# Reliable Power Electronics for Windmill Generators

In the megawatt range, high-power electronics applications need powerful semiconductors. However, even the largest semiconductors available today are still not strong enough for some applications. It is therefore necessary to connect them in parallel. **Dejan Schreiber, Senior Applications Manager, SEMIKRON, Nuremberg, Germany**

One possible solution is discussed in this context: power electronics assembly, IGBT base units containing IGBTs and diodes, heatsinks, DC-link capacitors, drivers and protection, auxiliary power supply and a PWM controller (one independent unit), arranged into a three-phase inverter. Such units can be connected in parallel, for example for a four-quadrant drive windmill with permanent magnet generator and a full-size 4MW converter, which is presented here. A method is described of obtaining higher levels of power in medium-voltage windmill applications that involves using line interface connection of variable-speed, medium-voltage PM generators with no voltage and power restrictions, as well as proven semiconductors and components. Basic power electronic units are connected in series for higher voltages and in parallel for higher power levels.

## Comparison of IGBT efficiency with different blocking voltages

IGBTs are the working horses of power electronics systems. Today, IGBTs are manufactured in various voltage classes, from 1200 or 1700V for different industrial applications, as well as for the medium-voltage classes 3.3, 4.5, and 6.5kV. Which voltage class is best suited to high-power applications? The answer to this question lies in putting the IGBTs in the largest casing available in order to obtain inverters. Of course, it is much simpler to simulate available power under optimal working conditions.

To do so, the largest standard casing (IHM, 190mm wide) is taken. The IGBTs are packed into this casing and the optimal operating regimes defined - $V_{dc}$ DC operational link voltage, $V_{ac}$ AC output voltage, a carrier switching frequency $F_{sw}$ of 3.6kHz and best possible cooling conditions. Figure 1 (left) shows the different available power levels, calculated on the basis of the given parameters.

The results show that the maximum available power using 3.3kV, 1200A individual modules would be one half of the equivalent power obtained using 1.7kV, 2400A IGBTs. The 6.5kV, 600A IGBT modules provide just one quarter of what would be obtained with a 1700V IGBT. The reason behind these results is the losses that occur in IGBT modules. If we calculate the efficiency of the three converters shown in Figure 1 (right) at same cooling conditions and $F_{sw}$ = 3.6kHz; cos$\varphi$ = 0.9 and same module, we can see that the losses have a ratio of 1:2:4.

For this comparison, we have used the same carrier switching frequency. This enables us to design inverters with relatively small filters. A comparison using different carrier switching frequencies would lead to variations in the output sinusoidal filters used. Given all of the above, it can be seen that the greatest efficiency is accomplished by using the 1700V IGBT, a standard industrial product with a very reasonable price per module.

IGBTs for 1700V are packed in various module casings. For comparison, we can take the largest single-switch module, the IHM 2400A/1700V, and compare two such modules with a dual module of similar size and length, SKiiP1513GB172. If the two SKiiPs are put back to back on one heat sink, a half-bridge is obtained for currents 2 x 1500A = 3000A (case temperature = 25°C), or 2250A for a case temperature of 70°C. Two single-switch modules will provide a half-bridge for 2400A. If we compare the results of the calculations, we can see that the SKiiP solution provides higher output currents throughout the complete range of switching frequencies than a standard module in the largest available case would (see Figure 2).

If a more powerful SKiiP module is

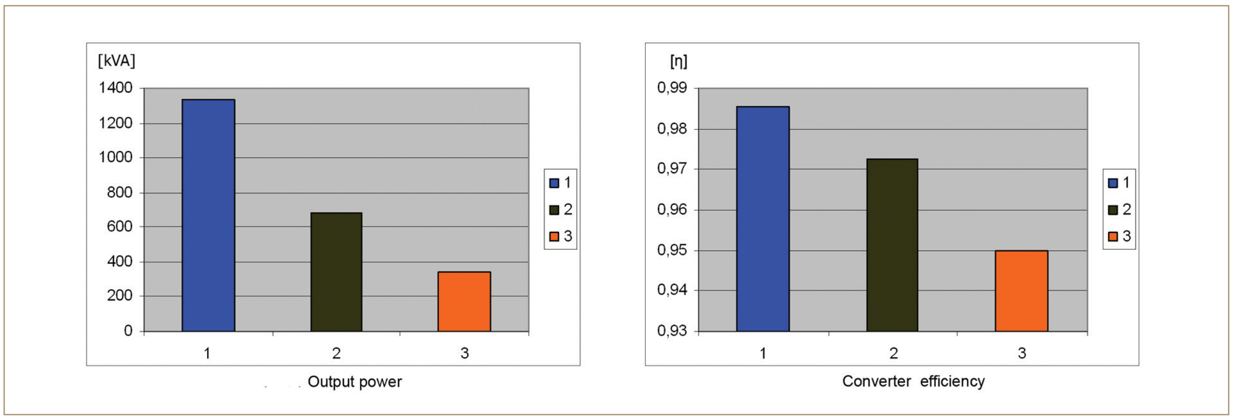


**Figure 1: Comparison of output power (left) and efficiency of IGBT converters with different blocking voltages at same cooling conditions and $F_{sw}$ = 3.6kHz; cos$\varphi$ = 0.9 and same module**

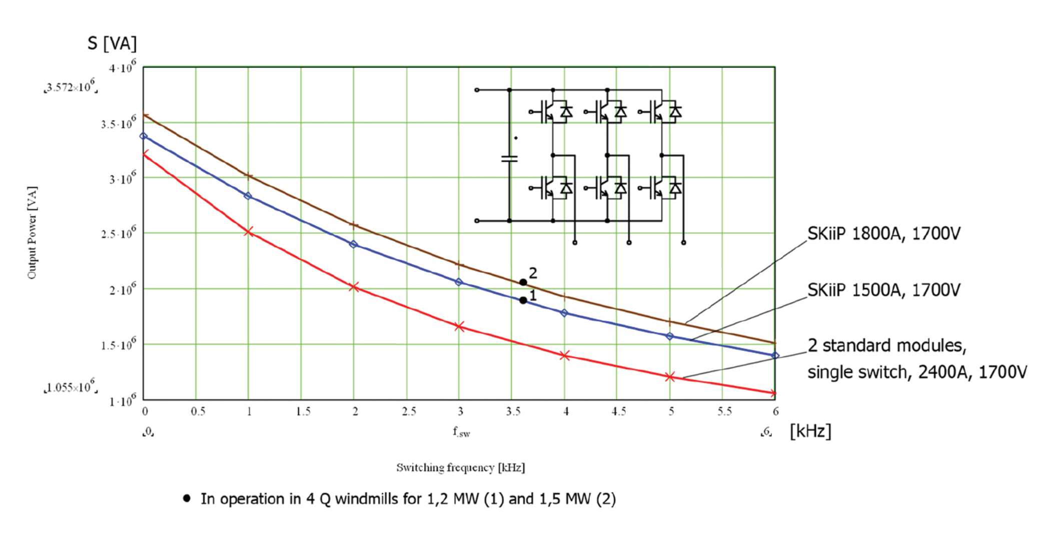


**Figure 2:** **Available inverter power versus switching frequency**

taken, for example the SKiiP 1800A, 1700V, which uses an aluminum nitrate (ceramic) substrate, even more power is available from a three-phase inverter, i.e. 1800kVA (see Figure 3).

## Paralleled IGBT modules

Numerous solutions are feasible for the parallel operation of IGBT modules, i.e. one three-phase inverter for the entire power. Here the phase leg is constructed with several IGBT modules connected in parallel and one powerful driver. Each IGBT module must have its own gate resistor and symmetrical DC link and AC output connection [1]; and hard paralleling of three-phase IGBT base units. The whole system is controlled via one controller and its PWM signals. All of the three-phase inverters are connected to a common DC link voltage. Paralleling is achieved using driver paralleling boards for each individual base unit driver. Slight variations in driver propagation times (less than 100ns) are compensated for with small AC output chokes; (<5µH inductance). All of the three-phase inverters run simultaneously, with the small time delays that occur being compensated for with additional AC chokes. To ensure proper load-current sharing, symmetrical layouts and positive temperature coefficients for IGBT saturation voltages are used [2].

An other solution as described under [2] features additional PWM signal correction for each base unit. Additional PWM corrections are performed to control precise load-current sharing in paralleled base units; parallel operation of several units with synchronous PWM and the elimination of circulated current using additional sophisticated PWM control [3]; or galvanic load isolation for each base unit. Each base unit supplies power to the load through insulated windings. Each base unit has its own controller. PWMs are independent, non-synchronous, free-running signals, and each base unit has its own separate DC link. On the grid side, each base unit has its own sinusoidal LC filter. Circulated currents between different DC links do not exist provided the outputs are galvanically insulated. This is the easiest parallelisation method for standard independent basic units with standard independent controllers. A simple design based on galvanic insulation on the generator side is shown in Figure 4.

Three 1500kVA four-quadrant drive units are connected to separate generator windings of a permanent magnet windmill generator. Each four-quadrant drive is a standard drive with its own generator-side and grid-side controllers. The purpose of the fourth controller is to provide uniform generator torque sharing. Should problems occur in one of the 4Q drives during operation, the remaining drives will continue to operate. The system described is used in a 3.6MW windmill with a PM generator with three separate windings. The system is designed for up to 12 four-quadrant drives in parallel and for the connection of 12 generators or 12 generator windings [4].

## Series connection of base units

Windmill design engineers have a number of aspects to take into their designs, i.e. high-power wind turbine, low losses, variable speed, high degree of efficiency, use of proven semiconductors, clean sinusoidal line current using a simple line transformer, good line power factor

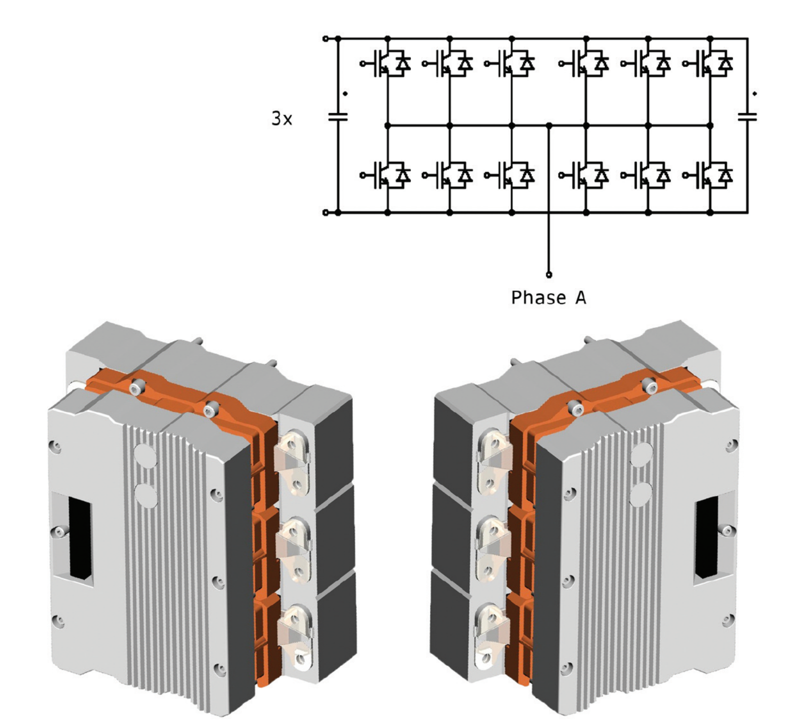


**Figure 3:** **Example of a 1800kVA base unit**

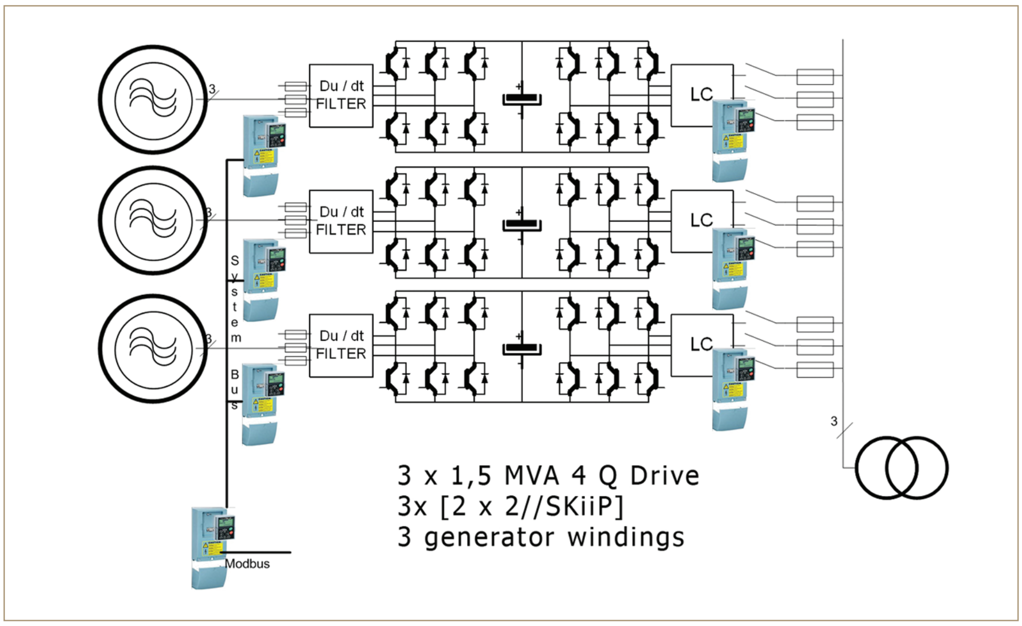


**Figure 4:** **Three independent 4Q drives in parallel with separate motor windings, the drive can operate with one or two drives in parallel**

and low THD, active and reactive power control, modular design to allow for use with various powers and voltages, quick assembly, high degree of reliability, and lowest possible costs. Best solution is the medium-voltage generator.

A medium-voltage generator is a must in high-power windmill designs of the future. Medium-voltage silicon, however, is not suitable for such applications. The right solution is therefore to connect base units in series.

An example: a 5MW windmill generator with 6.3kV rated output voltage has output currents of 3 x $436A_{rms}$. The rectified variable speed generator voltage is in the range of 1 to 10kVDC. How can such variable voltage be connected to the grid?

Each windmill needs to have its own transformer to allow for connection to the grid; grid voltage would be in the range of 20 to 30kV, which would be the transformer output voltage. The transformer can be produced with several - in this case 10 - three-phase windings, each for 3 x 690V, which are used as input voltages. The new medium-voltage windmill principle is shown in Figure 5.

One base unit, a 600kVA three-phase inverter, is attached to each three-phase winding. A fourth IGBT leg can be connected in front of each base unit. This arrangement can be referred to as a medium-voltage cell. All of the cells can be connected in series, as shown in Figure 7. If the IGBT switch of the fourth leg is switched-off, the generator DC current will charge the cell DC-link voltage. The three-phase inverter on the cell-grid side discharges, controlling its own DC-link voltage. For 3 x 690VAC voltage, the DC-link voltage will be 1050V. Ten base units in series can produce a Counter Electro Motive Force (EMF) of up to 10 x1050 = 10.5kV. The voltage remains balanced with the rectified generator voltage. If the generator speed is lower, the generator voltage will be lower, too. For this reason, to control the rectified DC current, which in turn means controlling the generator torque, some of the cells have to be bypassed. If five cells are bypassed, the remaining counter EMF is 5 x 1050 = 5.25kV. Bypassing more cells will increase the DC current and the generator torque. Bypassed cells can deliver full reactive power to the grid. If one cell is not functioning, it will also be bypassed. The maximum cell DC link voltage is 1200V. For this reason, even as few as nine cells in series can carry the rectified generator voltage of up to 9 x 1200V = 10.8kV.

## Conclusion

High-power applications use numerous IGBT modules. It is far better, however, to use more switches with separate controls, e.g. several units connected in parallel or in series rather than one large single unit. The advantages are as follows: good line power factor and low current THD with a lower switching frequency and fewer passive components, modular design that is suitable for various powers and voltages, as well as quick assembly, use of proven semiconductor elements, greater efficiency, high degree of reliability, and extremely low costs per kW.

## References


*[1] D. Srajber 'IGBT with Homogeneous Structure used for High Power Converter Design' PCIM 1991 Nuremberg Germany*

*[2] SEMIKRON Application Notes 'SKiiP Parallel Operation of 'GB'-type SKiiP Systems' http://www.neu.skd.semikron.com/internet/webcms/objects/pdf/Application_notes_SKiiP_engl.pdf*

*[3] D. Boroyevich: 'MODELING AND CONTROL OF PARALLEL THREE-PHASE PWM CONVERTERS'*

*[4] The Switch, www.theswitch.fi*

*[5] United States Patent US 6,680,856 B2*


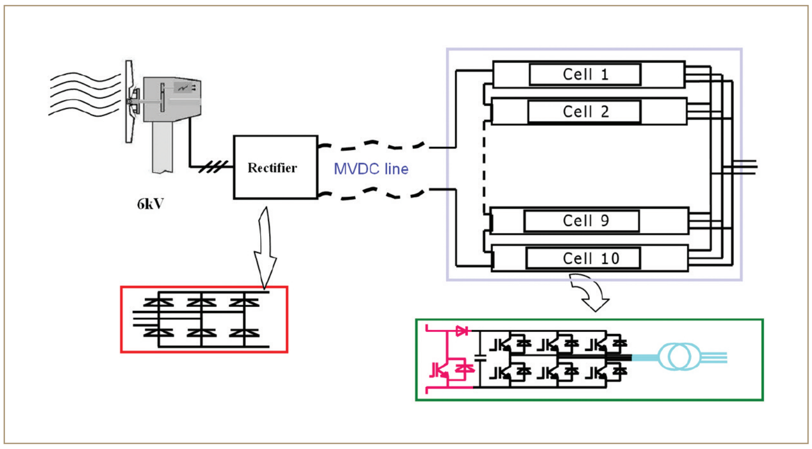


**Figure 5:** **Cell-based medium-voltage windmill**