Topologies, voltage ratings and state of the art high power semiconductor devices for medium voltage wind energy conversion

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Abstract **– Today, the main topologies for power conversion for medium voltage applications are mainly determined by the available voltage ratings of the power semiconductor devices. In this paper we shall examine the main existing topologies for medium voltage wind power energy conversion and determine the voltage levels that can be can be achieved with the currently available high voltage semiconductor components such as the IGCT and IGBT. The paper will also provide an insight into development trends for future power semiconductor device concepts with increased power levels and improved overall static and dynamic performance.**

Keywords - IGBT, IGCT, topology, voltage rating

I. POWER SEMICONDUCTORS FOR WIND POWER

In modern wind power applications, to fulfil the requirements from the grid operators regarding net quality, it is hardly possible to connect a wind turbine to the grid without the inclusion of power electronics. The purpose of the power electronics circuits is to ensure that the generated power has the correct frequency and voltage independently of the current state of the wind generator and also to ensure that the fault behaviour is conforming to the grid requirements. Depending on the applied configuration, the power electronics will directly control between 20% up to 100 % of the generated power where the lower percentage figures are only valid for systems using the most common wind generation topology with a Doubly Fed Induction Generator (DFIG). On the other hand, by using a circuit topology allowing for the full power conversion, an electrical decoupling from the generator side to the line side can be achieved, which in many cases is a viable solution although the converter itself will be much larger. Independent of the chosen topology the only way to control high levels of power flows are through the utilisation of high power electronic devices that have to be selected carefully to achieve the intended performance. Two major aspects of the selection is the converter topology and the connected voltage dimensioning that will be discussed in detail in this paper.

II. TOPOLOGIES AND VOLTAGE RATINGS

Due to the better availability of asymmetric and reverse conducting turn-off power semiconductors compared to symmetrical devices, the VSI-topology (Voltage Source Inverter) has achieved a dominant position in the field of frequency conversion both for low as well as for medium voltage applications. For low voltage conversion the 2 level VSI, figure 1, is the solution of choice but this simple inverter topology is also used for medium voltage circuits. However, the voltage ratings of the available power semiconductor components remains a limiting factor, since serial connection of power devices is a complex issue with many related technical difficulties. The 2-level inverter is mainly used in wind power for the rotor control in DFIG systems.

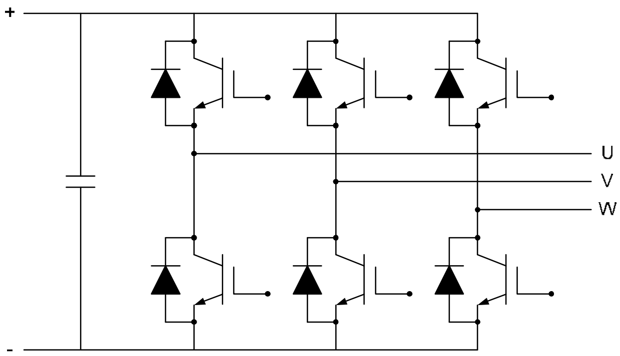

Figure 1. A 2-level Voltage Source Inverter with IGBTs.

To accomplish a higher output voltage without series connection of power devices other topologies are needed and the most common is the 3-level inverter, figure 2, which enables an output voltage that is twice as high as a 2-level inverter with the same power semiconductor voltage rating. This topology is the main solution for the Medium Voltage Drives (MVD) on the market since with existing devices it is possible to achieve output voltages of up to 4.16 kV without series connection of devices and/or converters

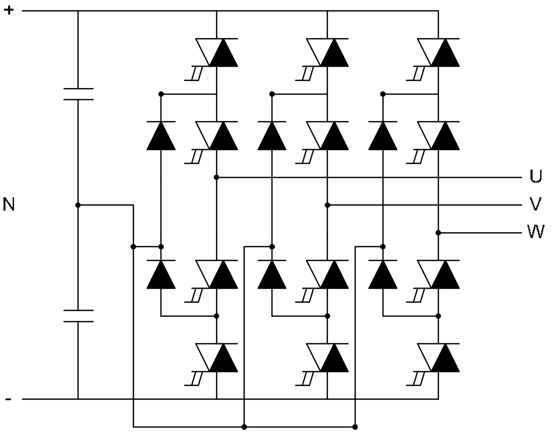

Figure 2. A 3-level Voltage Source Inverter with reverse conducting IGCTs and NPC-diodes.

The 3-level inverter in wind power applications is mainly employed in systems with full power conversion as with medium voltage permanent magnet synchronous generators.

When considering what voltage levels can be achieved with available power semiconductors, there are three voltage ratings to be considered:

1) The DC-voltage which determines the cosmic radiation failure rate [1] [2] and long-term leakage current stability.
2) The repetitive overshoot voltage spikes during turn-off which must not exceed the rated V_{DRM} (for GTO and IGCT) or V_{CES} (for IGBT) of the device.
3) The maximum voltage against which the device is supposed to switch a specified current to guarantee its Safe Operating Area.

A. Voltage Source 2-Level Inverter

In this configuration, each semiconductor will support the total DC-voltage. The required DC-voltage (V_{DC}) as a function of the phase-to-phase supply voltage (V_{NOMRMS}) is calculated using E^{qn} 1.

$$V_{DC} = V_{NOMRMS} \times \sqrt{2} \times \left(1 + \frac{x}{100}\right) \qquad E^{qn}\ 1$$

For typical industrial networks, the over voltage factor, normally corresponding directly to the network tolerance; x = 10 % for low voltage systems and x = 15 % for medium voltage systems. For traction lines, typically, x = 20 %.

To calculate the required peak repetitive voltage rating (V_{DR}), E^{qn} 2 is used,

$$V_{DR} = V_{DC} \times \left(1 + \frac{y}{100}\right) \qquad E^{qn}\ 2$$

where y is a safety factor that has to be selected based on the switching conditions and stray inductances. For low stray inductances, a safety margin of about 50 % is used and for medium stray inductances, a safety margin of about 60 % is used. The preferred device rating is then normally selected as the next highest standard device voltage rating.
Using E^{qns} 1 and 2, the preferred voltage ratings for the semiconductor at standard line voltages, both AC and DC, are shown in Table 1.

TABLE I. PREFERRED BLOCKING VOLTAGE RATINGS FOR HIGH POWER SEMICONDUCTORS USED IN 2-LEVEL VSIS

Nominal line voltage	**Nominal DC-link voltage for cosmic ray rating (V)**	**Preferred repetitive blocking voltage rating (V)**
400 V_{RMS}	620	1200
750 V_{DC}	900	1700
690 V_{RMS}	1070	1700
1500 V_{DC}	1800	3300
1700 V_{RMS}	2800	4500
3000 V_{DC}	3600	6000
3300 V_{DC}	4000	6500

B. Voltage Source 3-LevelIinverter

Due to the 3-level connection, each semiconductor will only support half of the total DC-voltage. The required DC-voltage as a function of the supply voltage is calculated using E^{qn} 3.

$$V_{DC} = \frac{V_{NOMRMS} \times \sqrt{2} \times \left(1 + \frac{x}{100}\right)}{2} \qquad E^{qn}\ 3$$

Using E^{qns} 2 and 3 and considering the same over voltage and safety factors as for the 2-level inverter we obtain table 2 for the 3-level inverter.

TABLE II. PREFERRED BLOCKING VOLTAGE RATINGS FOR HIGH POWER SEMICONDUCTORS USED IN 3-LEVEL VSIS

Nominal line voltage	**Nominal DC-link voltage for cosmic ray rating (V)**	**Preferred repetitive blocking voltage rating (V)**
2300 V_{RMS}	1900	3300
3300 V_{DC}	2000	3300
3300 V_{RMS}	2700	4500
4160 V_{RMS}	3400	5500
6000 V_{RMS}	4900	8000
6600 V_{RMS}	5400	8500
6900 V_{RMS}	5600	9000
7200 V_{RMS}	5900	9500

C. Other Topologies

Still higher output voltages can be achieved by using multilevel inverters. The variety of possibilities using such topology would expand this paper beyond the given limits, but what it all comes down to is to realize a converter for high voltages by breaking down the voltage for each device to a level that allows the power semiconductor devices to operate at conditions within their given specification to reach an acceptable performance and reliability as can be seen when comparing the 2-level and 3-level inverter topologies.

D. Pros and Cons for the Different Topologies

A comparison between the different topologies can be summarized in that every additional level is increasing the complexity for both the converter itself as well as for the control system. The increased complexity and the added amount of components have a negative impact on the reliability that normally can only be reduced by measures as de-rating of the used components. The positive aspects of the additional levels is that the out-put voltage gets a better shape thus reducing the need for filtering, and this can be achieved with a lower switching speed for the power semiconductors thus decreasing their losses. In addition, the higher voltage levels can be achieved without the introduction of complex series connections of power electronic devices.

II. POWER SEMICONDUCTORS FOR MVD

To reach the control possibilities required in a wind turbine the use of turn-off devices are almost mandatory and for medium voltage conversion there is the choice between two families of turn-off devices, the IGBT (Insulated Gate Bipolar Transistor) and the IGCT (Integrated Gate-Commutated Thyristor).

The Insulated Gate Bipolar Transistor IGBT

The IGBT is a well established device for power conversion in applications as low and medium voltage drives, UPS and battery charges and is available in many different types of packages, mainly with an insulated base plate. Most of the standard packages were developed mainly for low voltage applications and when going to medium voltage systems one package family is becoming predominant and it is the HiPak-type of modules. The HiPak IGBT-module, figure 3, is the standard device for high power traction applications but is also used in its various configurations in converters for wind energy applications. The available ratings are 1700 – 6500 V enabling inverter ratings up to about 2400 Vrms, equations 1 and 2. With devices current ratings up to 2400 A, 1700 V and 750 A, 6500 V it is possible to accomplish converters with ratings beyond 500 kW even with forced air cooling, without series or parallel connection, making them very useful for DFIGs up to about 2.5 MW. These devices with an insulated base plate are seldom used in 3-level inverters due to insulation issues. The highest insulation voltage on the market is 10.2 kV for a 6500 V module. The HiPak modules have been developed for high reliability traction applications making them very suitable for harsh environments.

Although the devices due to the large size and high power ratings cannot be switched as fast as IGBT-modules for lower power applications, it is still possible to reach switching frequencies of 2 – 4 kHz for the 1700 V HiPaks which for most wind application should be sufficient.

Figure 3. The Standard IGBT HiPak module family.

Since higher voltage requires thicker silicon which gives higher switching losses, the high voltage devices will have a stronger frequency dependency of the possible output power then low voltage devices, which can be seen in figure 4 for devices in the same housing at the same conditions but with different voltage ratings. Hence, this will reduce their possible usage for applications requiring high switching frequencies.

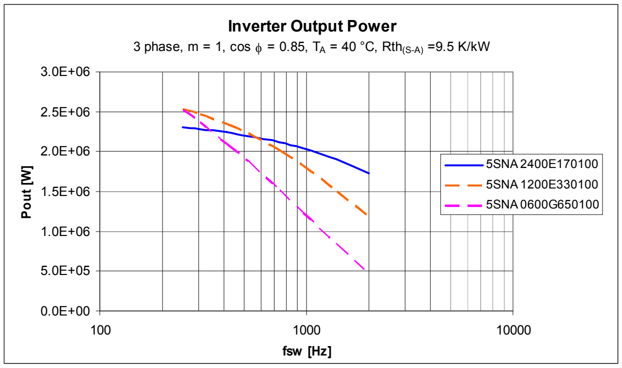

Figure 4. Output power as function of switching frequency at given conditions.

The Integrated Gate Commutated Thyristor IGCT

The IGCT, see figure 5, has since its introduction in 1997 [3] established itself as the device of choice for medium voltage drives mainly for industrial applications but it also have been used in wind mill converters as for the ABB PCS 6000. Due to the integration with a low inductive gate unit this GTO-based device conducts like a thyristor and switches like a transistor. Compared with the GTO this design allows switching of high currents without the need of snubbers thus simplifying the circuit compared with a GTO-solution significantly. The IGCT is available as asymmetric and reverse conducting devices where the latter has an integrated free-wheel diode. Both devices have been optimized for VSI -applications. With ratings of 4500V, 4000 A, it is possible to design water-cooled converters in a 3-level connection with rating of about 8 MVA without the need of series or parallel connection, making the IGCT a viable solution for wind turbines with full converters and also for the coming wind turbine generation.

Figure 5. 4.5kV IGCT 5SHY 55L4500.

Available voltage ratings are 4500, 5500 and 6500 V enabling 3-level inverters beyond 4.16 kV. The press-pack design is well suited for 3-level inverters since there is no inherent insulation, which only has to be provided for the assembled stack and the gate unit supply voltage. The control is made through fibre optics.

III. POWER DEVICE DEVELOPMENTS

Intensive development programs in the field of power semiconductors continue today in order to further improve the devices performance in terms of increased power levels and reliability. The near future will see improvements in the device technologies for enabling the design of even more powerful inverters. The HiPak family was introduced using the very robust (Soft-Punch-Through) SPT-chip high voltage technology with its planar design and typical SPT-buffer. The SPT-IGBT rugged performance is shown in figure 6 for a 1200 A / 3300V Hipak module under extreme dynamic avalanche and Switching-Self-Clamping-Mode (SSCM) conditions.

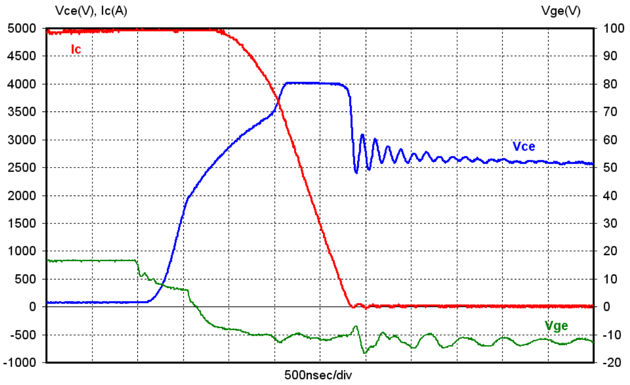

Figure 6. Turn-off waveforms for 1200A/3300V HiPak module at 125°C. I_C=5.0 kA (>4 x nominal), V_{DC}=2.6 kV, L_S = 5µH, L_s = 280 nH.

The next step in the chip design was to improve the emitter design for lower losses and hence the SPT+ technology was introduced for the whole voltage range utilising an Enhanced Planar technology. The robustness has been kept but by decreasing the losses, see figure 7, the introduction of the SPT+-platform [4] [5] has already increased the power density in the HiPak IGBT-modules with up to 20 %. Due to the improvement it is possible to either increase the output power of the inverter without making any changes to the circuitry and without sacrificing the robustness and controllability that has become a trademark for the SPT-chip family. Both SPT and SPT+ module contain low loss, soft and rugged freewheeling diodes to match the IGBT performance.

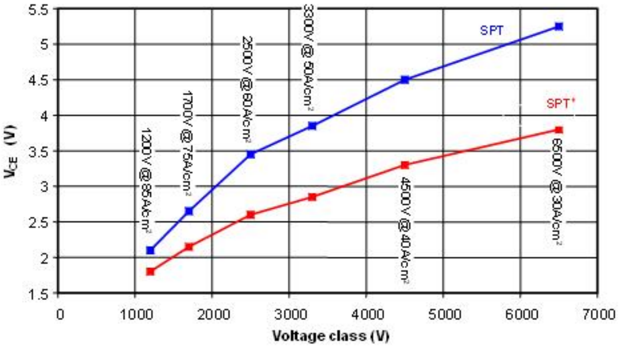

Figure 7. 1200V -6500V IGBT improvements, SPT to SPT+.

The quest for improved ratings has not stopped by the introduction of the SPT+. Further possibilities to improve the IGBT performance were explored and a very promising technology is in the pipeline. The Reverse Conducting IGBT (RC-IGBT) [6], referred to as the BIGT (Bi-mode Insulated Gate Transistor) in its advanced design, promise another performance increase in at least the same magnitude as the change from SPT to SPT+. By using the same die both as diode and as IGBT, see figure 8, the power density can increase significantly since the available chip area within a module is more efficiently utilised.

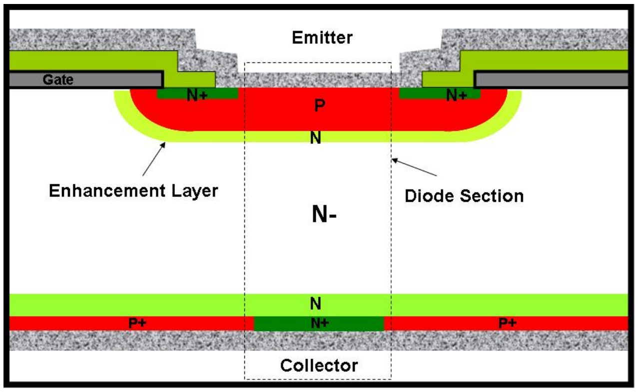

Figure 8. The BIGT, IGBT and Diode in one die.

The BIGT concept would mean another step forward in realizing very powerful compact converters since a BIGT-module would have a rating that is about 50 % higher than a solution with SPT+ in the same package. Improvements in terms of device softness and reliability are also predicted with the new concept.

Improvements are though not made for IGBTs alone. Solutions for expansion of the operating field for IGCTs are also investigated. The recently introduced High Power Technology HPT-IGCT [7] gives an increase in the IGCT-SOA (Safe Operating Area) of up to 50 % which opens new perspectives for control and fault handling compared to the standard devices. Figure 9 shows an example of the powerful turn-off switching capability of the new 4.5kV 91mm HPT-IGCT generation. The switching was performed in a test circuit without a snubber and was carried out to establish the safe-operating Area (SOA) limits of the device which means that the conditions were outside the boundaries given in the device data sheet. The IGCT was capable turning off in excess of 5000A by withstanding extreme conditions with a large stray inductance while also supporting the Switching-Self-Clamping-Mode of operation successfully.

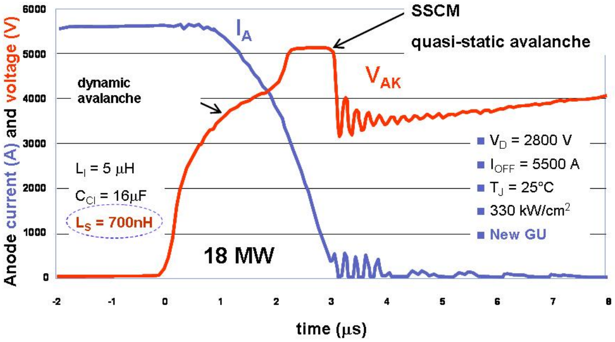

Figure 9. Turn-off wave forms for the HPT-IGCT 5SHY 55L4500 last pass at 25°C. I_T=5.5 kA, V_{DC}=2.8 kV, L_{COMM} = 5µH, L_s = 700 nH.

Further more, the technology development of the 10 kV IGCT and diode [8], enabling voltages in a 3-level configuration of up to 7.2 kV, without series connection see table 2, open up new fields for the use of power semiconductors in power conversion. By using the advanced corrugated p-base design, similarly to the HPT-IGCT, the envisaged turn-off capability is much higher than what could be previously expected for a turn-off device of this voltage level. 91mm 10kV IGCT and diode technology demonstrators have been produced and show very promising results and good switching behaviour as can be seen in figure 10 and 11.

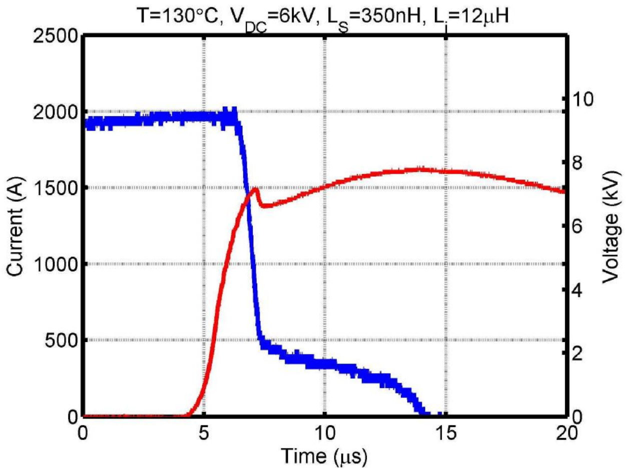

Figure 10. Wave forms of snubberless turn-off for a 10 kV IGCT demonstrator with area 40 cm^2 at T_j = 130 °C, and V_{DC} = 6000 V, I_T=2.0 kA.

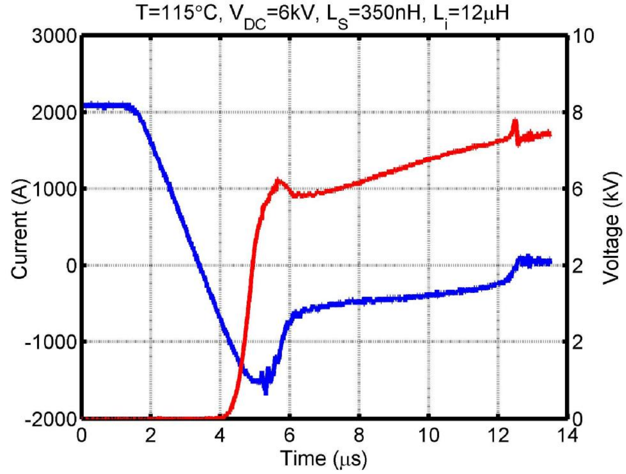

Figure 11. Wave forms of reverse recovery for a 10 kV diode demonstrator with area 40 cm^2 at T_j = 130 °C, and V_{DC} = 6000 V, I_T=2.0 kA.

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