Power electronics - key technology for renewable energy systems

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Power Electronics - Key Technology for Renewable Energy Systems

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Abstract – **The electrical energy consumption continues to grow and more applications are based on electricity. We can expect that more 60 % of all energy consumption will be converted and used as electricity. Therefore, it is a demand that production, distribution and use of electrical energy are done as efficient as possible. Further, the emerging climate changes is arguing to find sustainable future solutions. Of many options, two major technologies will play important roles to solve parts of those future problems. One is to change the electrical power production from conventional, fossil based energy sources to renewable energy sources. Another is to use high efficient power electronics in power generation, power transmission/distribution and end-user application. This paper discuss trends of the most emerging renewable energy sources, wind energy and photovoltaics, which by means of power electronics are changing and challenging the future electrical infrastructure but also contributes steadily more to non-carbon based electricity production. Most focus in the paper is on the power electronics technologies used. In the case of photovoltaics transformer-less systems are discussed as they have the potential to obtain the highest efficiencies**

I. INTRODUCTION

In classical power systems, large power generation plants are located at adequate geographical places to produce most of the power, which is then transferred towards large consumption centers over long distance transmission lines. Now the power system is changing, as a large number of dispersed generation (DG) units, including both renewable and non-renewable sources such as wind turbines, wave generators, photovoltaic (PV) generators, small hydro, fuel cells and gas/steam powered Combined Heat and Power (CHP) stations, are being developed and installed all over the world [1]-[2]. A wide-spread use of renewable energy sources in distribution networks is seen. E.g. Denmark has a high power capacity penetration (> 30 %) of wind energy in major areas of the country and today 28 % of the whole electrical energy consumption is covered by wind energy. The main advantages of using renewable energy sources are the elimination of harmful emissions and the inexhaustible resources of the primary energy. However, the main disadvantage, apart from the higher costs is the uncontrollability as they are completely weather-based. The availability of renewable energy sources has strong daily and seasonal patterns and the power demand by the consumers could have a very different characteristic. Therefore, it is difficult to operate a power system installed with only renewable generation units due to the characteristic differences and the high uncertainty in the availability of the renewable energy sources without any load control. This is further strengthened as no real large scale electrical energy storage systems exist.

The wind turbine technology is one of the most emerging renewable energy technologies [3]-[12]. It started in the 1980'es with a few tens of kW production power per unit to today with multi-MW size wind turbines that are being installed. It also means that wind power production in the beginning did not have any impact on the power system control but now due to their size they have to play an active part in the grid operation. The technology used in wind turbines was in the beginning based on a squirrel-cage induction generator connected directly to the grid. By that power pulsations in the wind are almost directly transferred to the electrical grid. Furthermore, there was no control of the active and reactive power except from some capacitor banks, which are important control parameters to regulate the frequency and the voltage in the grid system. As the power range of the turbines increases those control parameters become very important and power electronics [5] is introduced as an interface between the wind turbine and the grid. The power electronics is able to change the basic characteristic of the wind turbine from being an energy source to be an active power source. The electrical technology used in wind turbine is not new. It has been discussed for several years but now the price pr. produced kWh is so low, that solutions with power electronics are very attractive [3]-[35].

The development of photovoltaics has also been progressive. Every year the price pr. produced kWh is decreasing by improving the PV-cells themselves as well as making the PV-inverters more efficient and reduce the prize. The PV-technology is working along a couple of technology lines – all are needing large investment to move from basic research to use in

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commercial large scale products. Power electronics is again the key to enable the photovoltaics technology to be connected to the grid system [62]-[78].

Both technologies are changing the grid to be much more uncontrolled and heterogeneous. Power system operators are developing new methods to control the grid – e.g. in a smart-grid structure where new demands to communication, control, safety, protection and so on are becoming defined [2].

The scope of this paper is to give an overview and discuss some trends in wind turbine and photovoltaics technologies. First, the basic market developments are discussed for photovoltaics and wind turbines. Next different wind turbine configurations are explained both aerodynamically and electrically – including a comparison. That includes also new power converter topologies for Multi-MW wind turbines. Different control methods are further explained for state-of-the art wind turbines including the grid codes which are also pushing the technology. Further the PV-technology is presented including the necessary basic power electronic conversion in different topologies. Different power converters are explained with special focus on how to reach a very high efficiency using transformer-less systems which is the one of the present key development trends. Finally, some conclusions are given for the two technologies.

II. Status for Wind Power and Photovoltaics

A. Wind power

The wind power has grown to a cumulative worldwide installation level of 160 GW with over 38 GW alone installed in 2009, according to BTM Consult. The total electrical power capacity market is presently around 200 GW and this number is indicating that wind power is really an important factor. The worldwide penetration of wind power was 1.6% and the prediction for 2019 is more than 8% or 1 TW cumulative installations. China was the largest market in 2009 with over 13 GW installed and in general EU, USA and China are sharing around one third of the total market. The evolution of the wind turbine market is shown in Fig. 1.

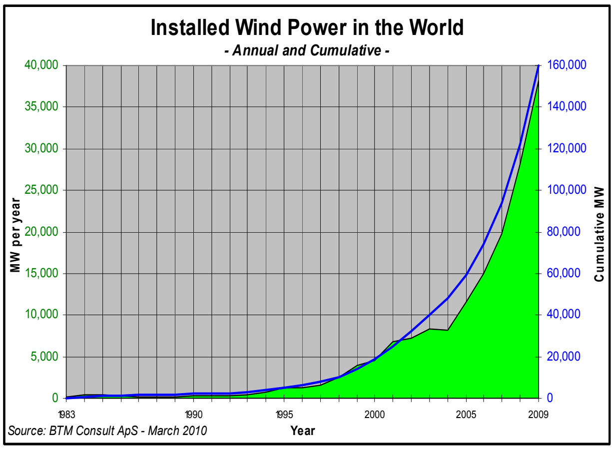

Fig. 1. Annual and cumulative installed Wind Power Capacity from 1985 to 2009 (source: BTM Consult).

The Danish company Vestas Wind Systems A/S was in 2009 still on the top position among the largest manufacturers of wind turbines in the world, closed followed by GE Wind, as the second largest in the world. The Chinese company Simovel, the German Company Enercon and Chinese company Goldwind are in third, fourth and fifth positions, respectively. It is interesting to notice that three Chinese manufacturers are in the Top 10 and with a total share of 23.3%. Fig. 2 shows the wind turbine top-suppliers in 2009.

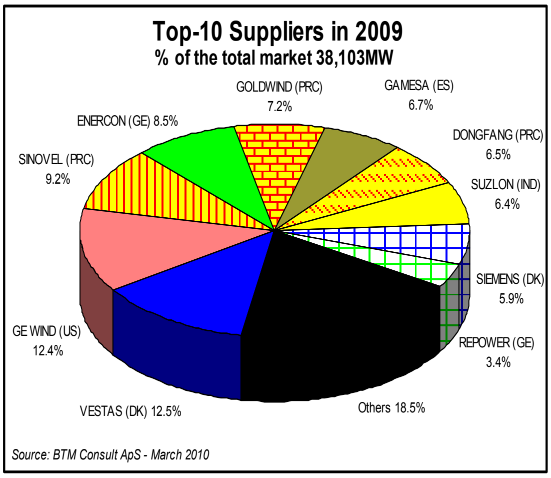

Fig. 2. Wind turbine market share distributed by manufacturers in 2009. (source: BTM Consult).

Nowadays, the most attractive concept seemed to be the variable speed wind turbine with pitch control [3]-[22]. Still some manufacturers are providing the 'classical' active stall, fixed speed turbines especially for countries where the grid codes do not demand dynamic reactive power control (presently e.g. in China, parts of USA) However, recently Siemens Wind Power released a multi-megawatt class variable speed full-scale power converter (FSC) with a permanent magnet generator. The most used generator type is still the induction generator but Enercon is using the wounded synchronous generator while other companies have launched new wind turbines with Permanent Magnet Synchronous Generators (PMSG). All wind turbine manufacturers are using a step-up transformer for connecting the generator to the grid. However, the general trend is to move from Doubly-Fed Induction Generator (DFIG) to full-scale power converter wind turbines. Today the DFIG is still dominating the market but in the future FSC is expected to take over. The transition is mainly valid for larger wind turbines (3-6 MW).

B. Solar power

Photovoltaic (PV) based solar power is like the wind turbines a booming industry; since 1980, when the terrestrial applications began. The annual installation of PV power has increased to above 7 GWp leading to cumulative installed PV power by the end of 2009 reaching to approximately 15 GWp according to EPIA which actually is 10 % of the wind power capacity. Fig. 3 shows the cumulative PV installed capacity.

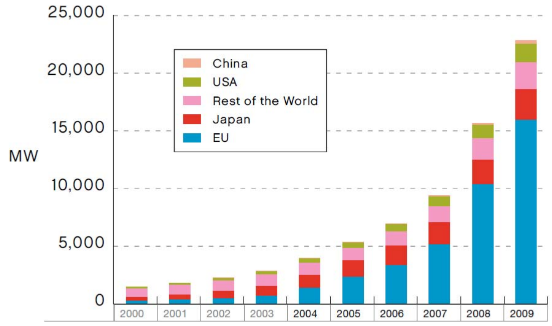

Fig. 3. Cumulative PV installed capacity from 2000 to 2009 (source: EPIA, http://www.epia.org) [78].

The annual growth rate is still very high (>30%) especially for the last 3 years. As in the previous years the vast majority of new capacity was installed in EU with Germany as dominating the market followed by Spain and Italy. USA market is also growing fast According to Photon Magazine, the prices for PV modules are decreased by the end of 2009 to around 1.5-2 €/Wp with stronger trends for using thin film technology in order to reach the psychological threshold of 1 €/Wp, which really will trigger the mass-penetration of PV as an energy and power source. In addition to the PV module cost, the cost and reliability of PV inverters are also important issues. The inverter cost share represents about 10-15% of the total investment cost of a grid connected PV system.

The prices for PV inverters in the 1-10 kW range are shown in Fig. 4. It can be seen that the inverter cost of this power class has decreased by more than 50 % during the last decade. The main reasons for this reduction are the increase of the production quantities and the implementation of new system technologies (e.g. string-inverters). A further 50 % reduction of the specific cost is anticipated during the coming decade which requires the implementation of specific measures in the development and the manufacturing processes.

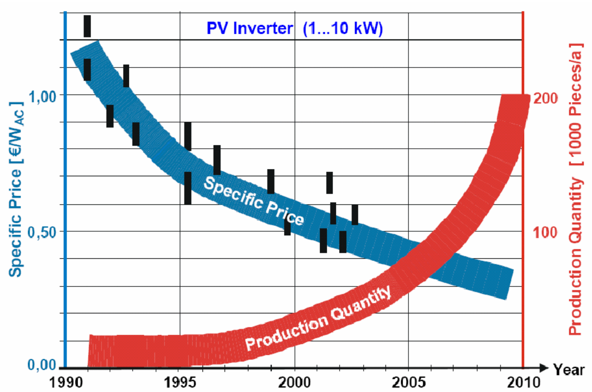

Fig. 4. Development of specific cost and production quantity for the PV inverter of nominal powers between 1 and 10 kW during two decades (¦ indicates specific prices of products on the market).

III. Wind Power conversion

Wind turbines capture power from the wind by means of aerodynamically designed blades and convert it to rotating mechanical power. As the blade tip-speed should be lower than half the speed of sound the rotational speed will decrease as the radius of the blade increases. For multi-MW wind turbines the rotational speed is 8-13 rpm. So far the most weight efficient way to convert the low-speed, high-torque power to electrical power is to use a gear-box and a standard fixed speed generator as illustrated in Fig. 5

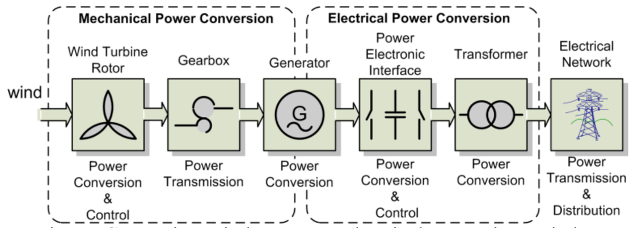

Fig. 5. Converting wind power to electrical power in a wind turbine with the option to use a gearbox and a power converter [5].

The gear-box is optional as multi-pole generator systems are interesting solutions. Between the grid and the generator a power converter is inserted which gives flexibility in control of power to the grid and power from the generator.

There exist many technical solutions and a technical roadmap is shown in Fig. 6 starting with wind energy/power and converting the mechanical power into electrical power. The electrical output can either be ac or dc. In the last case a power converter has to be used as interface to the grid which also gives maximum controllability.

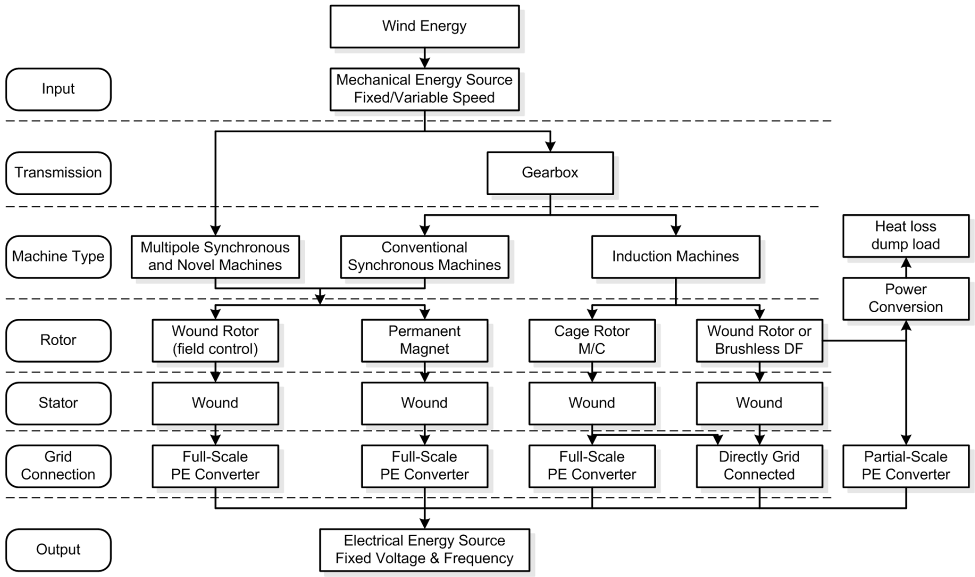

Fig. 6. Roadmap for wind turbine technology from wind to electricity [7].

A. Basic control methods for wind turbines

The development in wind turbine systems has been steady for the last 35 years [3]-[35] where four to five generations of wind turbines have been developed and the power capacity has increased by a factor of 100. In a wind turbine it is essential to be able to control and limit the converted mechanical power at higher wind speeds, as the power in the wind is a cube of the wind speed. It is also important to maximize the energy capture from the wind below maximum power production. The power limitation is done either by stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (here the blades are turned out of the wind at higher wind speed). The basic output characteristics of a wind turbine using these three methods of controlling the power are summarized in Fig. 7.

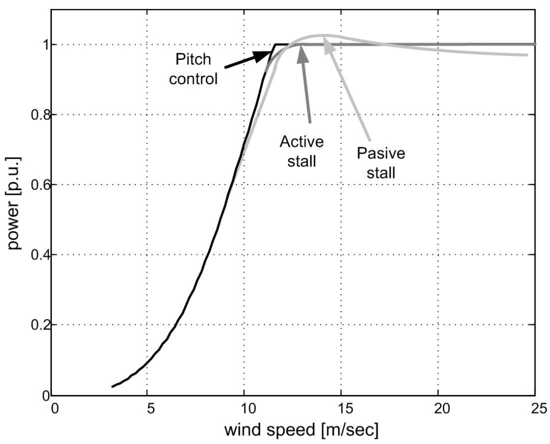

Fig. 7. Power characteristics of different wind turbine systems. Passive stall is based on fixed speed operation.

Another control variable in wind turbine system is the rotational speed. A fixed speed wind turbine has the advantages of being simple, robust, reliable, well proven and with low cost of the electrical parts. Its direct drawbacks are the uncontrollable reactive power consumption, mechanical stress during wind gusts and limited power quality control. Due to its fixed speed operation, wind speed fluctuations are converted to mechanical torque fluctuations, beneficially reduced slightly by small changes in generator slip, and then transmitted as fluctuations into electrical power to the grid.

The variable speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speed. By introducing variable speed operation, it is possible to continuously adapt (accelerate or decelerate) the rotational speed of the wind turbine to the wind speed, in such a way that the tip speed ratio is kept constant to a predefined value corresponding to the maximum power coefficient of the blades. In a variable speed system the generator torque is nearly kept constant, the power variations in the wind being absorbed by the generator speed changes.

Seen from the wind turbine system point of view, the most important advantages of the variable speed operation compared to the conventional fixed speed operation are: reduced mechanical stress on the mechanical components such as shaft and gearbox, increased power capture and reduced acoustical noise.

Additionally, the presence of power converters in wind turbines also provides high potential control capabilities for both large modern wind turbines and wind farms to fulfill the high technical demands imposed by the grid operators such as: controllable active and reactive power (frequency and voltage control); quick response under transient and dynamic power system situations, influence on network stability and improved power quality. Those features are becoming dominant in the development of the technology.

B. *Wind Turbine Concepts*

The most commonly applied wind turbine designs can be categorized into four wind turbine concepts [9], [12]. The main differences between these concepts are in the generating system and the way in which the aerodynamic efficiency of the rotor is limited during above the rated value in order to prevent overloading.

*1) Fixed Speed Wind Turbines (**WT Type A**)*

This configuration corresponds to the so called Danish concept that was very popular in 80's. This wind turbine has a fixed speed controlled machine, with asynchronous squirrel cage induction generator (SCIG) directly connected to the grid via a transformer as shown in Fig. 8.

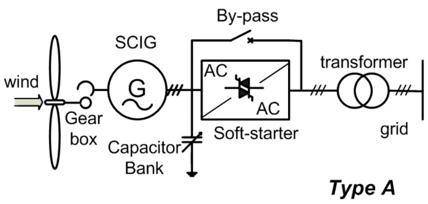

Fig. 8. Fixed speed wind turbine with directly grid connected squirrel-cage induction generator.

This concept needs a reactive power compensator to reduce (almost eliminate) the reactive power demand from the turbine generators to the grid. It is usually done by continuously switching capacitor banks following the power production variation (5-25 steps) Smoother grid connection occurs by incorporating a soft-starter as shown in Fig. 8. Regardless the aerodynamic power control principle in a fixed speed wind turbine, the wind fluctuations are converted into mechanical fluctuations and further into electrical power fluctuations. These can yield to voltage fluctuations at the point of connection in the case of a weak grid.

Thus, the main drawbacks of this concept are: does not support any speed control, requires a stiff grid and its mechanical construction must be able to support high mechanical stress caused by wind gusts.

*2) Partial Variable Speed Wind Turbine with Variable Rotor Resistance (**WT Type B**)*

This configuration corresponds to the limited variable speed controlled wind turbine with variable rotor resistance, known as OptiSlip (Vestas^{TM}) as presented in Fig. 9.

It uses a wound rotor induction generator (WRIG) and it has been used by since the mid 1990's.

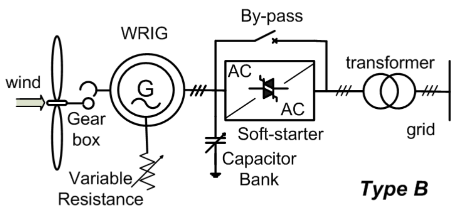

Fig. 9. Partial variable speed wind turbine with variable rotor resistance.

The generator is directly connected to the grid. The rotor winding of the generator is connected in series with a controlled resistance, whose size defines the range of the variable speed (typically 0-10% above synchronous speed). A capacitor bank compensates the reactive power. Smooth grid connection occurs by means of a soft-starter. An extra resistance is added in the rotor circuit, which can be controlled by power electronics. Thus, the total rotor resistance is controllable and the slip and thus the power output in the system are controlled. The dynamic speed control range depends on the size of the variable rotor resistance. The energy coming from the external power conversion unit is dissipated as heat loss activated at full load operation.

*3) Variable Speed WT with partial-scale frequency converter (**WT Type C**)*

This configuration is known as the doubly-fed induction generator (DFIG) concept, which gives a variable speed controlled wind turbine with a wound rotor induction generator (WRIG) and partial power-scale frequency converter (rated to approx. 30% of nominal generator power) on the rotor circuit. The topology is shown in Fig. 10.

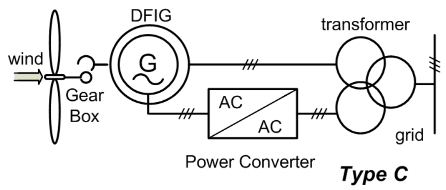

Fig. 10. Variable speed wind turbine with partial scale power converter.

The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed. The power rating of this partial-scale frequency converter defines the speed range (typically ±30% around synchronous speed). Moreover, this converter performs the reactive power compensation and a smooth grid connection. The control range of the rotor speed is wider compared to the variable rotor resistance type. The smaller frequency converter makes this concept attractive from an economical point of view. In this case the power electronics is enabling the wind turbine to act as a dynamic power source to the grid. However, its main drawbacks are the use of slip-rings and the protection schemes/controllability in the case of grid faults.

*4) Variable Speed Wind Turbine with Full-scale Power Converter (**WT Type D**)*

This configuration corresponds to the full variable speed controlled wind turbine, with the generator connected to the grid through a full-scale frequency converter as shown in Fig. 11.

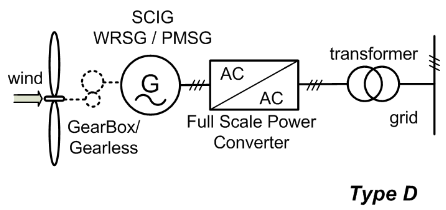

Fig. 11. Variable speed wind turbine with full-scale power converter.

The frequency converter performs the reactive power compensation and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator WRSG) or permanent magnet excited type (permanent magnet synchronous generator PMSG). The stator windings are connected to the grid through a full-scale power converter.

Some variable speed wind turbine systems are gearless – see the dotted gearbox in Fig.11. In these cases, a more heavy direct driven multi-pole generator may be used.

C. System Comparison of Wind Turbines

Comparing the different wind turbine topologies in respect to their performances it will reveal a contradiction between cost and performance to the grid. A technical comparison of the main wind turbine concepts, where issues on grid control, cost, maintenance, internal turbine performance is given in TABLE I. More details can be found in [9], [12].

TABLE I.
System comparison of wind turbine configurations.

System	Type A	Type B	Type C	Type D
Variable speed	No	No	Yes	Yes
Control active power	Limited	Limited	Yes	Yes
Control reactive power	No	No	Yes	Yes
Short circuit (fault-active)	No	No	No/Yes	Yes
Short circuit power	contribute	contribute	contribute	limit
Control bandwidth	1-10 s	100 ms	1 ms	0.5-1 ms
Standby function	No	No	Yes +	Yes ++
Flicker (sensitive)	Yes	Yes	No	No
Softstarter needed	Yes	Yes	No	No
Rolling capacity on grid	Yes, partly	Yes, partly	Yes	Yes
Reactive compensator (C)	Yes	Yes	No	No
Island operation	No	No	Yes/No	Yes
Investment	++	++	+	0
Maintenance	++	++	0	+

IV. POWER CONVERTERS FOR WIND TURBINES

Currently, concepts Type C and Type D are dominant in the modern wind turbines, and as shown in Fig. 10 and Fig. 11. The performance of power converters plays a key role in these two wind power generation systems. Some promising power converters are shown in the following.

A. Two-level power converter

Pulse Width Modulation-Voltage Source Converter with two-level output voltage (2L-PWM-VSC) is the most frequently used three-phase power converter topology. The knowledge available in this field is extensive and very well established. As an interface between generator and grid in the wind turbine system, two 2L-PWM-VSCs are usually configured as back-to-back structure (2L-BTB) with a transformer on the grid side, as shown in Fig. 12.

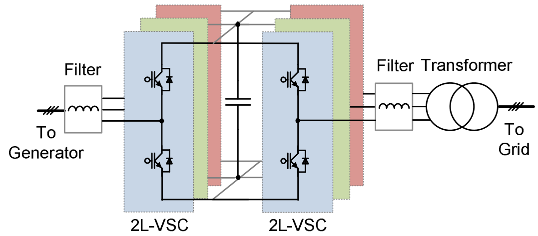

Fig. 12. Two-level back-to-back voltage source converter for wind turbines. (***2L BTB***).

A technical advantage of the 2L-BTB solution is the relative simpler structure and fewer components, which contributes to give a robust and reliable performance.

However, as fast increasing in power and voltage range of the wind turbines, 2L-BTB converter may suffer from larger switching losses and lower efficiency at Mega-Watts (MW) and Medium-Voltage (MV) power level. Also the available switching devices should probably need to be paralleled or series-connected in order to obtain the required power and voltage of wind turbines - this will lead to reduced simplicity and reliability of the power converter [41].

Another problem in 2L-BTB solution is the two-level output voltage. The only two voltage stages introduce relative higher *dv/dt* stress to the generator and transformer. Bulky output filters may be needed to limit voltage gradient and reduce the THD [36].

B. Multi-level power converter

As mentioned before, the power capacity of a wind turbine keeps climbing up to even 10 MW, it is more and more difficult for the traditional 2L-BTB solution to achieve acceptable performances with available switching devices. With the abilities of more output voltage levels, higher voltage amplitude and larger output power, multi-level converter topologies are becoming the most popular candidates in the wind turbine applications [37], [38].

Generally, multilevel converters can be classified into three categories [38]-[42]: neutral-point diode clamped structure, flying capacitor clamped structure, and cascaded converter cells structure. In order to get a cost-effective design, multilevel converters are mainly used in the 3 MW to 10 MW variable-speed full-scale power converter wind turbines. The generator can be squirrel-cage induction generator (SCIG), wound rotor synchronous generator (WRSG), or permanent magnet synchronous generator (PMSG). Several promising multilevel solutions are presented as follows.

*1) Three-level Neutral Point diode Clamped back-to-back topology (**3L-NPC BTB**)*

Three-level Neutral Point diode Clamped topology is one of the most commercialized multilevel converters in the market. Similar like 2L-BTB, it is usually configured as back-to-back structure in wind turbines, as shown in Fig. 13, which is called 3L-NPC BTB. It achieves one more output voltage level and less *dv/dt* stresses compared to the 2L-BTB, thus the filter size is smaller. The 3L-NPC BTB is able to output doubled voltage amplitude compared to the two-level topology by using switching devices at the same voltage rating.

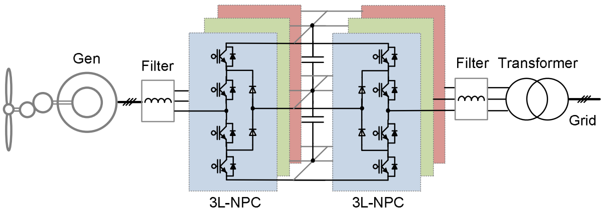

Fig. 13. Three-level Neutral Point Clamped back-to-back converter for wind turbines. (***3L-NPC BTB***).

The mid-point voltage fluctuation of DC bus has normally been a drawback of the 3L-NPC BTB. However, this problem has been extensively researched and is considered solved by the control of redundant switching status [41]. However, it is found that the loss distribution is unequal between the outer and inner switching devices in a switching arm, and this problem could lead to de-rated converter power capacity when it is practically designed [41], [43].

*2) Three-level H-bridge back-to-back topology **(3L-HB BTB)***

The 3L-HB BTB solution is composed of two H-bridge converters which are configured as back-to-back structure and shown in Fig. 14. It can achieve the similar output performance as the 3L-NPC BTB solution, but the unequal loss distribution and clamped diodes are eliminated. More efficient and equal usage of switching devices as well as higher designed power capacity can be expected [44].

Moreover, because only half of the DC bus voltage is needed in 3L-HB BTB compared to the 3L-NPC BTB, there are less series connected capacitors and no mid-point in the DC bus, the size of DC link capacitors can be further reduced.

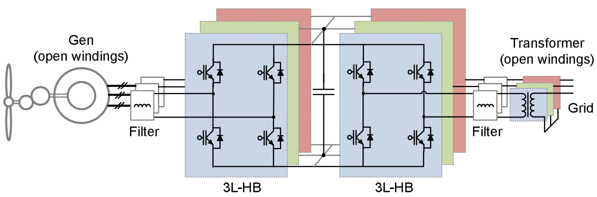

Fig. 14. Three-level H-bridge back-to-back converter for wind turbines. (***3L-HB BTB***).

However, the 3L-HB BTB solution needs an open winding structure in the generator and transformer in order to achieve isolation between each phase. This feature has both advantages and disadvantages: on one hand, open winding structure enables relative isolated operation of each phase, potential fault tolerant ability is thereby obtained if one or even two phases of the generator or the generator side converter are broken. On the other hand, an open winding structure requires doubled cable length and weight in order to connect the generator and transformer. Extra cost, losses and inductance in the cables should also be a major drawback. The open-winding impact on the loss/weight of generator and transformer still need to be further investigated.

*3) Five-level H-bridge back-to-back topology **(5L-HB BTB)***

The 5L-HB BTB converter is composed of two back-to-back H-bridge converters making use of 3L-NPC switching arms, as shown in Fig. 15. It is an extension of 3L-HB BTB, and shares the same special requirements for open-winding generator and transformer.

With the same voltage rating switching devices, 5L-HB BTB can achieve five level output voltage, and doubled voltage amplitude compared to the 3L-HB BTB solution. These features enable smaller output filter and less current rating in the switching devices as well as in the cables [38], [45].

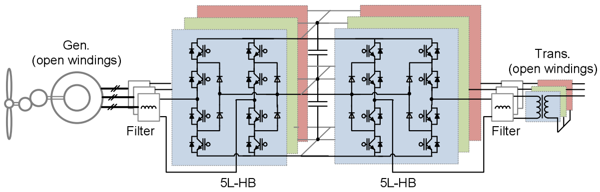

Fig. 15. Five-level H-bridge back-to-back converter for wind turbines. (***5L-HB BTB***).

However, compared to 3L-HB BTB, the 5L-HB BTB converter introduces more switching devices, which could reduce the reliability of total system. Problems with unequal loss distribution as well as larger DC link capacitors unfortunately also comes back.

*4) Three-level Neutral Point diode Clamped topology for generator side and Five-level H-bridge topology for grid side **(3L-NPC + 5L-HB)***

Generally, the output quality requirements of grid side are much stricter than those of the generator side [61]. To adapt this unsymmetrical requirements for wind power converters, this "compound" configuration employs 3L-NPC topology on the generator side, and 5L-HB topology on the grid side to achieve an unsymmetrical performances, as shown in Fig. 16.

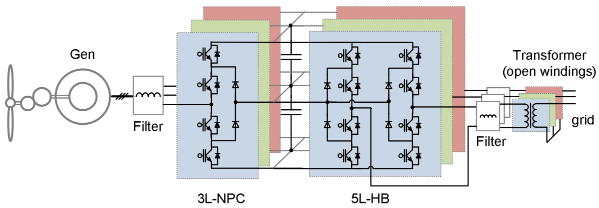

Fig. 16. Three-level Neutral Point Clamped and five-level H-bridge converter for wind turbines. (***3L-NPC + 5L-HB***).

On the generator side, this configuration has the similar performance of 3-NPC BTB solution. While on the grid side, it shares the same performance of 5L-HB BTB. The voltage levels and amplitude of grid side is higher than those on the generator side. It is noted that an open winding structure in the generator is avoided, cable length on the generator side is reduced to half, but the potential fault tolerant ability is also eliminated. It has less switching devices compared to 5L-HB BTB, but unequal loss distribution in the switching devices still exists.

*5) Cascaded H-bridge Back-to-back converter with Medium-Frequency-Transformers (**CHB-MFT**)*

Up until now, one of the most commercialized cascaded converter cells multilevel topologies is Cascaded H-Bridge (CHB) converter. Unfortunately, the CHB needs isolated DC-link for each converter cell. This characteristic may involve complex multi-pulse transformer on the generator side, resulting in larger weight and volume [38], [46].

A configuration which shares the similar idea with some of the next generation traction converters [47], [48], and European UNIFLEX-PM Project [49] is proposed in Fig. 17, whose converter cell is indicated in Fig. 18. It is based on a back-to-back Cascaded H-bridge converter structure, with galvanic insulated DC/DC converters as interface.

The DC/DC converters with medium frequency transformer (MFT) operate at several kHz to dozens of kHz, the transformer size is thereby reduced. Because of the cascaded structure, this configuration can be directly connected to the transmission power grid (10 kV-20 kV) with high output voltage quality, filter-less design, and the redundancy ability [47]-[49].

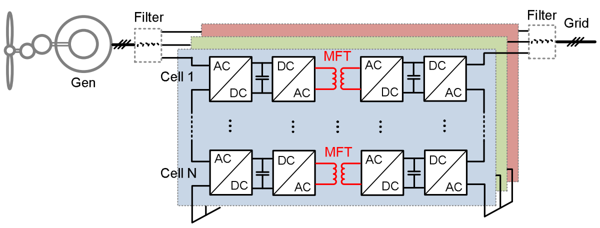

Fig. 17. Cascade H-bridge back-to back converter for wind turbines with Medium Frequency Transformer. (***CHB-MFT***).

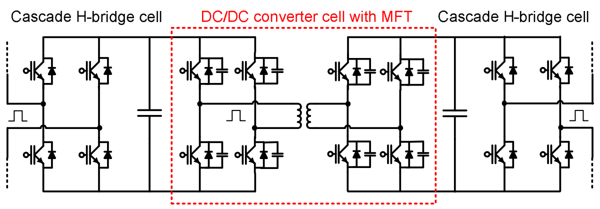

Fig. 18. Converter cell of the Cascade H-bridge back-to-back converter with Medium Frequency Transformer.

However, the large amount of power semiconductors as well as auxiliary components could largely reduce this converter's reliability and increase the cost. The total system weight and volume reduction in the wind turbine application still needs to be further investigated.

The comparisons between the six solutions for full-scale power converter wind turbines are shown in TABLE II, regarding the performances of output voltage levels, power semiconductor numbers, maximum output voltage amplitude, fault tolerant ability, as well as filter and transformer size.

TABLE II.

Comparisons of the multilevel solutions for wind turbines.

Configurations	**2L BTB**	**3L-NPC BTB**	**3L-HB BTB**	**5L-HB BTB**	**3L-NPC +5L-HB**	**CHB-MFT**
Output voltage levels	2	3	3	5	3 / 5	2N+1 [1]
IGBT number [2]	1 pu.	2 pu.	2 pu.	4 pu.	3 pu.	4N pu.
Diode number [2]	1 pu.	3 pu.	2 pu.	6 pu.	4.5 pu.	4N pu.
Max output voltage [2]	1 pu.	2 pu.	2 pu.	4 pu.	2 / 4 pu.	2N pu. [1]
Fault tolerant ability	No	No	Limited [3]	Limited [3]	No	Yes
Filter size [4]	+++	++	++	+	++ / +	0
Transformer size [4]	+++					+

Note:
1. N is the cascade converter cell number.
2. Value is normalized based on 2L BTB configuration.
3. Fault tolerant ability in the grid side converter may be not allowed.
4. The more +, the larger and heavier.

C. *Unidirectional power converter solution*

Nowadays there is also a trend to use the permanent magnet synchronous generator (PMSG) in the full-rated power converter wind turbines. As there is no reactive power needed in such generator system and active power flows uni-directionally from PMSG to the grid a simple diode rectifier can be applied as the generator side converter then will be a cost-effective solution. While for the grid side converter, some of the previously presented four-quadrant topologies, which offer all the grid support features, can be directly used.

These wind turbines with PMSG can have a gearbox or they can be direct-driven [50]. In order to get variable speed operation and stable DC bus voltage, a boost DC-DC converter could be inserted in the DC-link, as shown in Fig. 19.

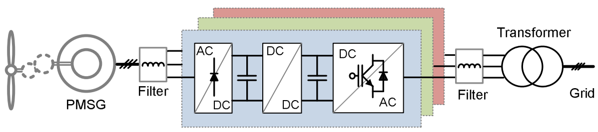

Fig. 19. Full-rated power converter wind turbine with permanent magnet generator.

V. Control of Wind Turbines and Grid Requirements

Controlling a wind turbine involves both fast and slow control dynamics [23]-[35]. Overall the power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by a dispatched center or locally with the goal to maximize the power production based on the available wind power. The power controller should also be able to limit the power. An example of an overall control scheme of a wind turbine with a doubly-fed generator system is shown in Fig. 20.

Below maximum power production the wind turbine will typically vary the speed proportional with the wind speed and keep the pitch angle θ fixed. At very low wind the turbine speed will be fixed at the maximum allowable slip in order not to have over voltage. A pitch angle controller limits the power when the turbine reaches nominal power. The generated electrical power is done by controlling the doubly-fed induction generator through the rotor-side converter. The control of the grid-side converter is simply just keeping the dc-link voltage fixed. Internal current loops in both converters are used which typically are PI-controllers, as it is illustrated in Fig. 20. The power converters to the grid-side and the rotor-side are both voltage source converters.

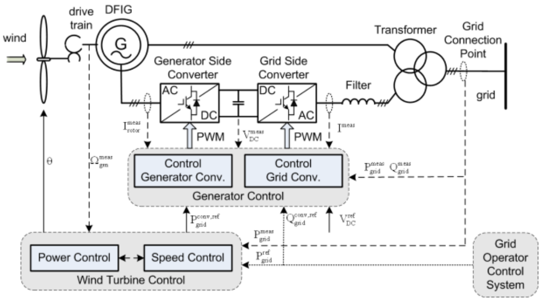

Fig. 20. Control of a wind turbine with doubly-fed induction generator (WT Type C).

Another solution for the electrical power control is to use the multi-pole synchronous generator and a full scale power converter. A passive rectifier and a boost converter can be used in order to boost the voltage at low speed. The system is industrially used today and it is shown in Fig. 21.

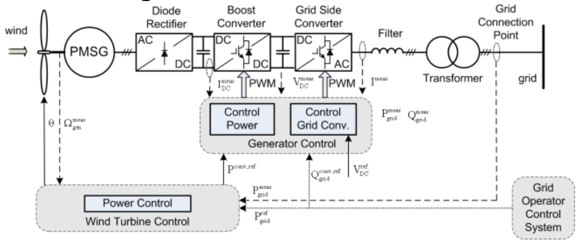

Fig. 21. Control of active and reactive power in a wind turbine with multi-pole synchronous generator (WT Type D).

A grid-side converter is interfacing the dc-link to the grid. Common for both discussed systems are that they are able to control active and reactive power to the grid with high dynamics. Another advantage of the system in Fig. 21 is that the dc-link partly is performing a decoupling between the wind turbine and the grid. The dc-link will also give an option for the wind turbine to have an added energy storage connected which can accommodate for extra active power demand (both positive and negative) from the utility side – further improving the system capabilities of the wind turbine.

Most European countries have dedicated grid codes for wind power and they are updated regularly [51]-[61]. These requirements reflect, in most of the cases, the penetration of wind power into the electrical network.

The requirements for wind power cover a wide range of voltage levels from medium voltage to very high voltage. The grid codes for wind power address also issues that make wind farms to act as a conventional power plant into the electrical network. These requirements have focus on power controllability, power quality, fault ride-through capability and grid support during network disturbances. Examples of Active and Reactive Power Control, Power Quality and Ride-Through operation capabilities are given.

A) Active power control

According to most grid codes the wind turbines must be able to control the active power in the Point-of-Common-Coupling (PCC) in a given power range. The active power is typically controlled based on the system frequency e.g. Denmark, Ireland, Germany so that the power delivered to the grid is decreased when the grid frequency rises above 50 Hz. A typical characteristic for the frequency control in the Danish and Irish grid code is shown in Fig. 22.

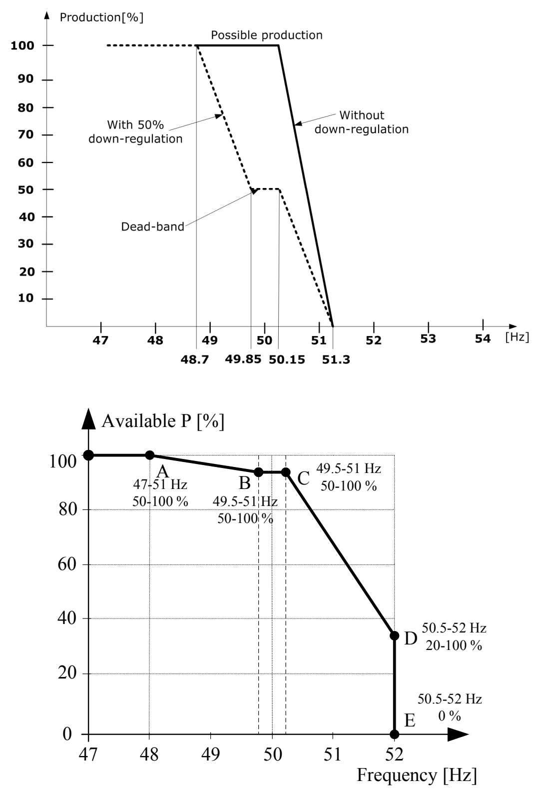

Fig. 22. Frequency control characteristic for the wind turbines connected to the Danish grid (upper) and Irish system (lower).

On the contrary other grid codes, e.g. Great Britain specifies that the active power output must be kept constant for the frequency range of 49.5 Hz to 50.5 Hz, and a drop of maximum 5% in the delivered power is allowed when the frequency drops to 47 Hz [61].

Wind farms connected at the transmission level shall act as a conventional power plant providing a wide range of controlling the output power based on Transmission System Operator’s (TSO) demands and also participate in primary and secondary control. Seven regulation functions are required in the wind farm control. Among these control functions, each one is prioritized and the following can be mentioned: delta control, balance control, absolute production and system protection as illustrated in Fig. 23.

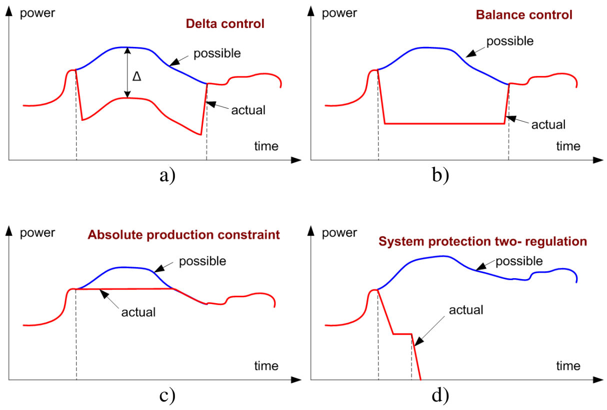

Fig. 23. Regulation functions for active power control implemented in wind farm controller required by the Danish grid codes. a) delta control, b) balance control, c) absolute production constraint and d) system protection.

B) Reactive power control and voltage stability

Reactive power is typically controlled in a given range. The grid codes specify in different ways this control capability. The Danish grid code gives a band for controlling the reactive power based on the active power output as shown in Fig. 24.

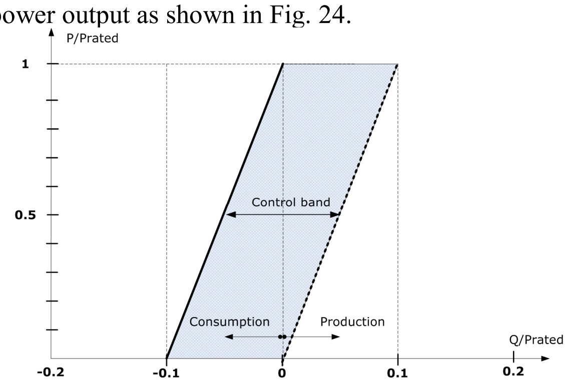

Fig. 24. Danish grid code demands for the reactive power exchange in the PCC [51], [52].

The German transmission grid code for wind power specifies that the wind power units must provide a reactive power provision in the connection point without limiting the active power output as shown in Fig. 25.

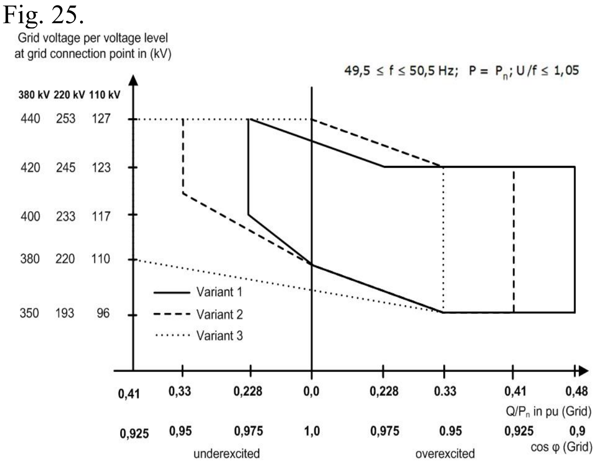

Fig. 25. Requirements for reactive power provision of generating units without limiting the active power output in the German transmission grid code [55].

As it can be noticed in Fig. 25 there are actually three possible V-Q profiles depending on the specific strength of the transmission system close to the PCC. This basic form of voltage control should be realized very slowly with a time constant in the range of two minutes [61].

C) Power Quality

Power quality issues are addressed especially for wind turbines connected to the medium voltage networks. However, some grid codes, e.g. in Denmark and Ireland have also requirements at the transmission level.

Mainly two standards are used for defining the power quality parameters namely: IEC 61000-x-x and EN 50160. Specific values are given for fast variations in voltage, short term flicker severity, long term flicker severity and the total harmonic distortion. A schedule of individual harmonics distortion limits for voltage are also given based on standards or in some cases e.g. Denmark custom harmonic compatibility levels are defined. Inter-harmonics may also be considered.

D) Ride through capability

All considered grid codes require fault ride-through capabilities for wind turbines to overcome grid faults. Voltage profiles are given specifying the depth of the voltage dip and the clearance time as well. One of the problems is that the calculation of the voltage during all types of unsymmetrical faults is not very well defined in some grid codes. The voltage profile for ride-through capability can be summarized as shown in Fig. 26.

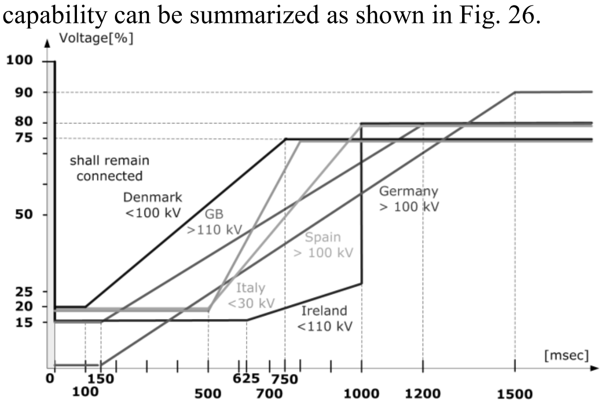

Fig. 26. Voltage profile for fault ride-through capability in European grid codes for wind power [61].

Ireland's grid code is very demanding in respect to the fault duration while Denmark has the lowest short circuit time duration with only 100 ms. However, the grid code in Denmark requires that the wind turbine shall remain connected to the electrical network during successive faults, which is a technical challenge.

On the other hand Germany and Spain requires grid support during faults by reactive current injection up to 100% of the rated current. This is illustrated in Fig. 27.

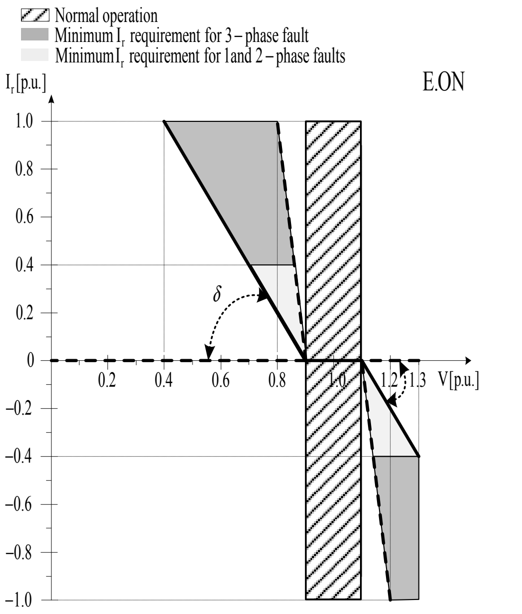

Fig. 27. Reactive current support during faults as specified in the German grid code [61].

As it can be seen in Fig. 27, the 1 pu reactive current should be injected already at 0.4 – 0.8 pu voltage. The slope should be flexible and should be decided by the TSO.

This demand is relative difficult to meet by some of the wind turbine concepts e.g. active stall wind turbine with directly grid connected squirrel cage induction generator (**WT Type A**).

The grid codes have the last ten years challenged the wind turbine technology and forced the use of power electronics. It has on one hand increased the cost pr. kWh slightly but on the other hand the technology itself is much more technical sustainable. The grid codes will also in the next years challenge the wind turbine technology which means new control concepts may still be developed. Further on – new research in the field of smart grid may even extend the demands to the wind turbine systems – they are not defined yet [2].

VI. SOLAR ELECTRIC POWER CONVERSION

Photovoltaic (PV) power supplied to the utility grid is gaining more and more visibility due to many national economic incentives [62]-[114]. With a continuous reduction in system cost (PV modules, DC/AC inverters, cables, fittings and man-power), the PV technology has the potential to become one of the main renewable energy sources for the future electricity supply.

The PV cell is an all-electrical device, which produces electrical power when exposed to sunlight and connected to a suitable load. Without any moving parts inside the PV module, the tear-and-wear is very low. Thus, lifetimes of more than 25 years for modules are easily reached. However, the power generation capability may be reduced to 75% ~ 80% of nominal value due to ageing. A typical PV module is made up of around 36 or 72 cells connected in series, encapsulated in a structure made of e.g. aluminum and tedlar. An electrical model of a PV cell is shown in Fig. 28.

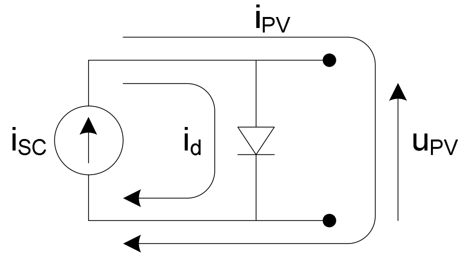

Fig. 28. Ideal equivalent circuit of a PV cell.

Several types of proven PV technologies exist, where the crystalline (PV module light-to-electricity efficiency: η = 10% - 15%) and multi-crystalline (η = 9% - 12%) silicon cells are based on standard microelectronic manufacturing processes.

Other types are: thin-film amorphous silicon (η = 10%), thin-film copper indium diselenide (η = 12%), and thin-film cadmium telluride (η = 9%). Novel technologies such as the thin-layer silicon (η = 8%) and the dye-sensitised nano-structured materials (η = 9%) are in their early development. The reason to maintain a high level of research and development within these technologies too is to decrease the cost of the PV-cells, perhaps on the expense of a somewhat lower efficiency. This is mainly due to the fact that cells based on today's microelectronic processes are rather costly, when compared to other renewable energy sources both in terms of manufacturing lines and production cost.

The series connection of the cells benefit from a high voltage (around 25 V ~ 45 V) across the terminals, but the weakest cell determines the current seen at the terminals.

This may cause reduction in the available power, which to some extent can be solved by the use of bypass diodes, in parallel with the cells. The parallel connection of the cells solves the 'weakest-link' problem, but the voltage seen at the terminals is rather low.

Some typical curves of a PV cell current-voltage and power-voltage characteristics are shown in Fig. 29.

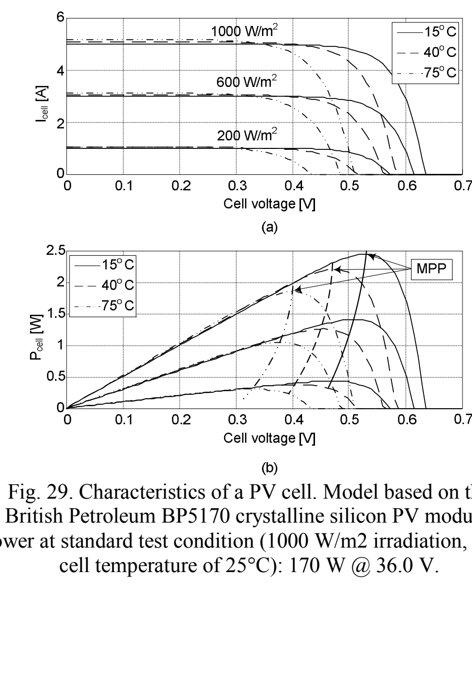

Fig. 29. Characteristics of a PV cell. Model based on the British Petroleum BP5170 crystalline silicon PV module. Power at standard test condition (1000 W/m2 irradiation, and a cell temperature of 25°C): 170 W @ 36.0 V.

Fig. 29 reveals that the captured power is determined by the loading conditions (terminal voltage and current). This leads to some basic requirements for the power electronics used to interface the PV module to the utility grid in order to ensure maximum power from the module.

An overview of the basic power converter topologies for PV systems is given in the following sections. That includes basic PV configuration and power converter topologies which are most feasible for the highest efficiency – the transformer-less inverters.

Structures for PV systems

In order to decrease the cost-to-efficiency ratio of PV systems, new inverter designs have continuously been developed [72]-[74]. A general classification of grid connected PV inverters is as follows:

- central inverters
- string inverters
- module integrated inverters
- multi-string inverters

A. Central inverters

PV plants larger than 10 kWp arranged in parallel strings, are connected to one common central inverter (as shown in Fig. 30a). At first, line commutated thyristor-based inverters were used for this purpose. These were slowly replaced by force commutated inverters using IGBTs, because the efficiency of these inverters was higher and their cost was lower.
However, the list of its disadvantages is significant:

- need for high-voltage DC cables between PV panels and inverter
- power losses due to common MPPT
- power loss due to module mismatch
- losses in the string diodes
- reliability of the whole system depends on one inverter

B. String inverters

String inverters, shown in Fig. 30b, were introduced into the European market in 1995. They are based on a modular concept, where PV strings, made up of series-connected solar panels, are connected to separate inverters. The string inverters are paralleled and connected to the grid. If the string voltage is high enough - no voltage boosting is necessary, thereby improving the efficiency. Fewer PV panels can also be used, but then a DC-DC converter or a line frequency transformer is needed for a boosting stage.
The advantages compared to the central inverter are as follows:

- no losses in string diodes (no diodes needed)
- separate MPPTs for each string
- better yield, due to separate MPPTs
- lower price due to mass production

C. AC-Module inverters

An AC module is made up of a single solar panel connected to the grid through its own inverter, as shown in Fig. 30c. The advantage of this configuration is that there are no mismatch losses, due to the fact that every single solar panel has its own inverter and MPPT, thus maximizing the power production. The power extraction is much better optimized than in the case of String inverters. One other advantage is the modular structure, which simplifies the modification of the whole system because of its “plug & play” characteristic. One disadvantage is the low overall efficiency due to the high-voltage amplification, and the price per watt is still higher than in the previous cases. But this can in the future maybe be overcome by mass production, leading to low manufacturing and retail costs [75].

D. Multi-String inverters

Multi-String inverters have recently appeared on the PV market. They are an intermediate solution between String inverters and Module inverters. A Multi-String inverter, shown in Fig. 30d, combines the advantages of both String and Module inverters, by having many DC-DC converters with individual MPPTs, which feed energy into a common DC-AC inverter. In this way, no matter the nominal data, size, technology, orientation, inclination or weather conditions of the PV string, they can be connected to one common grid connected inverter [80], [81].
The Multi-String concept is a flexible solution, having a high overall efficiency of power extraction, due to the fact that each PV string is individually controlled.

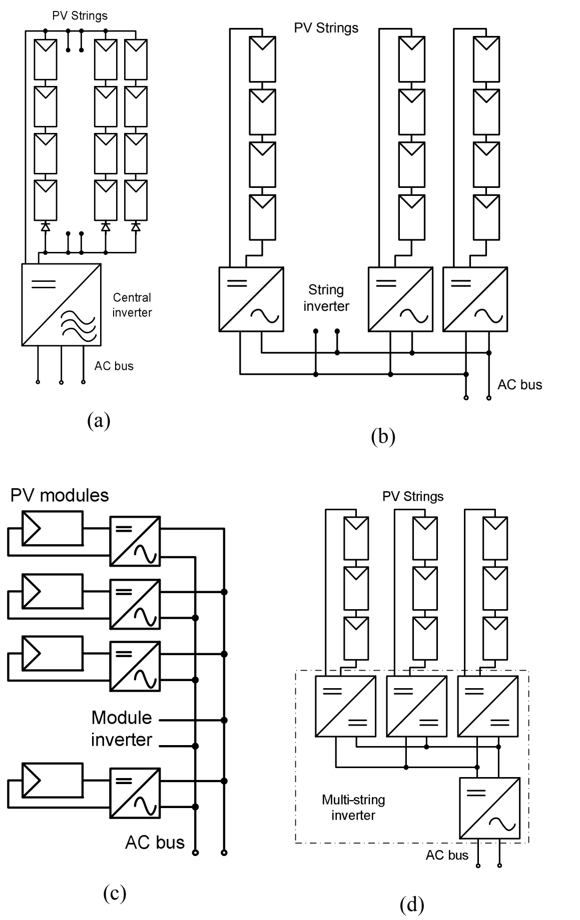

Fig. 30. Different grid-connected PV inverter structures. a)Central inverter; b) String inverter; c) Module inverter; d) Multi-string inverter.

E. Galvanic isolation vs. transformer-less topologies

Depending on the electrical isolation between the PV panels and utility grid, the inverter can be isolated or non-isolated. This galvanic isolation is usually realized by means of a transformer, which has major influence on a grid-connected PV systems efficiency [84]. The presence of the galvanic isolation in a grid connected PV system depends also on the local country regulations [85]. In some countries, like in the UK and Italy, galvanic isolation is a requirement and is done either by a low-frequency step-up transformer on the grid side or by a high-frequency transformer on the DC side of the converter. On the other hand, in countries like Germany and Spain, the galvanic isolation can be left out and in these cases another technological solution is used to separate the PV array from the electrical grid [86].

One disadvantage of transformer-less systems is that the missing line-frequency transformer can lead to DC currents in the injected AC current by the inverter, which can saturate the core of the magnetic components in the distribution transformer, leading to overheating and possible failures [87],[88]. An important advantage of transformer-less solutions is the increase in the total efficiency of the system by approximately 2% [83],[89]-[93]. Therefore more and more commercial solutions are based on this technology.

F. Standards for Transformer-less Inverters

There is only one standard that specifically deals with transformerless PV systems regarding fault and leakage current levels: the German VDE-0126-1-1 standard.

According to the German standard, there are three different currents that have to be monitored:

- Ground Fault current, which happens in the case of insulation failure when the current flows through the ground wire;
- Fault current, which represents the sum of the instantaneous values of the main currents, that in normal conditions leads to zero;
- Leakage Ground currents, which is the result of potential variations of capacitive coupled parasitic elements.

The monitoring is typically done using a Residual Current Monitoring Unit (RCMU), which measures the fault and leakage current of the whole system. The standard states that disconnection from the grid is necessary within 0.3 s in case the leakage current is higher than 300 mA. Furthermore, it recommends a table detailing the Root Mean Square (RMS) value of the fault/leakage current jumps and their respective disconnection times are as specified in TABLE III.

TABLE III.
Leakage current jumps and their corresponding disconnection times given in VDE 0126-1-1

Leakage current jump value (mA)	Disconnection time (s)
30	0.3
60	0.15
100	0.04

As shown in TABLE III, in the cases where the RMS value of the fault/leakage current increases by 30 mA, then the disconnection is mandatory within 0.3 s. In case of a fault/accident or too high leakage ground current, the system is disconnected and de-energized.

G. Efficiency of PV inverters

PV inverters usually have two efficiencies reported by the manufacturer: the highest DC-AC conversion efficiency, also called as “Maximum Efficiency”, and a weighted efficiency dependent on efficiencies at different irradiation levels, called “European efficiency”, based on [90] which takes into account the PV is operating at different load conditions:

$$\eta_{EU} = 0,03\eta_{5\%} + 0,06\eta_{10\%} + 0,13\eta_{20\%} + 0,1\eta_{30\%} + 0,48\eta_{50\%} + 0,2\eta_{100\%}$$

Fig. 31 has been made from a database of more than 400 commercially available PV inverters, presented in a commercial magazine about the photovoltaic industry [94], giving details of, amongst other things, the maximum efficiency, weight and size of the different inverters.

Transformer-less inverters are represented by (○), while (∗) represents the topologies including a high-frequency DC-DC transformer and (▼) represents the inverters that have a low-frequency transformer on the grid side, adding a galvanic isolation between the PV and grid. It is shown that in the case of PV systems up to *6.5 kW*, transformer-less inverters can reach maximum efficiencies up to *98%*, while inverters with galvanic isolation only have maximum conversion efficiency around *96-96.5%.*

The main conclusion drawn from Fig. 31 is that the majority of transformer-less inverters has higher efficiency, smaller weight and size than their counterparts with galvanic separation.

In the case of Fig. 31, the reason to limit the power up to *6.5 kW* was the fact that only 20 inverters between *6.5 kW* and *15 kW* are available on the market.

Depending on the voltage level of the PV array, a voltage-boosting stage can be used, which raises the DC-link voltage of the inverter to the required level. This is the case of a two stage topology, where the PV system includes either a DC-DC boost converter, followed by a DC-AC grid side inverter or a step-up transformer on the AC side [95].

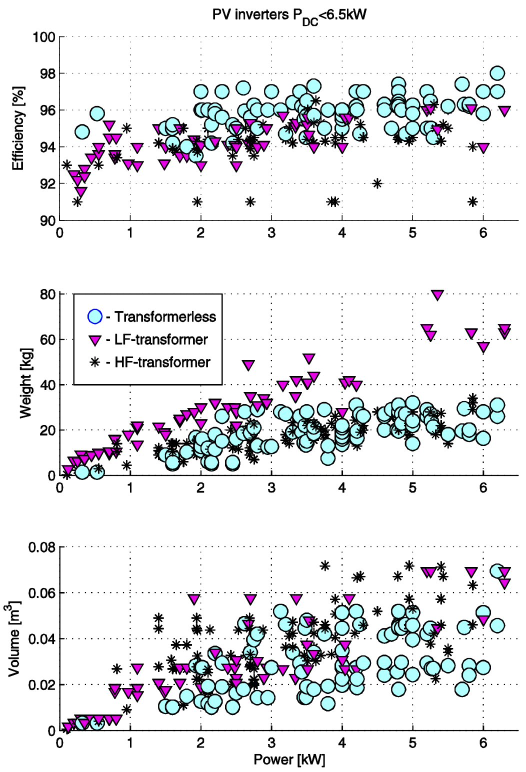

Fig. 31. Comparison of commercial PV inverters in terms of efficiency, weight and volume [79].

The first PV inverters were based on the technologies used in electrical drives from the beginning of the 1980s. These were line commutated inverters with power ratings of several kW. The major advantages were high efficiency, cheap and robust, but the power factor to the grid was a major drawback with values between *0.6* and *0.7*.

Nowadays inverters are forced commutated inverters having power ranges above 1.5 kW. A "classic" transformer-less topology has typically an H-Bridge configuration with switching frequencies greater than 16 kHz to avoid acoustic noise, which makes it a robust, cheap and also a well known technology [96].

In case the voltage level from the PV is lower than the required minimum, then a boost converter is added between the PV array and the inverter. This boosts the input voltage from the PV so the inverter has a DC-link voltage around 400 V for single-phase systems and up to 700 V for three-phase grid connection in the European case.

H. Parasitic capacitance of PV arrays

Nowadays most photovoltaic panels have a metallic frame, which is required to be grounded in almost all countries, in order to comply with the safety regulations and standards. Since PV panels have a considerable surface area, the metallic frame forms a parasitic capacitance, as shown as ($C_{G\text{-}PV}$) in Fig. 32.

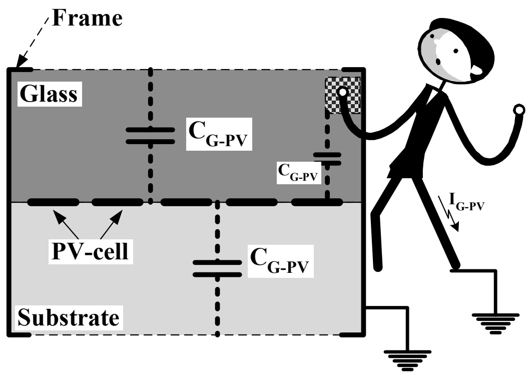

Fig. 32. Parasitic capacitance in PV panels [73].

The value of this parasitic capacitance depends on:

- Surface of the PV array and grounded frame
- Distance of PV cell to the PV module
- Atmospheric conditions
- Dust and humidity, which can increase the electrical conductivity of the panel's surface [73]. In [97] the parasitic capacitance of certain PV panels has been measured to be around 150 pF. If the surface of the panel is fully covered with tap water, the parasitic capacitance will increase to 9 nF, approximately 60 times its previous value. According to measurements of the parasitic capacitance it varies between 50 nF and 150 nF for each kW of installed PV panels. In [97], [98] and [99] the parasitic capacitance has been measured for different PV panels, varying from 100 pF to 3.6 µF. It is also mentioned that in the case of thin film modules the measured parasitic capacitance reaches values up to 1 µF/kW, due to the metallic sheet on which the cells have been deposited.

I. Leakage ground current

A transformer-less topology lacks the galvanic isolation between the PV array and grid. In this way the PV panels are directly connected to the grid, which means that there is a direct path for the leakage ground currents caused by the fluctuations of the potential between the PV array and the grid.

These voltage fluctuations charge and discharge the parasitic capacitance formed between the surface of the PV and grounded frame, shown as ($C_{G\text{-}PV}$) in Fig. 32. The parasitic capacitance together with the DC lines that connects the PV array to the inverter, form a resonant circuit and the resonance frequency of this circuit depends on the size of the PV array and the length of the DC cables [100],[101].

A study, presented in [97] discus the electrical hazards when a person touches the surface of the PV array. Based on the inverter topology, PV panel structure and modulation strategy, when touching the surface of the panels, a ground current can flow through the human body and with the risk of personal injury, as also discussed in [102],[103]. The path of the ground current ($I_{G\text{-}PV}$) flowing through the parasitic capacitance of the PV array is shown with a grey intermittent line in Fig. 33.

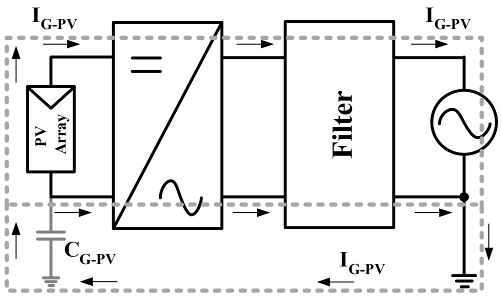

Fig. 33. Transformer-less PV system showing the parasitic capacitance between the PV and the grounded frame of the array and the path of the alternating ground leakage current.

The VDE0126-1-1 standard recommends the use of a Residual Current Monitoring Unit (RCMU) in order to monitor the safe operation of the grid connected PV system. Several experimental tests have been done in order to test two commercially available current sensors that could be used for ground leakage current measurement.

VII. Transformer-less PV inverter topologies

In the following different transformer-less PV-inverter technologies are discussed as they can obtain the highest efficiency.

A. H-Bridge topology with Bipolar PWM

The H-Bridge is a well-known topology and it is made up of two half bridges. This topology has also been used in motor drives and UPS applications. To control the four switches in this topology several PWM techniques can be implemented. The simplest one is the bipolar PWM, which modulates switches T1-T4 (see Fig. 34) complementary to T2-T3, resulting in a two level output voltage. The conversion efficiency is reduced due to the fact that during the free-wheeling period the grid current finds a path and flows back to the DC-link capacitor. Fig. 35 shows some measurements on such a converter.

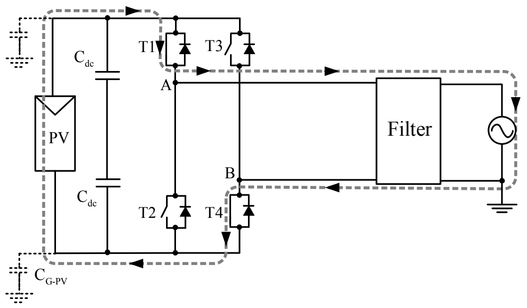

Fig. 34. Full-bridge topology with bipolar PWM.

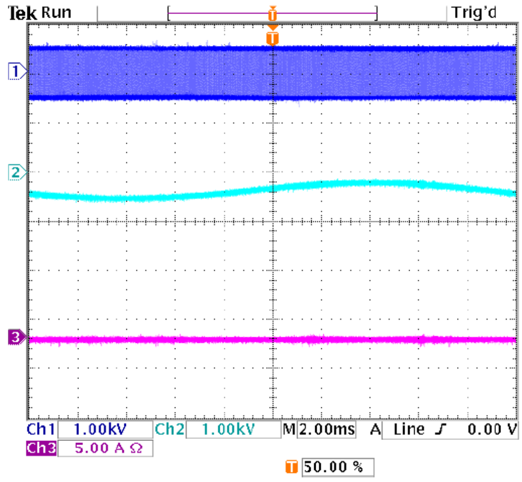

Fig. 35. Experiments on full-bridge topology. 1) bipolar output of the converter, 2) the voltage to ground (DC- terminal of the PV array), 3) the leakage ground current for the single-phase inverter with bipolar PWM.

B. H-Bridge topology with Unipolar PWM

Using the H-Bridge topology with different PWM schemes than the bipolar one, will result in unipolar output voltage (+Vdc, 0 and -Vdc) that has twice the switching frequency. The advantage of this method is that the grid side filter needs to be much smaller due to the unipolar output voltage of the converter and also due to the fact that the frequency of the output voltage is twice the switching frequency. Furthermore, during the freewheeling period, the grid current finds a path through the short-circuited output of the converter, either through T1-T3, as shown in Fig. 36 or similarly through T2-T4.

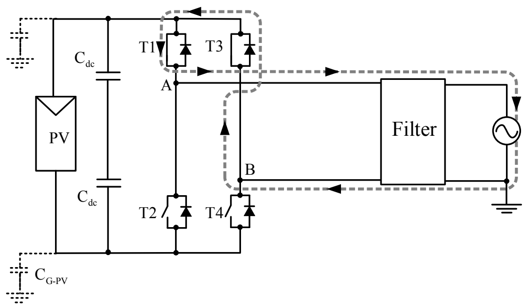

Fig. 36. Full-bridge topology with unipolar PWM.

On the other hand, there is a significant disadvantage using unipolar PWM transformer-less PV systems, regarding the voltage to ground of the PV array and the ground leakage currents. As shown in Fig. 37, the modulation strategy generates a varying common-mode voltage. An FFT of the voltage to ground, as detailed in Fig. 38, shows that voltage components at the switching frequency have very high amplitudes in the range of V_{dc}.

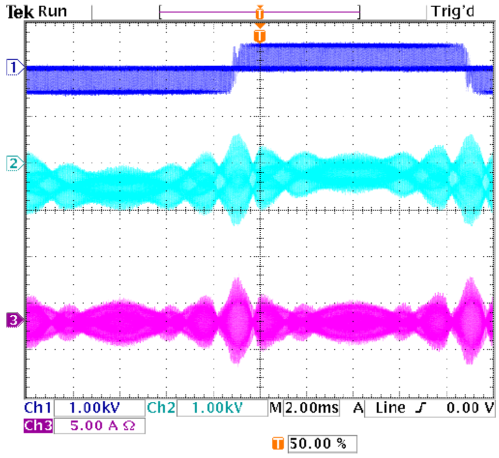

Fig. 37. Experiments on a full-bridge topology with unipolar PWM. 1) unipolar output of the converter, 2) voltage to ground (DC- terminal of the PV array), 3) leakage ground current for the single-phase inverter with unipolar PWM.

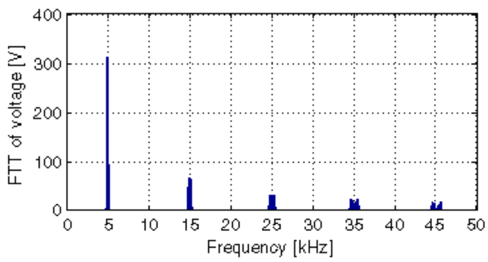

Fig. 38. FFT of voltage to ground using a unipolar PWM in an H-brigde converter.

Also the measurements, shown in Fig. 38, confirm the high frequency voltage components present in the voltage to ground measured between the DC- terminal and the ground connection, leading to high leakage ground current, with peaks well above 5 A. Knowing this fact, it can be stated that the H-Bridge topology with unipolar PWM is not directly useful in transformer-less PV systems.

C. H-Bridge topology with hybrid modulation

Another type of modulation that can be used in case of an H-Bridge is a hybrid modulation, also called single-phase chopping [98]. In this case, one leg of the inverter is modulated with the switching frequency, while the second leg is switched with the grid frequency. In this way the neutral line of the topology is connected either to the positive or the negative DC rail, depending in which half period the reference signal is. In case the filter inductor is only placed in the phase connector and the neutral connector is left without inductance the voltage to ground of the PV array will have a square waveform with 50 Hz frequency. Due to the sharp changes in the voltage that happens every 10 ms (@ 50 Hz line frequency), the leakage ground current will have 100 Hz spikes. The amplitude of these spikes will depend on the value of the parasitic capacitance and therefore it might lead to a leakage ground current that is above the allowed limit set in the VDE 0126 standard. Besides the square wave shape of the voltage to ground, this modulation technique has another drawback, which is the two quadrant operation, making it impossible to have reactive power flow [98].

D. HERIC topology [104]

To keep high efficiency and all the advantages given by the unipolar PWM, but still have the common-mode behavior as in case of the bipolar PWM, the H-Bridge topology may be modified [104], the Highly Efficient and Reliable Inverter Concept (HERIC). The modification includes two extra switches (T5-T6) each connected in series with a diode. During the zero voltage vector, depending on the sign of the reference voltage, either T5 of T6 are turned ON, while T1, T2, T3 and T4 are all in their OFF state and the PV array is disconnected from the grid. In this way there is a possibility to achieve the zero voltage state and the output voltage will be unipolar, having the same frequency as the switching frequency and there will be no high frequency fluctuations present at the DC terminals of the PV array. Furthermore, the efficiency of the inverter is still kept high, because during the freewheeling period, the load current is short-circuited through T5 or T6, depending on the sign of the grid current.

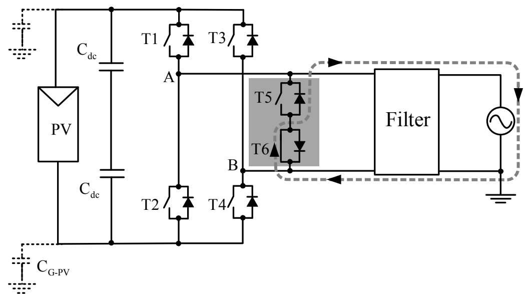

Fig. 39. Highly Efficient and Reliable Inverter Concept (HERIC) showing path of the current during the zero voltage state, for positive load current [104].

The common-mode behavior of the HERIC topology is similar to the H-Bridge with bipolar PWM. The voltage to ground of the PV array terminals will only have a sinusoidal shape, while having the same high conversion efficiency as the H-Bridge with unipolar switching. Based on these results, it can be stated that the HERIC topology is suitable for transformer-less PV systems. Unipolar output voltage is achieved and the PV array is disconnected from the grid during the period of the zero voltage state, using a method called AC decoupling. This topology is used in the power range of 2.7 kW – 5 kW.

E. H5 topology [105]

The H5 topology [105], used by SMA in many of their transformer-less inverters are using the same idea for the generation of the unipolar output voltage: disconnection of the PV array from the grid during the zero voltage state. The topology is shown in Fig. 40.

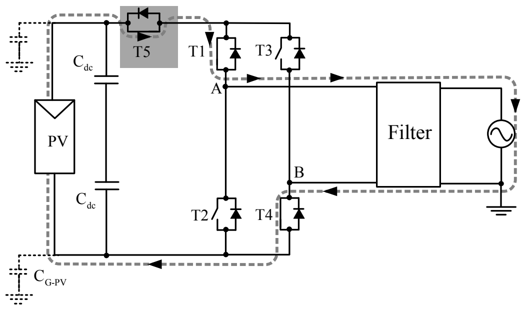

Fig. 40. H5-topology for high efficiency. Path of the current in the case of positive voltage state, for positive load current.

The used PWM method is a hybrid type. T1 and T3 are switched with the grid frequency; T1 is continuously ON during the positive half, while T3 is continuously ON during the negative half of the reference voltage. To make the positive voltage vector, T5 and T4 are switched simultaneously with high frequency, while T1 is ON and the current will flow through T5-T1 returning through T4, as shown in Fig. 40.

During the zero voltage state, T5 and T4 are turned OFF and the freewheeling current finds its path through T1-T3. The negative voltage vector is done by switching T5 and T2 simultaneously with high frequency, while T3 is ON, during the corresponding half period of the reference voltage and the current will flow through T5-T3 returning through T2.

The common-mode behavior of the H5 topology is similar to the H-Bridge with bipolar PWM. The voltage to ground of the PV array terminals will only have a sinusoidal shape, while having the same high conversion efficiency as the H-Bridge with unipolar switching. Based on these results it can be stated that the H5 topology is suitable for transformer-less PV systems. Unipolar output voltage is achieved by disconnecting the PV array from the grid during the period of the zero voltage state, using a method called DC decoupling.

F. Topology with DC decoupling

Another topology using the DC decoupling method is the one presented in [106], which adds two extra switches and two extra diodes to the H-Bridge topology as shown in Fig. 41. The modulation strategy is also a hybrid type. The active voltage vector is achieved by switching T5-T6 with high frequency. Switches T1-T4 are switched with the grid frequency and in anti-parallel to T2-T3, depending on whether the reference voltage is in the positive or negative half period. In this way the output voltage of the converter will be a unipolar voltage, like in case of the HERIC and H5 topologies.

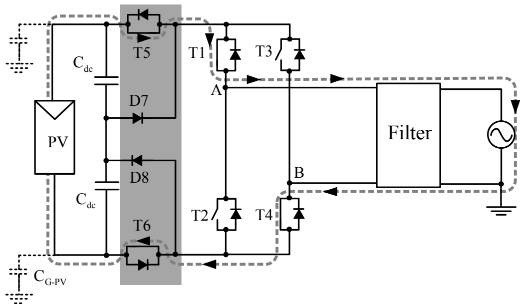

Fig. 41. Single-phase topology with DC decoupling used for transformerless PV systems.

The common-mode behavior of the topology is similar to the HERIC and H5 topologies, since the voltage to ground of the PV array has only a sinusoidal shape and the frequency is the grid frequency. Based on these results it can be stated that this topology is also suitable for transformer-less PV systems. Unipolar output voltage is achieved by disconnecting the PV array from the grid during the period of the zero voltage state, using DC decoupling.

G. H-Bridge Zero Voltage Rectifier topology (HB-ZVR)

Another solution for generating the zero voltage state can be done using a bidirectional switch made of one IGBT and one diode-bridge [109]. The topology is shown in Fig. 42, using the bidirectional switch, as an auxiliary component with a grey background. This bidirectional switch is clamped to the midpoint of the DC-link capacitors in order to fix the potential of the PV array also during the zero voltage state when T1-T4 and T2-T3 are open. An extra diode is used to protect from short-circuiting the lower DC-link capacitor.

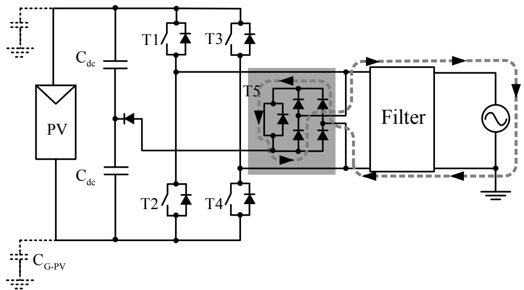

Fig. 42. H-Bridge Zero Voltage Rectifier topology. Zero vector is applied to the load, using T5, during positive half-wave.

The advantage of HB-ZVR is that the HERIC topology, with the implemented PWM strategy, is only ideal for PV systems that supply the grid with active power. This is due to the bidirectional switch of the HERIC topology made up of T5 and T6 is not controlled to be turned ON simultaneously, therefore the current can only flow in a predefined direction, defined by the currently turned ON-switch.

On the other hand, in the case of the HB-ZVR, it does not matter what the sign the load current is, it will always find a path through the bidirectional switch, made up of a diode bridge and the switch. This makes it possible to have a reactive power flow that can be used to support the utility grid with additional services any time during the operation of the inverter.

The disadvantage of HB-ZVR is the lower conversion efficiency compared to the HERIC topology, due to the high-frequency switching pattern of the auxiliary switch T5, while in case of the HERIC topology T5 and T6 are only switched with the grid frequency.

H. Half bridge topology

The half bridge topology uses only two switches to connect either the upper or the lower half of the DC-link to the phase of the grid, while the neutral wire is always connected to the middle of the DC-link capacitors [107]. The major disadvantages of this topology are that the DC-link needs to be twice the grid peak voltage and that the switches have to block the full DC-link voltage, while in case of the H-Bridge

topologies the same DC-link voltage was shared between two series-connected switches. The output of the converter will be a bipolar voltage, since T1 is controlled with high frequency in anti-parallel with T2. This means that larger filtering elements are needed and the conversion efficiency of the converter will be lowered. A major advantage is the fact that the middle of the DC-link is always connected to the neutral, thereby fixing the potential of the PV array, and the voltage to ground will be constant, when the switching ripple on the DC side is not taken into consideration.
Based on the common-mode behavior, the half bridge topology is suitable for transformer-less PV systems. The only drawback is the high DC-link voltage, which needs a boost stage to keep the DC-link voltage above *650 V* in the case of 220 V AC-line. Otherwise, in a single-stage system, the voltage at the maximum power point (V_{MPP}) has to be above *650 V*, which will give an open circuit voltage (V_{OC}) above *1000 V* of the PV-system. This is not allowed according to most PV datasheets rating.

I. Neutral Point Clamped topology

The Neutral Point Clamped (NPC) topology was introduced some years ago in [110] and has mostly been used for applications in AC drives. The voltage to ground measured at both PV array terminals is constant, when the switching ripple is not taken into consideration. This is due to the connection of the neutral line of the middle point of the DC-link that fixes the potential of the PV array to the grounded neutral [108]. Fig. 43 shows this topology.

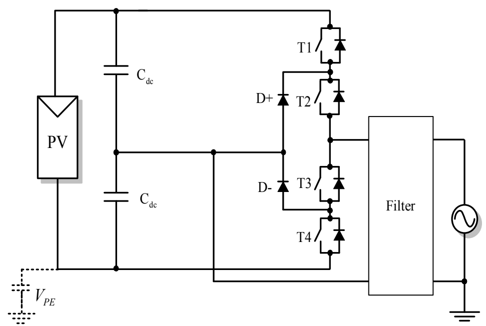

Fig. 43. Neutral Point Clamped topology [110] for PV.

The NPC topology is suitable for transformer-less PV systems, since the voltage to ground is constant in case of both terminals of the PV. The only drawback for the single-phase NPC topology is the high DC-link voltage, which has more than twice the grid peak voltage and might reach voltages higher than the allowed maximum system voltage, therefore a boost stage is needed before the inverter, which decreases the overall efficiency of the whole PV system.

J. Topology from Refu Solar[111]

In 2005, Refu Solar patented a new topology also derived from the classical H-Bridge [111]. The topology is actually using a half bridge with an AC side by-pass and a by-passable DC-DC converter as shown in Fig. 44.

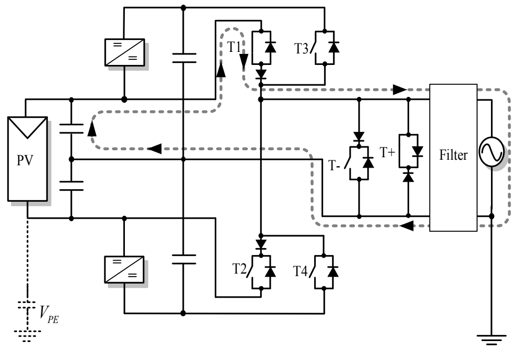

Fig. 44. Patented topology from Refu Solar [111] for single-phase PV-inverter.

The AC by-pass provides the same two vital functions as in the case of the HERIC-topology:

- it prevents reactive power exchange between the grid side filter elements and the DC-link capacitor during the zero voltage state and thus increases the efficiency.
- it isolates the PV array from the grid during the voltage state and thereby eliminates the high frequency content of the voltage to ground.

The AC bypass is implemented in a different way in comparison with HERIC as shown in Fig. 39 i.e. by using uni-directional switches composed of standard IGBT modules with a diode in series to cancel the free-wheeling path. Another specific characteristic of this topology is the use of a boost converter which is activated only when the DC input voltage is lower than the grid voltage.

K. Conergy NPC inverter [112]

A “variant” of the classical NPC is a half-bridge with the output clamped to the neutral using a bidirectional switch realized with 2 series back-to-back IGBTs as patented by Conergy [112], and shown in Fig. 45.
The main concept of the Conergy NPC inverter is that zero voltage can be achieved by “clamping” the output to the grounded “middle point” of the DC-link using T+ or T- depending on the sign of the current.

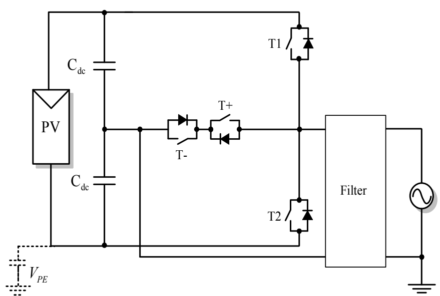

Fig. 45. Conergy topology used for single-phase converter [112].

L. Three-phase Full Bridge(3FB)

For more high power applications the Three-phase Full Bridge (3FB) topology is the simplest and most widely used one for general applications in three-phase systems like in wind turbines systems. The common-mode voltage generated by this topology is not constant. An FFT of the simulated ground voltage (see Fig. 46) shows high frequency components at the switching frequency and multiples of it, having high amplitude using a 3FB topology.

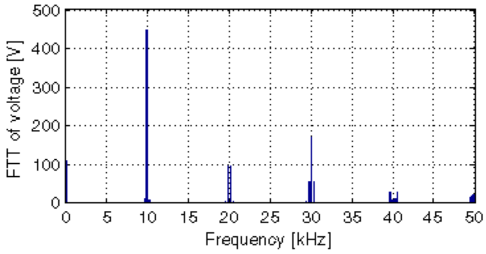

Fig. 46. FFT of voltage to ground for the 3FB topology.

It is also shown in Fig. 47, where the voltage to ground varies with the switching frequency and changes according to the PWM strategy.

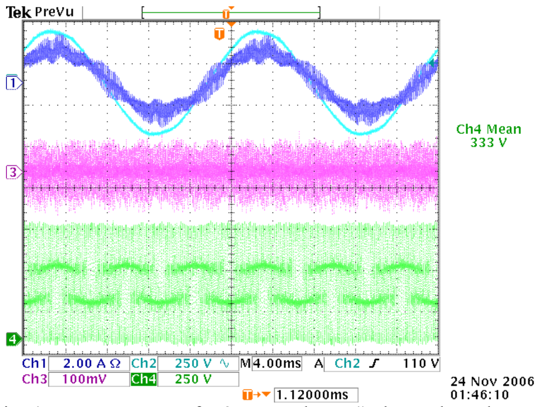

Fig. 47. Measurements for 3FB topology. 4) shows the voltage to ground of the DC+ terminal [250V/div].

Depending on the state of each leg, it has four different values: V_{DC}, $\frac{2}{3}V_{DC}$, $\frac{1}{3}V_{DC}$, 0.This means that the leakage ground current will only be limited by the parasitic capacitance of the PV array, which, in a kW size PV system, will be in the range of 100 nF, leading to very high leakage ground current, well above the limit stated in the VDE 0126.

Therefore, it can be stated that the 3FB topology is not suitable for transformer-less PV systems, due to the common-mode behavior of the topology. Nevertheless, choosing a different PWM strategy it is possible to reduce the leakage current as shown in [113], although for high power applications with a large PV array surface, the leakage current will still be too high, well above the level given by the VDE 0126-1-1.

M. Full Bridge with Split Capacitor

The Full Bridge with Split Capacitor (3FBSC) topology is similar to the 3FB, with the difference that the input DC-link capacitor is split into two halves and the middle point is connected to the grounded neutral line of the grid. Since the middle point of the DC-link is always connected to the grounded neutral of the grid, the PV array will be fixed to the potential of the neutral. Therefore, the measured voltage to ground of the PV array will be constant, based on which it can be said, that this topology is a suitable solution for transformer-less PV systems [108]. An other topologies using a transformer-less can be seen in [114].

VIII. CONCLUSION

The paper discussed the applications of power electronics in both wind turbines and photovoltaic systems. The applications of power electronics in various kinds of wind turbine generation systems are illustrated showing that the wind turbine behavior/performance is significantly improved by using power electronics. Wind turbines are able to act as a contributor to the frequency and voltage control in the grid by means of active and reactive power control using power electronics.

Further, PV systems are discussed including the technology of PV inverters. Several high-efficient single-phase and a few three phase transformer-less topologies have been discussed, focusing on the ground voltage measured at the terminals of the PV array as well as the suitability of each topology in transformer-less grid connected PV systems.

Overall, it can be concluded that the common-mode behavior of a PV system is influenced by the chosen topology and modulation strategy.

Common for both energy technologies are they will play a major role in the future power system – both enabled by the power electronics technology.

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