2000 V Class IGBT Concept for Renewable Energy Converter

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1. Introduction

It has been a long time since the 1500 Vdc rated photovoltaic converter acquired a large share of the market. The pressure to reduce costs continues to increase, as does the competition for CapEx savings. Led by the growth of the renewable energy market, there are growing expectations for the battery energy storage system (BESS) for a more sustainable distributed power network. In this market, the 1500 Vdc rated converters have started being installed in the field. Moreover, wind converters with high output voltages are being considered. The typical output voltage rating is 690 Vac or less, but a higher output voltage, e.g. 900 Vac, would bring the benefit of higher output power under the same output current. Such a highly rated wind converter has attracted much attention as a means of reducing system costs.

2. System Requirements

2.1 Operating DC voltage

To meet the requirements of the Low Voltage Directive, converter ratings must be lower than 1500 Vdc (or 1000 Vac).(1) Therefore, the highest Vcc is considered to be 1500 V. In reality, however, photovoltaic converters rarely see 1500 Vdc operation due to the panel output characteristics even if rated. Switching at a DC-link voltage of 1500 V with a small current at the start of operation (e.g., morning time) can occur, but voltages between 900 and 1300 V with a large current by maximum power point tracking (MPPT) control are typically expected. When the installed PV panel capacity is large, higher continuous voltages of up to 1400 V must be considered. Also, in grids with a high share of renewable energy, the energy feed-in PV power plant may be restricted, which increases the DC operating voltage. The BESS hardware design tends to be the same as that of the photovoltaic converter, but the operating voltage range is higher due to the difference in output characteristics between PV panels and Li-ion batteries. In a wind converter, on the other hand, a higher output current at 1500 Vdc can easily occur. The output power of a wind generator increases as the voltage increases. Therefore, in the case of a 900 Vac system, Vcc operation of around 1400 V should be considered. Even with the 690 Vac system, such a high Vcc operation can occur when necessary to meet severe high-voltage ride-through (HVRT) requirements from the grid codes.(2) Therefore, the full SOA must be secured under the condition of Vcc = 1500 V. Also, a possible increase in the long-term DC stability (LTDS) failure rate caused by higher DC-link voltages should be taken into consideration.(3)

2.2 Solutions for 1500 Vdc operation

In the 1500 Vdc photovoltaic converter or BESS, the three-level neutral point clamped (NPC; I type) topology with a 1200 V or even a 950 V device is commonly adopted.(4) The LTDS failure rate is considered sufficiently low,(5) but the number of devices is three times that of the two-level topology and thus the system cost is higher, as is the control complexity and stray inductance. In some cases, a 1700 V device is used for the 1500 Vdc system although its robustness against LTDS failures and voltage spikes is lower than that of the NPC. Here, the idea of using a higher voltage rated device, e.g. 2000 V, would bring advantages over the above solutions, while retaining the benefits of the two-level topology: reliable switching performance, less complexity, and sufficient robustness against LTDS. Nevertheless, the design of the performance and reliability trade-off must suit the market requirements to a realistic degree. For example, zero LTDS failure with a much higher power loss by choosing a far greater voltage class device, such as a 2500 V, would reduce the efficiency of the converter.

3. Performance Evaluation

Considering the above system requirements, the higher voltage class IGBT and diode with a 2000 V rating were fabricated and the characteristics were tested.

3.1 LTDS

The LTDS of a semiconductor device depends on the applied voltage, temperature, and altitude.(5) In addition, the fundamental device technology, e.g. the structural parameters, also affects the robustness. For the 2000 V rated device, the 7th generation IGBT and diode technology are on a design basis, and a sufficient LTDS design is intended for each target application. The N-drift thickness and resistivity are the key parameters for determining the design of not only the blocking

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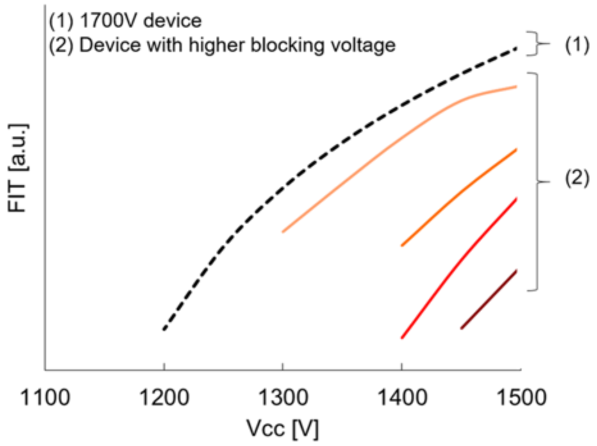
capability but also the LTDS.[6] Our 7th generation IGBT has a unique carrier stored trench-gate bipolar transistor (CSTBT™) structure, enabling a low conduction loss based on the optimal carrier density profile. The 7th generation diode has a relaxed field of cathode (RFC) structure on its cathode surface, which improves the power loss vs. snap-off behavior trade-off by utilizing the hole injection effect.[7] These unique technologies effectively compensate for the increase in power loss caused by the increase in thickness or resistivity.

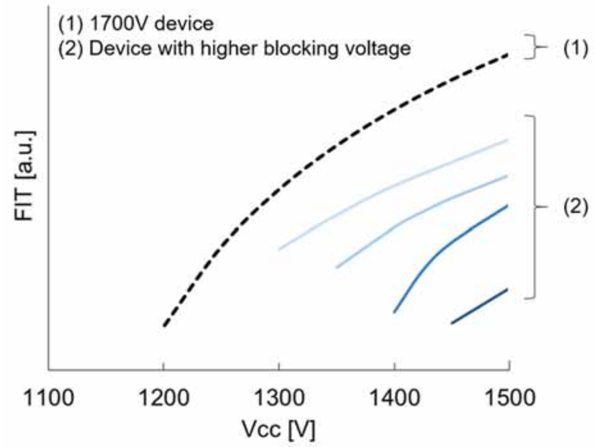
Figure 1 shows the results of the accelerated LTDS test using an artificial neutron beam for a comparison between the existing device with a 1700 V rating and devices with a higher blocking voltage capability. The LTDS can be selectively designed to a certain degree using the increase in wafer resistivity because it reduces the electric field strength. In Fig. 1, the lines with gradient colors (2) illustrate the LTDS with different wafer resistivity and fixed thickness values. The lines are represented as statistically processed data based on the actual test results, and thus the shape of the lines does not accurately represent the physical theory of cosmic ray induced failure. Although a higher resistivity improves the LTDS, the final design of the resistivity (and thickness) is carefully chosen taking into consideration other fundamental performances such as safe switching performance, power loss, etc.

3.2 Safe switching operation

The typical switching behavior of the 2000 V device was confirmed to maintain safe operation at Vcc = 1500 V. The test sample was chosen from the devices shown in Fig. 1, with a certain wafer thickness and resistivity that cover the LTDS requirements for the target applications. The current rating of the tested IGBT module was 400 A. Figure 2 shows the reverse-bias safety operating area (RBSOA) test waveforms. The IGBT turned off safely at the outermost boundary of the RBSOA (square area within the twice-rated current and rated blocking voltage of 2000 V) under the condition of

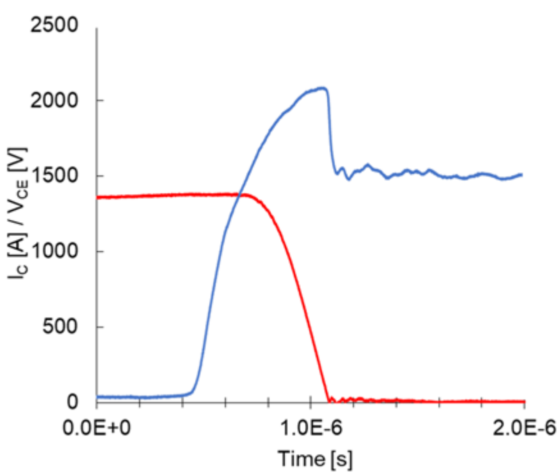


(a) IGBT

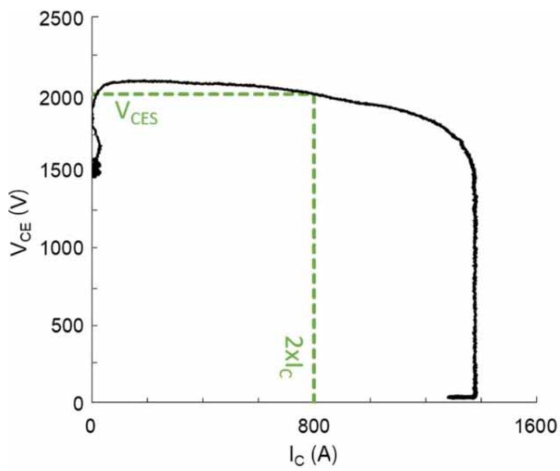


(b) Diode

Fig. 1 LTDS test results for differently tuned devices



(a) Time domain



(b) Lissajous curve of collector current and collector-emitter voltage with RBSOA (green dotted line)

Fig. 2 RBSOA test waveforms at Tvj = 150°C

Vcc = 1500 V.

The snap-off behavior of the diode was also confirmed, as shown in Fig. 3. At Vcc = 1500 V with a low current, no snappy reverse recovery behavior was found. For the final product design, internally paralleled devices and stray inductance effects must be carefully considered.

3.3 Power loss performance

By increasing the blocking voltage of the device to 2000 V, the power loss (both conduction and switching) inevitably increased. However, due to the benefits of the CSTBT™ and RFC structure, the increase in the total power loss was within the minimum sacrifice while maintaining a sufficient LTDS performance. In particular, avoiding an increase in the switching loss is the most critical factor. In addition to the relatively higher switching frequency in the target application (1–3 kHz), the increase in the operating Vcc itself plays a large role in increasing the switching loss of both the IGBT and diode.

The above key factors were considered in the trial design of the 2000 V device, and the benefits of the power loss performance of the 2000 V device were investigated through a comparison with the existing 1700 V device and the “1500 Vdc enablers.” One option was the three-level NPC (I type) topology with a 1200 V device. A two-level topology with a 3300 V device was also included in the comparison as a standard voltage class higher than 1700 V, although the 3.3 kV device is much more suitable for traction applications where significantly higher DC-link voltages are required. The comparison was made under the same output power per mounting area. The output power for the 1700 V device was set for the 690 Vac system while it was set for the 900 Vac system for the others. Therefore, the output current for the 900 Vac system was smaller by the factor of the reciprocal of the output voltage ratio. The same package size and technology were assumed for the mounting area and the thermal resistance was assumed. The 1200, 1700, and 2000 V modules were considered as 1200 A rated, and the 3300 V module was considered as a smaller rated current due to its relatively larger chip area. In the three-level NPC topology with a 1200 V device, the usage of three dual IGBT modules with a 1200 A rating was assumed. Hence, the output power conditions were tripled to maintain the same output power per mounting area. (Table 1.)

The 2000 V device performance was comparable to the existing 1700 V device in the range of 0.5 to 3 kHz. (Fig. 4) This result indicates that the increased power loss (both conduction and switching) can be well compensated by possible output current derating thanks to the increased output voltage. Thus, significant system benefits can be obtained (e.g. reduction in ohmic losses in cables, reduction in windings of the grid connection transformer, etc.) while keeping the same power feed-out to the grid. The other solutions for the 900 Vac bring the same advantages but with less output power. The 3300 V device technology is obviously too marginal for 1500 V operation. The performance of the three-level NPC topology with the 1200 V device was limited at lower switching frequencies by high conduction losses at

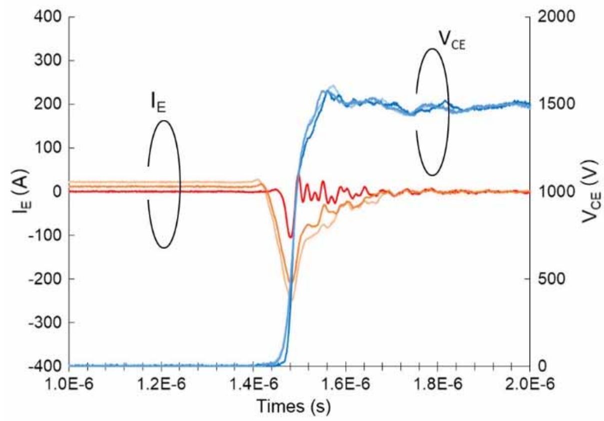
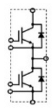
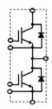
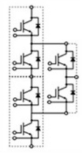
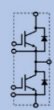


Fig. 3 Reverse recovery waveform at low current of 0, 10, 20 A at Vcc = 1500 V, Tvj = 25°C

Table 1 Conditions for power loss performance comparison

Voltage rating	1700V	3300V	1200V	2000V
Topology	2L 	2L 	3L-NPC 	2L 
Assumed current rating [A]	1200	600	1200	1200
Number of module / phase	1	1	3	1
Pout [a.u.]	1	1	3	1
V_{CC} [V]	1120	1450	1450	1450
Vout [Vac]	690	900	900	900
Rth(c-w) / module [a.u.]	1	1	1	1
Rth(j-c) / chip area [a.u.]	1	1	1	1
I_O [a.u.]	1	0.77	2.31	0.77
Pout density [a.u.]	1	1	1	1

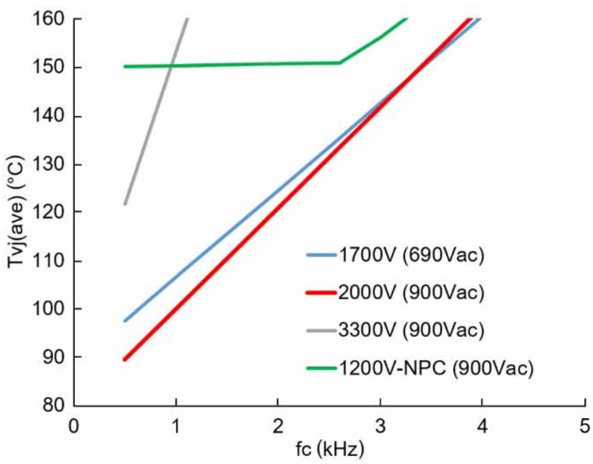


Fig. 4 Simulated junction temperature of the IGBT chip

the output stage. Therefore, the performance was typically maximized at higher switching frequencies, but under the test conditions, the switching loss at the input stages again limited the performance.

Additionally, the output power performance at a fixed switching frequency of 2.5 kHz was compared (Fig. 5). The achievable output power per mounting area was very similar between the 2000 and 1700 V devices. However, considering the benefits of the reduced output current, the 2000 V device performed better, as shown under “Output power / mounting area @Tvj = 150°C / output current” in Table 2.

4. Conclusion

The new voltage class 2000 V rated IGBT module can meet the requirements based on recent converter designs for renewable energy applications. An increase in the operating Vcc and even system voltages from 690 to 900 V are feasible. The design boundary of the two-level converter is expanded with improved optimization including power loss performance, LTDS reliability, and converter system cost.

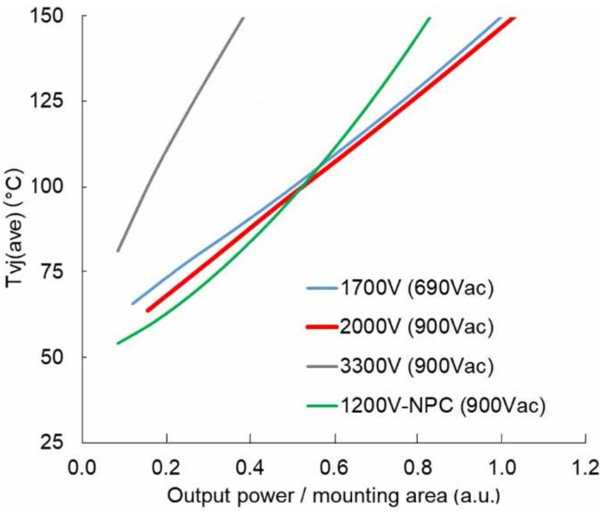
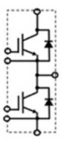
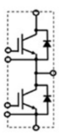
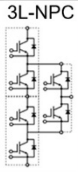
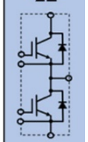


Fig. 5 IGBT chip temperature vs. output power per mounting area @ fc = 2.5 kHz

Table 2 Relative performance comparison

Voltage rating	1700V	3300V	1200V	**2000V**
Topology	2L 	2L 	3L-NPC 	**2L** 
Output power / mounting area @Tvj=150°C [a.u.]	1	0.38	0.82	1.02
↑ **Divided by output current [a.u.]**	1	0.50	1.07	**1.33**

References

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