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New Design Proposals for High-Power Renewable Energy Applications

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New Design Proposals for High-Power Renewable Energy Applications

Renewable energy applications are a great challenge for Power Electronics, with efficiency and reliability being the prevailing requirements. Today, 1700V low-voltage Silicon is vastly superior. For input/output powers of several MW, dozens of modules with dozens of chips need to be connected in parallel. The best solution is paralleling inverters / power blocks, but such solutions require additional low-voltage transmission from the source to the medium-voltage (MV) transformer. An alternative solution is a MV source and transmission connected to MV grid-side inverter based on low-voltage Silicon - power blocks - connected in series. In addition, interleaved PWM reduces the size of the sinusoidal filter and the switching frequency, as well as the total losses. **Dejan Schreiber, Senior Application Manager, Semikron, Nuremberg, Germany**

Existing new high-power renewable energy sources are wind turbines (WT) and photovoltaic (PV) applications. The average power of new WTs is over 2MW, but up to 5MW are also in use. As for PV, over the last few years, the trend has been to use individual units of up to 0.5MW, with an increasing tendency towards 1MW+ per unit. Large PV systems of 10MW are the most common and up to 60MW are in operation. Both are connected to the grid through line-side inverters, and both supply the grid with low THD (total harmonic distortion) sinusoidal currents via sinusoidal filters.

WTs have generator-side converters with boost features, rectifying the variable generator voltage to constant DC voltage required for optimal operation of the grid-side converter. Similarly, PV panels supply converters with voltage proportional to sunlight intensity, ambient temperature, load current, and power. The result is a variable input voltage in the range of more than 1:2. Typically high-power PV grid-side inverters do not use additional front-end converters.

Power converting efficiency is the No.1 priority. Today, power electronics (PE) uses industrial Silicon-based components of 1200V and 1700V for WTs and 1200V for PV applications (600V for low-power single-phase supply). The system efficiency can be improved with reduced converter losses by using the right Silicon and new better semiconductors technologies. This article shall not, however, dwell on this for the simple reason that IGBT's will remain the work horse of power electronics for the next 5 to 10 years, with no notable changes to speak of.

WT designs based on a doubly fed induction generator (DFIG) are going out of fashion. In fact, WT companies that employ DFIG technology are now basing their new developments on the full-size principle, the traditional 4-quadrant drive. WT converter efficiency today, for a full-size construction with two serial power electronics converters placed in one casing, and measured from the generator output through generator dv/dt filter, generator-side converter, DC link, grid-side inverter and output sinusoidal filter, is in the range of 96-97%. Power converter sizing is driven by price and high reliability requirements.

Reliability is a very important factor. A wind turbine must not stop working, must not stop turning! First-rate components are therefore an absolute must. What is also important, however, is to have a turbine design which enables continued operation should an individual component fail. The large inverter powers in the range of several MVA require considerable quantities of semiconductor chips in parallel, and this is accomplished by paralleling modules.

Solutions for parallel operation of IGBT modules

1) One inverter phase unit is used for the entire power with one driver for many

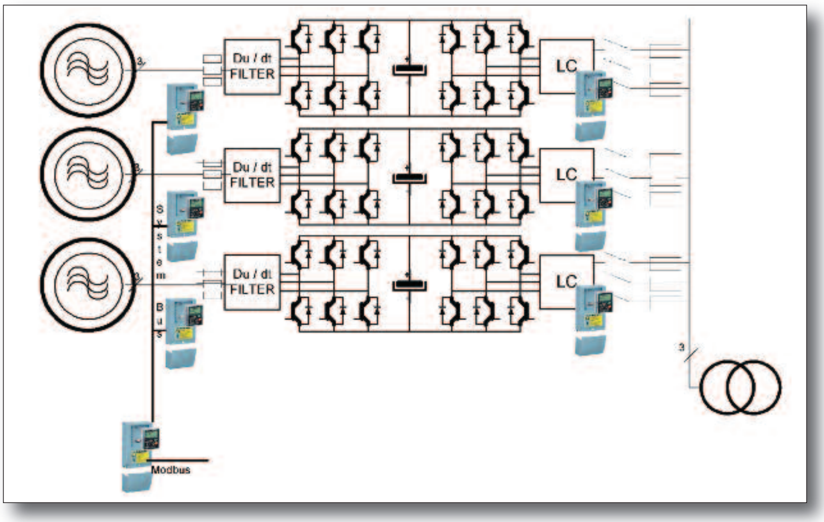

Figure 1: **Turbine construction with three generator windings and independent drive trains**

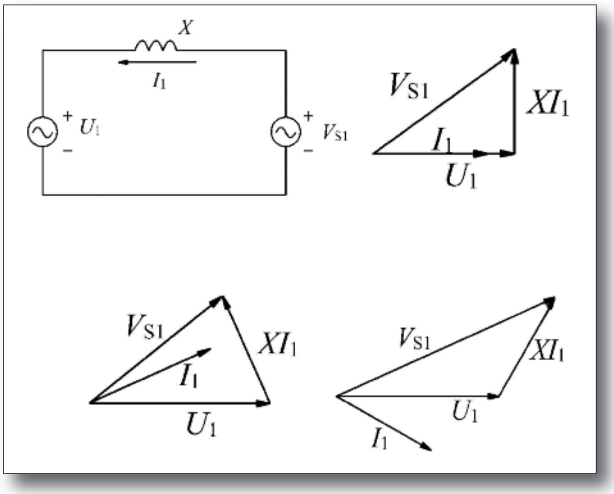

Figure 2: Per phase equivalent circuit of the line-side inverter and phasor diagrams for unity, leading, and lagging power factor operation

IGBT modules in parallel. Each IGBT module has its own gate resistors and symmetrical DC & AC connections. One successful example is SEMIKUBE IGBT power STACK, for use in PV applications.

2) Paralleling of several inverter-phase units, each with own driver operating in parallel. Due to different driver delay times, small AC output chokes are also required (paralleling of SKiiP IPM power stack).
3) Paralleling of three-phase units with a DC link and several modules in parallel, driven by its own drivers. For higher power, several three-phase inverters are connected in parallel. Due to different driver delay times, AC output chokes are still needed. One PWM signal and one DC link are in use.
4) Parallel operation of three-phase inverters with one PWM controller and additional control of load current sharing of parallelized inverters (sophisticated PWM control).
5) Master-slave drivers with short delay times, driving the several modules connected in parallel. There is no need for any additional inductances, and in the event of damage to a semiconductor chip, only one module will be damaged.
6) Parallel inverter operation with galvanic isolation on input or output side - is the operation in parallel of standard, independent basic units with different PWM and separate controllers.

In some WT designs, the generator and the entire drive train, as well as the MV transformer, are placed in the nacelle. In these cases, the total weight of the nacelle is very high, but it's the only way to make the transmission losses between the LV generator and the MV grid bearable. In other designs, the WT drive train is located at the bottom, at the base of the tower. Power transmission over that distance of about 100m is low-voltage, with high power losses and cost.

Standard industrial Silicon-based IGBT modules of 1700V have to be used in parallel for one three-phase inverter of 1MW; the maximum available power of a single three-phase inverter today is 1.5MW. Therefore, solutions with several generator windings facilitate parallelization of independent drive trains. At the same time, the reliability of this design is higher than that of designs with one high-power converter with the same number of modules connected in parallel (see Figure 1).

WT generators

Generator requirements such as minimum size, ripple torque, and short circuit torque, especially for low-speed, direct-drive generators, result in generator solutions with a number of phases, such as 2 or 3 x three-phase windings, or 6 x three-phase windings. Generators with poly-phase systems of 5 or 7 or more phases are not used, because of standard industrial three-phase inverters and controllers. For generator sizes in the range of several MW, the traditional method is a medium-voltage output. MV inputs & outputs, however, require the use of MV PE components. State-of-the-art MV converters used on the grid side, with switching frequencies of several kHz, have a much lower efficiency and are far more expensive per kW.

Additional requirements for renewable energy sources are: active power control, reactive power control, low-voltage ride-through capability, as well as a requirement mentioned less often, namely operation under unsymmetrical grid voltages. Reactive power control for renewable energy sources, initially used in WTs, and more recently for PV applications, calls for higher DC link voltage input to the line-side inverter.

Power flow in the PWM converter is controlled by adjusting the phase shift angle δ between the source voltage U1 and the respective converter reflected input voltage Vs1.

When U1 leads Vs1 the real power flows from the AC source into the converter. Conversely, if U1 lags, Vs1 power flows from the converter's DC side into the AC source. The real power transferred is given by equation 1:

$$P = \frac{U_1 V_{s1}}{X_1}\sin(\delta)$$

The AC power factor is adjusted by controlling the amplitude of Vs1. The per phase equivalent circuit and phase diagrams of the leading, lagging and unity power factor operation is shown in Fig.2. The phasor diagram shows that to achieve a unity power factor, Vs1 has to be according to equation 2

$$V_{s1} = \sqrt{U_1^{\,2} + (X_1 I_1)^2}$$

Proposal for series connection of high power WT inverter cells

WT designs with full size converters based on separate generator windings have many advantages, but also one large drawback. Many cables are required between the generator and the converter - 3 x three-phase winding set. All of these converters are therefore situated near the generator, in the nacelle. For high powers at low voltages, the generator currents are >> 1500A. An attractive solution is the MV synchronous generator and only a diode rectifier. However, in this case, the DC

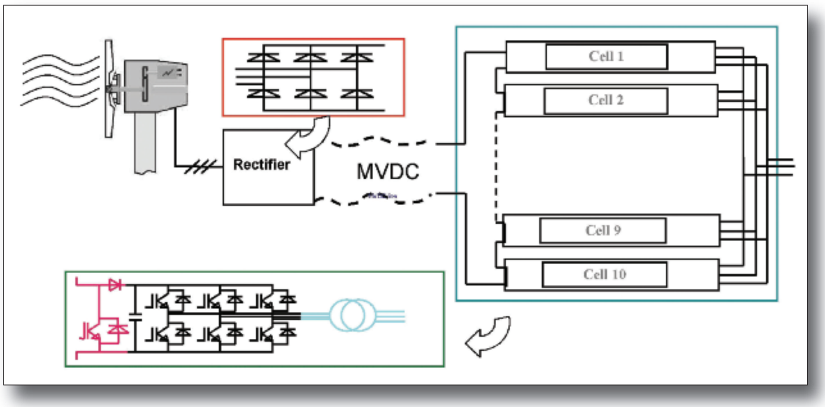

Figure 3: MV generator with MV grid-side inverter with several cells connected in series

voltage variations are large (1:2) and require MV Silicon devices. As the WT is supposed to produce power even at minimal rotation speed and a minimal DC voltage, for instance for 1000VDC, the output voltage at the MV transformer is relatively low, i.e. 660V. At the same time, DC voltage may reach more than 2kV.

A logical solution to the MV grid-side inverter is a string of series connected inverters, which can divide the variable rectified generator voltage. These grid-side inverter cells are connected to the primary windings of the MV line transformer, and independently maintain their DC link voltages. For lower generator voltages, some of the cells must be bypassed, so that the equivalent total voltage of the cells is lower and corresponds to the generator voltage. The WT torque requirement is the same as the generator current requirement; it is therefore compared with the real, actual value of the DC current. If the torque demand is higher than the actual current DC value, the sum of bypass times should be larger, more cells are bypassed and the equivalent counter-EMF will be lower, thus increasing DC current.

Each of the grid-side inverters used controls and maintains constant input DC voltage, for instance 1000V, and is connected to the primary winding of the transformer. If the DC voltage is higher than a set value, the discharge currents will be larger. The grid-side inverters can be single- or three-phase units. Single-phase units have only one transformer winding. The rectified generator MV, for instance a dozen kV, supplies this string of inverter cells. Some cells have input bypass switches which allow for DC link control, and some cells can have no input bypass. They are always connected in series and the sum of their voltages corresponds to the minimum generator voltage.

Described below is a power conversion scheme for MW-class wind turbines consisting of a medium-voltage synchronous generator, a diode rectifier in the nacelle, and an MV DC-efficient power transmission down to the MV line-side inverter and the high-voltage grid transformer (see Figure 3). Several cells that share the variable output generator voltage are also used. Each cell has a grid-side inverter, three-phase or single-phase, separate transformer windings and DC link capacitors. The input power - the current from the MV generator - charges the DC link, and the converter discharges it. This is why the DC link voltage remains constant, because the grid-tie inverter controls the DC discharge current to the grid. The cell input features one half-bridge configuration, for instance a conventional booster; this operates, however, as a bypass switch only.

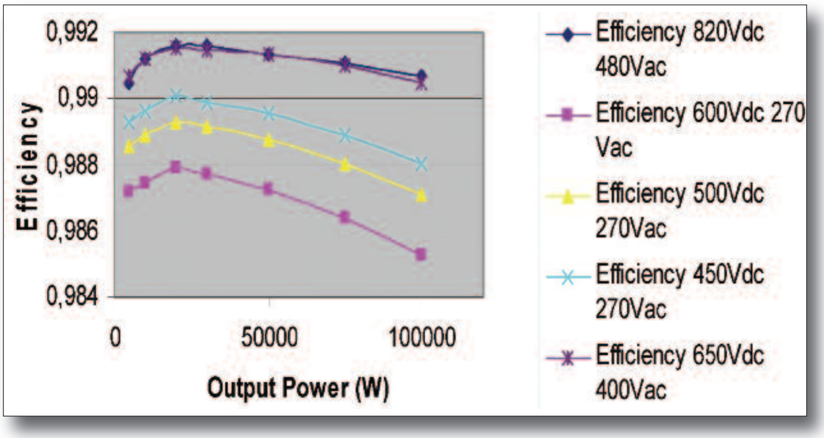

Figure 4: GTI (grid-tied inverter) efficiency at various power; switching frequency 5kHz

If the generator voltage is lower than the sum of the series connected cells, the current from the generator will decline. More cells therefore have to be bypassed, reducing the number of series cells and increasing the generator current.

PV applications

PV applications usually have only one PE line-side grid-tie inverter (GTI). GTI AC output voltage is proportional to the minimum DC input voltage - the start-up PV voltage proportional to the minimum sunlight. If the chosen AC output voltage is lower, the currents for the rated power will be higher; at the same time, however, the start-up voltage will be lower. The AC output voltage is therefore a compromise: some products use 3 x 270V, while others use 3 x 328 V.

The higher AC output voltage design neglects the minimum energy that could be used if the PV voltage / output AC voltage is lower. In a PV application, GTI operate at approximately 1/2 of the rated output voltage only; 1200V silicon is developed for input/output voltage of up to 480VAC, and PV applications today use just 270V...330V. The efficiency of such operation is lower, because it is strongly related to the modulation factor m, VAC/VDC ratio. For 400VAC/650VDC or 480VAC/800VDC, the efficiency is very similar and higher than the ratio used in PV applications of 270VAC (500...900VDC) (see Figure 4).

Described below is a power conversion scheme (Figure 5) for MW-class PV consisting of solar panels, an active front-end with symmetrical voltage boosters next to the solar panels, a DC transmission line to the inverter station, industrial grid-side converter, sinusoidal filter, and standard line voltage / MV transformer.

Inverter input voltage is optimized to the AC transformer input voltage, and the modulation factor m is close to 1 according to equation 3:

$$m = 2 \cdot \frac{\sqrt{3}}{3} \cdot \sqrt{2} \cdot \frac{Uac}{Vdc}$$

Sample application from the USA: Circuit from Figure 5 PV voltage is in the range of 200V-600V; booster output voltage / transmission voltage is 800VDC; output: 3x480V, a standard transformer is in use. 600V Silicon is used for the front end, and 1200V for the inverter. For a PV voltage of 400V, for example, the DC transmission losses are four times lower, while the transmission voltage is 800V. The requirement is to have a relatively low ripple current from PV panels, and this can be achieved with higher inductance between the PV panels and the front-end unit, but also with increased switching frequency. The inductance of the

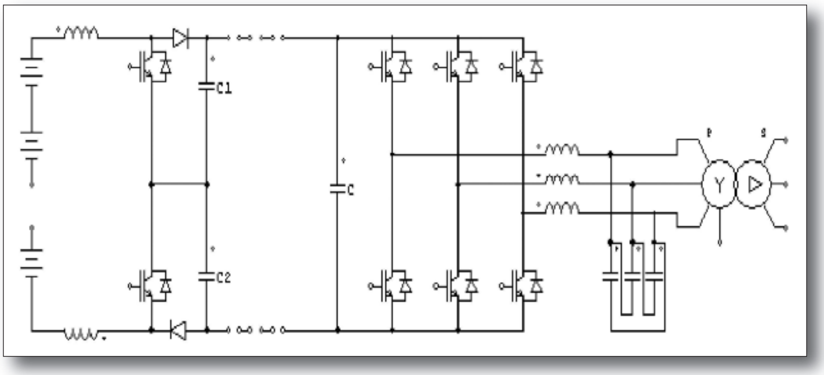

Figure 5: Voltage booster and GTI

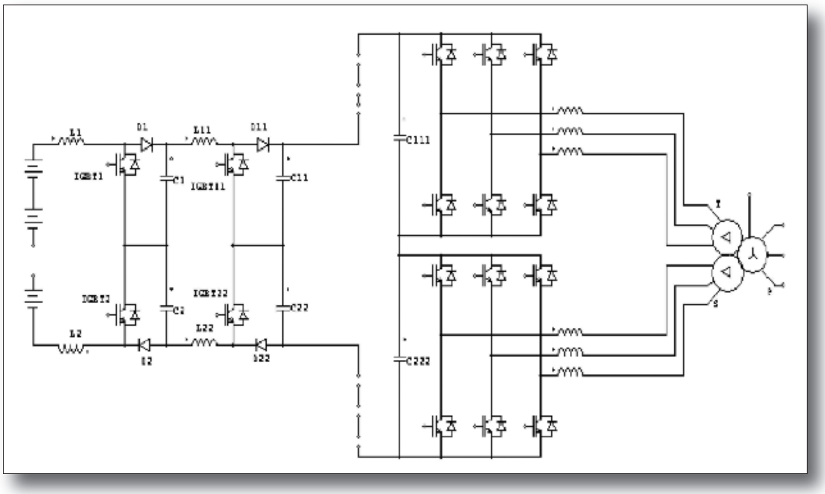

Figure 6: **Voltage duplicator, second bypass or booster, two GTI with interleaved PWM**

connection cables have a positive influence on the reduction of the current ripple. A 100m long cable has an inductance of more than 0.1mH.

Sample application from the EU: For a PV in the 400-900V range, the front booster will produce 650V for 3 x 400V, or 800V for 3 x 480V. If the PV voltage is higher than 650V or 800V, the booster function is turned off and the PV voltage goes to the GTI unaltered.

The front-end booster alternately supplies the upper and lower half of the output voltage, and when the top IGBT1 and the bottom IGBT2 are turned-on for half of the switching period, i.e. 180° electrics, it operates as a voltage duplicator. This method of operation has great advantages because the output current of the PV panel is constant and does not use additional high inductance L1 and L2. A connection cable length of 50-100m is sufficient. The scheme presented in Figure 6 is used because of this advantage.

The PV voltage is always doubled, i.e. it is in the range of 800V...1800V. As 1800V is too high for the low-voltage silicon used in the GTI, we can use the same idea as for MV wind turbines with two cells in series. The cell bypass circuit can be mounted near to the voltage duplicator and it can adjust the necessary DC voltage for two inverters in series. That way, the transmission voltage will be up to 4 times higher than the PV output voltage.

Example 1: PV voltage 400V...900V; duplicator voltage 800...1800V; second booster output voltage/transmission voltage/inverter voltage: 1600V...1800V, without boosting effect after 1600V, for the transformer 2 x 3 x 480V. All switches in use are for 1200V.

Example 2: PV voltage: 400...900V, duplicator voltage 800...1800V; second booster output voltage/transmission voltage/inverter voltage: 2200V=2x1100V, for the transformer 2 x 3x690V. Voltage duplicating silicon is for 1200V, and the remaining IGBTs & diodes are for 1700V. The inverter efficiency with 1700V silicon is higher than that for 1200V, if the carrier switching frequency is lower than 4kHz.

For a 2200V transmission voltage, the transmission losses are 16 times lower than the losses of a classic, direct connection and a PV voltage of 550V (using the same connection cables).

The grid-side inverters, top and bottom side, have the same power and phase current values, and are connected to windings with galvanic insulation. Interleaving PWM can therefore be easily applied. For two inverters operating in parallel, the interleaved phase shifting is half of the switching period (i.e 180° el). In this way, the size of the sinusoidal filter, with only one inductance L, is significantly reduced. The simulation example in Figure 7 shows inverter 1 and 2 currents, with a carrier switching frequency of 1kHz only and THD=19%, as well as the sum of these currents - the grid current, with very low THD=3.8%.

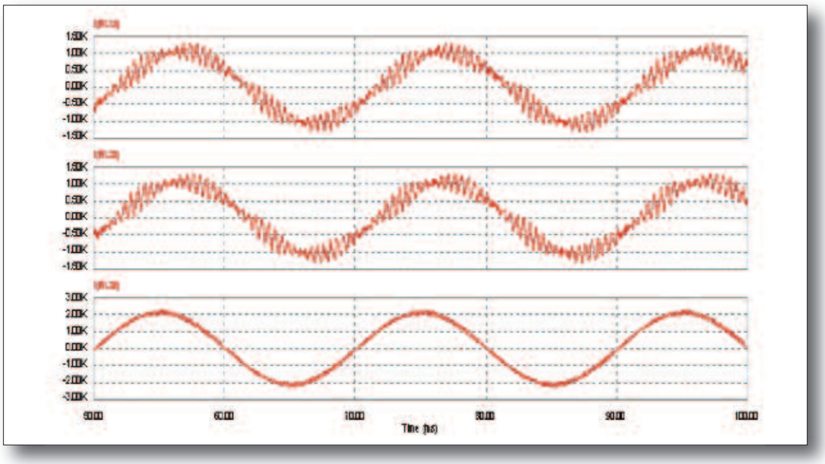

Figure 7: **Top-side inverter phase current; bottom-side inverter phase current, both with THD=19% and the grid current, with THD=3.8%; Filter inductance L_total=12%; F_{sw}=1kHz**

The advantage of interleaving is clear. Only a low-pass filter with a single inductance, plus stray transformer inductance, corresponding to the short circuit transformer voltage u_k=4%. L_total=12% is used. For a current THD below 4%, one grid-tie inverter with 12% inductance of the sinusoidal output filter needs a carrier switching frequency of more then 6 kHz.

Conclusions

WT power electronics are based exclusively on 1700V silicon IGBT & diodes. DFIG-WTs are becoming less popular, with current trends moving towards full-size configurations featuring two inverters connected back-to-back. WTs in development have powers in the range of 3-5 MW. The principle with 2, 3 and even 6 three-phase generator windings, using the same number of independent drive trains, with independent control, provides high modular power, as well as a redundant operation in case of a failure. The new design proposal for the WT is a MV generator with MV line-side inverter featuring a string of cells with bypass circuits and LV GTIs connected to independent MV transformer windings.

PV applications are based on GTIs of up to 1MW of power, connected directly to the PV panels. For PV applications, the proposal aims for higher system efficiency, i.e. consists of a voltage duplicator and two cells in series, with 4 times higher transmission voltage and inverter operation with modulation factor 1, using interleaving in PWM control, to significantly reduce the output filter.

Literature

Dejan Schreiber: "High-Power Renewable Energy Applications - State-of-the-Art & New Design Proposals", PEE Special Session "Power Electronics for Efficient Inverters in Renewable Energy Applications", PCIM Europe 2010, May 4, Room Paris