>
</tr>
<tr>
<td>$Q_g$</td>
<td>$V_{G,S}=520 V$, $V_{C,D}=10 V$, $L=42 A$</td>
<td>204 nC</td>
</tr>
<tr>
<td>$V_{SD}$</td>
<td>Pulsed: pulse duration=300 μs, duty cycle 1.5%</td>
<td>1.5 V</td>
</tr>
<tr>
<td>$t_{rr}$</td>
<td>$V_{G}=100 V$, $L=64 A$, di/dt=100 A/μs</td>
<td>544 ns</td>
</tr>
<tr>
<td>$Q_{rr}$</td>
<td>$V_{G}=100 V$, $L=64 A$, di/dt=100 A/μs</td>
<td>14 μC</td>
</tr>
</tbody>
</table>

These improvements translate into benefits such as simplified thermal design of power electronic systems (reduced cooling requirements) as well as BOM cost reduction, thanks to the trim down of passive components spacing.
2.4. Test results

The test results show very low power losses throughout the output power range. In particular, thanks to the exceptionally low $R_{DSS}$ (on) and the output capacitance profile of SiC MOSFET, the low-load losses are extremely low, making otherwise unattainable levels of efficiency easily achievable. The graphs below show the total losses of the converter and the individual contributions at the following conditions:

- Input Voltage: 380Vdc;
- Switching frequency: 100kHz;
- Output Voltage: 200Vac;
- Output Power per channel: 3x1.6kW;
- Output Line Frequency: 1kHz.

Fig. 8. Overall Full-Bridge estimated Power Losses vs. Load

The STY145N65M5 allows to reduce the conduction losses in the Low Frequency leg compared to the STW88N65M5, thus increasing the overall system efficiency. In this topology, since the LF leg is not affected by switching losses, the larger die enables anyway higher efficiency.

Fig. 9. LF leg conduction losses per switch vs. Load (STW88N65M5 vs STY145N65M5)

3. Conclusions

The investigation carried out on a multi-output inverter has shown that the combination of two technologies, one of which (Si MOSFETs) has largely mature and another emerging (SiC MOSFET), allows the achievement of high levels of efficiency, minimization of losses and of the cooling system, so finally the compactness of the overall solution. The future expansion of silicon carbide MOSFET in the inverters’ market will mainly depend on the increase in the number of systems with adjustable output in a wide frequency range as well as the availability of the designers to benefit of SiC advantages in applications traditionally prerogative of silicon technologies.

References

[3] AN3994, STMicroelectronics, Managing the best in class MDmesh™ V and MDmesh™ II super junction technologies: driving and layout key notes