Windenergy and Offshore Windparks: State of the Art and Trends

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Abstract

Wind energy and cost effective transmission and distribution of wind power generated electricity presents a stimulating engineering challenge. Several aspects such as generators, converters and power electronics, cables are addressed in the paper. Offshore wind parks as an application of wind energy are among the latest developments in the field of wind energy. Special attention is paid to the electrical infrastructure of offshore wind parks.

Introduction

Renewable energy sources and wind energy as a part of it is at this moment a very promising answer to rising energy needs of a mankind. According to Shell studies [1],[2] in the year 2060 the energy needs will triple and the share of renewable energy will be around 60%. According to these studies, wind energy will get a share of 10 %. The application of wind energy throughout the world is thus expecting a fast growth. In this context, cost of wind energy also plays an important role.

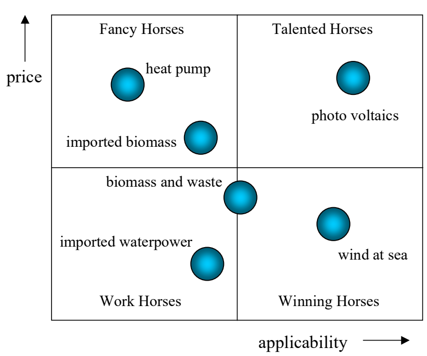


Fig. 1. Renewable energy sources

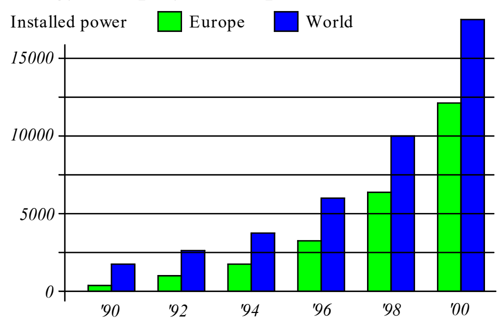


Fig. 2. Installed wind power in Europe and world

In the previous years, the cost of energy from wind has lowered 5-10% on a yearly basis. In coming years, further decrease of 3% on a yearly basis is expected. At this moment, the cost of electricity delivered from a windy location placed on shore is about 5-6 Eurocent per kWh. For comparison, electricity from gas costs around 3,5 Eurocent per kWh at this moment. Worldwide, there was 17 500 MW of installed wind turbine power in the year 2001 with a growth of 30% on a yearly basis (Fig. 2). The purchase and placing of the wind turbines costs about 1000 euro per kW of installed power. Wind farms located offshore are planned because of higher average wind speeds at sea and space limitations on shore. Offshore wind farms will be different from their on-shore counterparts for several reasons: the turbines will on average have a larger diameters and rated powers; less turbulence allows the turbines to harvest energy more effectively and lower wind shear allows the use of shorter tower. However, the farm will be difficult to access during periods with high winds. Also, erection and maintenance will be more expensive. The turbine noise will probably not be an important issue, and a submarine electrical connection to shore will be required. The functional objective of offshore wind farms is to convert wind power to electrical power and to feed this electrical power to the public grid. In Fig. 3. the basic components of the total power conversion train is schematically shown.

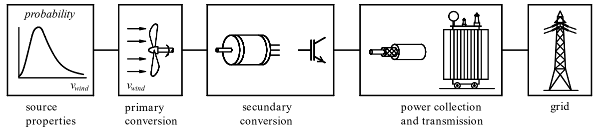


Fig. 3. Basic components of the power conversion

In this paper all the components between the shaft of the generator and the public grid are considered. In particular the Generators, Power electronic converters, Cables, transmission distance, ampacity, Power and speed control of turbines are considered in this paper. Fig. 4 shows the power extracted from the wind turbine as a function of the blade tip speed/wind speed for a 34 meter vertical axis wind turbine [3]. The blade tip speed ratio is defined as (1) where R is the turbine rotor radius, U is the wind speed, Ω is the rotor rotational speed (in rad/s), and λ is the tip speed ratio. For a constant-speed machine, the system is designed so that λ is maximum around average wind speed. Then for lower wind speeds, λ is increased, and according to Fig. 4, the Cp,r factor decreases. Cp,r is the rotor power coefficient. It is defined as (2) where Pr is the mechanical power produced on the turbine rotor shaft and ρ is the air density. Thus a decreasing Cp,r gives a lower power on the rotor shaft, and less energy is extracted from the wind.

$$\frac{Tipspeed}{Windspeed} = \frac{\Omega R}{U} = \lambda \quad (1)$$

$$C_{p,r} = 2\frac{P_r}{\rho \pi R^2 U^3} = \frac{Rotor - mechanical - power}{Wind - power} \quad (2)$$

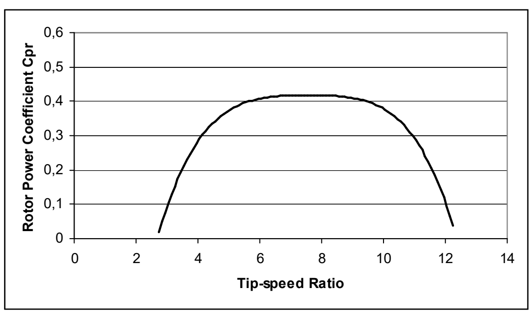


Fig. 4: Typical wind turbine power curve vs blade tip speed/wind speed

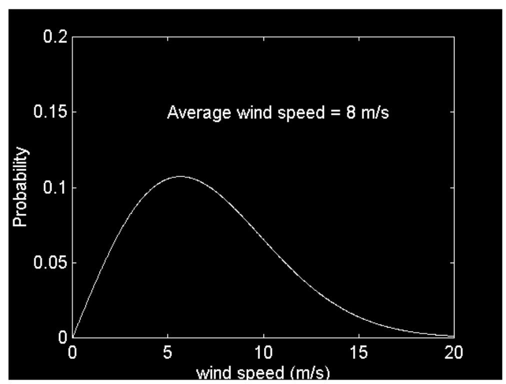


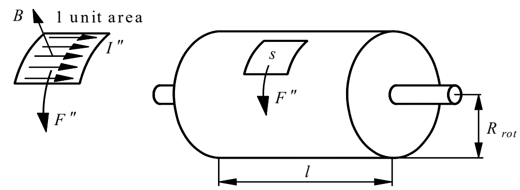
Fig. 5: Typical wind speed probability curve

How wind speed changes varies depending on the site selected for the turbine. Fig. 5 illustrates a typical wind speed distribution curve. In many cases, wind speeds follow a Weibull distribution curve [12]. Fig. 5 shows the probability function for 800 steps of wind speeds (or bins). Each bin has a width of 0.025 m/s. Depending on the site selected, average wind speed will vary from 6 to 10 m/s. The wind turbines are designed to operate nominally (where they give maximum power) at speeds between 11 - 17 m/s, depending on the manufacturers. It is clear from Fig. 5 that occurrence of the nominal speed is not frequent. As a consequence, the wind turbine operated at constant-speed will operate in non-optimal conditions (where Cp,r is low) most of the time [3].

Generator - Converter Systems

Generator power density principles

In wind turbines both volume and weight of the generator may be of importance in the turbine design. To be able to determine which design parameters are of importance to size and weight, we will first have a look at the fundamentals of force and torque generation in electric machines. The force F that is applied on a current carrying wire of length L is equal to (3), where B is the magnetic flux density and I is the magnitude of the current. Although the conductors are mostly in slots where the flux density is very low, this rule can generally be applied to calculate force. In a cylindrical machine the tangential component of this force results in a shear force on the surface of the rotor (see Fig. 6).



$$F = B\ I\ L \tag{3}$$

$$F'' = \frac{B\ N\ I\ L}{S} = \frac{B\ N\ I\ L}{\Delta w L} = B\ I'' \tag{4}$$

$$T = \int_{\theta=0}^{2\pi} F''\ R_{rot}\ R_{rot}\ L\ d\theta = 2k\, V_{rot}\ B\ I'' \tag{5}$$

$$P = 2\ k\ \ \omega_{mech}\ B\ I''\ V_{rot} \tag{6}$$

Fig. 6. Rotor of a machine with shear tension

Instead of shear force on conductors we consider shear tension per unit of surface. For the (average) shear tension F" on a small strip with width Δw that contains N parallel conductors with current I, where the length of the strip is L we can write (4), see Fig. 6. For the average shear tension we get (5). Here R_{rot} is the radius of the rotor and V_{rot} is the volume of the rotor. The factor k depends on the specific distribution of I" and B along the circumference (in particular the spatial phase shift between the mostly sinusoidally distributed quantities). Although this equation is based on a simplification, it shows that the torque depends mainly on three quantities B, I" and rotor volume V_{rot}. To obtain the highest possible torque in a limited volume (or limited weight) it is important to apply the highest possible values B and I". A limiting factor with increasing the current is the developed heat in the armature windings. By application of liquid cooling the current distribution can be increased with several factors. The maximum value of B is material dependent and is between 1.5 and 2.0 T for standard machine laminations. In recent years permanent magnets are applied more often which results in higher air gap flux and in the absence of losses in the field windings. Typical values of the average shear tension force for air cooled machines are 20-50 kN/m^2. Formula (6) shows that the specific power not only increases with B en I", but also with the rotational speed. To obtain a low volume and thus low weight generator the generator speed should be as high as possible.

Sizing of the generator-converter system

The aerodynamic power that can be extracted from a turbine with a certain diameter increases with the cube of wind speed. As the frequency of occurrence of high wind speeds is low, it makes sense to limit the design-power rating of components of the systems. To design the system for seldom occurring wind speeds would mean that the components have to be designed for higher torque and higher power which means extra costs, while the extra energy yield is low because of the low occurrence. Limitation of the power in all components of the drive train, means that the aerodynamic power has to be limited in some way. For constant speed turbines this is normally automatically done with the stall phenomenon, while for variable speed turbines pitch control is mostly applied.

Fixed versus variable speed

The type of generator-converter system is to a large extent determined by the type of control of the wind turbine. From the electrical point of view, constant speed systems allow a drive train which is simple, robust and relatively low cost. However, variable speed brings the following advantages:

- higher energy yield (10-15%)
- lower mechanical stresses (a wind gust results in acceleration of the blades instead of a torque spike)
- more constant electrical power (the wind rotor acts as an intermediate energy buffer)
- reduced acoustical noise at lower wind speed

Fig. 7 illustrates the power extraction of a wind turbine for different wind speeds [12]. Fig. 7 shows that a fully variable-sped system extracts more energy than the constant-speed system. The use of 2 speeds allows to keep a good level of energy extraction, but it is still below the total energy yielded by the fully variable-speed system. The doubly-fed induction generator allows variable-speed operation. The degree of speed variation depends upon the converter power rating. In most of the cases, the converter power rating is limited to 25% of the nominal turbine rating, in order to keep the cost and the losses as low as possible. Very good energy extraction can be reached with such converter rating, especially if the converter is made bi-directional.

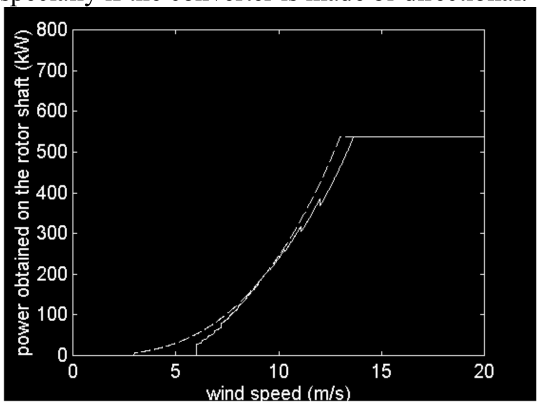


Fig. 7 Power extraction with 100% variable-speed (dotted line) and constant-speed (continuous line) wind turbines for a 34 m diameter rotor and average wind speed 8 m/s

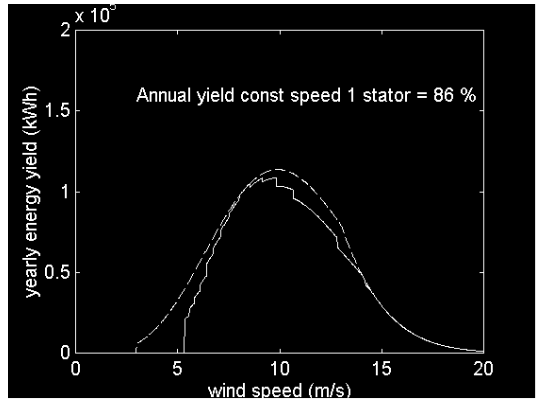


Fig. 8: Yearly energy extraction from the wind as a function of wind speed. Dotted line = fully variable speed system, Solid line = constant speed system with 2 constant speeds

In wind turbines, three main effects are to be considered. These are current fluctuations caused by the blades passing the tower (so-called “shadow effect”), various current amplitudes caused by variable wind speeds and voltage harmonics caused by power electronics. The last type of disturbance can be overcome, if sufficient filtering is provided at the output of the converter. However, the first two types of disturbance have time constants much too large to be filtered by passive electrical components. Strong grid connection is required to reduce the effects of these disturbances on the network. Besides the solution of strong grid connection, the first type of disturbance can be largely reduced if a variable-speed wind turbine is used. Fig. 9 illustrates the power output of a constant-speed wind turbine (data taken from [10]).

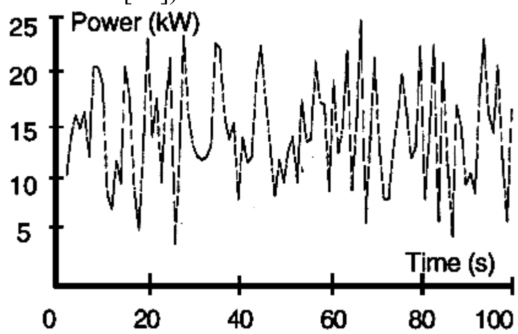


Fig. 9: Power fluctuation of a constant-speed wind turbine [10]

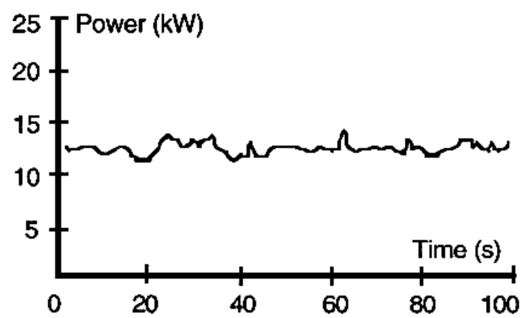


Fig.10.:Power fluctuation of a variable-speed wind turbine [10]

Fig. 10 illustrates the power output of a variable-speed wind turbine subjected to the same wind conditions. The difference is explained by the ability of the variable-speed system to reduce or increase speed in case of torque variation. The big inertia of the turbine rotor is used to store mechanical energy, and therefore acts as a natural filter. Since both the direct-drive technology and the doubly-fed induction generator operate in variable-speed mode, they offer a substantial advantage compared to the constant-speed system.

The disadvantage of variable speed is the more complex drive train and often the need for pitch control. The additional costs that are required for power electronic converters in variable speed systems is one of the major draw backs. For that reason several variable speed systems have been developed were the power rating of the power electronic converter is relatively small at the expense of a reduced speed-control range. The balance between these advantages and disadvantages determines the final choice were component costs are a major factor in the final choice. This means that future changes in component cost may cause big changes in chosen concepts.

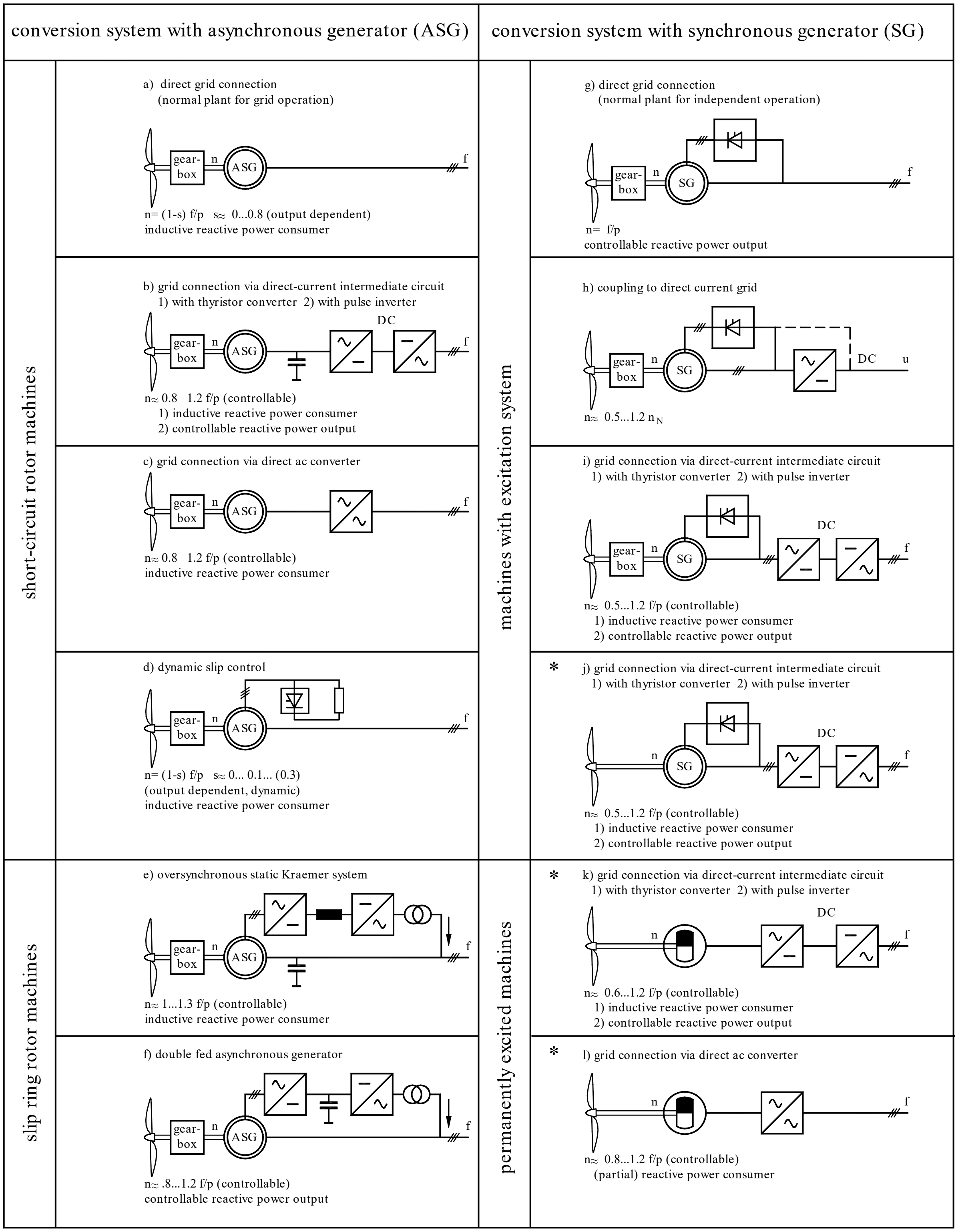


Fig. 11. Overview of generator – converter systems

Grid connection systems

The generators can be connected with the grid in three ways and namely directly connected to the grid, connected via a full inverter coupling or connected via a partial inverter coupling, where only the rotor power is fed via an inverter. In Fig.11 an overview is given of possible combinations of generators types and methods to connect these generators to the grid. We will discuss the important systems of this figure. The majority of drives in installed wind turbines has a gearbox and a grid-connected asynchronous generator (system a) as it is simple and robust and relatively low cost. Sometimes, the generators have two stator windings with different numbers of pole pairs to enable two speeds and a higher energy yield. Some wind turbine manufacturers apply machines with increased rotor resistance and increased slip (2-3%) to allow a little bit of up speeding during wind gusts in order to reduce the mechanical stresses during such a wind gust at the expense of increased losses. However, for the wind turbines in the multi-megawatt range there is a trend towards the application of variable speed systems to limit the mechanical stresses. In system d), the rotor resistance can be varied electronically. Some manufacturers use this to change the rotor resistance dynamically. During static operation the rotor resistance is low, with associated low slip and during a wind gusts the rotor resistance is increased to allow speeding up. In this way the slip can dynamically increase to 10% or more without sacrificing efficiency to much. This system is called Opti-slip by Weier. The losses in the rotor circuit may cause excessive heating of the rotor. For that reason sometimes the rotor is equipped with slip rings so that the rotor resistance can be placed outside the rotor. To extent the speed range further without spoiling the efficiency wound rotor machines are used with power electronic converters in the rotor circuit (systems e) and f). Instead of dissipating the slip power in the rotor resistances, the slip power is fed back to the grid. This means that speed control is possible without loss of efficiency. The required power rating of the inverter is sP_{nom}, where s is the maximum occurring slip. Because the inverters are bi-direction the rotor power can be positive and negative, which means that s can be positive and negative to. For a converter with a power rating of for instance 30% of the power rating of the generator, the speed control range is from 70% to 130% of the synchronous speed. At 70% speed the slip is $s=-0.3$ and 30% of the power is fed from the grid to the rotor via the converter. At 130% speed $s=+0.3$ and power is fed from the rotor to the grid. In practice system f) is in favor of system d) because of the larger control range and because of the lower losses. System e) is not applied because the technology with thyristor converters is becoming obsolete. In systems b) and c) the induction machine is connected to the grid via an full inverter coupling. These systems are more expensive and have a lower efficiency than system f) because the full power has to go through the inverter, and therefore, they are rarely applied. System g), consisting of a directly grid-connected synchronous generator, is not applied because of the very stiff characteristics of synchronous generator. Wind gusts are directly transformed to torque spikes and mechanical stresses in the structure. A power electronic converter has to be added in the stator circuit to enable speed variations and to reduce the mechanical stresses. Such a converter is costly because it has to be designed for the rated power of the generator. Therefore, system i) is more expensive and less efficient than system f) and practically not applied in larger turbines. Synchronous machines play a role in wind energy because they are applied in direct-drive wind turbines (systems j), k) and l). To eliminate the problems with the gearboxes, several wind turbine manufacturers started producing direct drive wind turbines. Direct drive generators necessarily have a large diameter because of the high torque. In gearless drives induction machines cannot be used because of the excessive excitation losses in these large machines due to the large air gap. For that reason synchronous machines are applied, either electrically excited or permanent magnet excited. As mentioned earlier, synchronous machines are too stiff for a direct grid connection, so that coupling via an inverter is necessary. The larger direct drive manufacturers nowadays use synchronous generators with electric excitation, system j). Direct drive systems with permanent magnet excitation (system k) are more expensive, but have lower losses.

Trends in generators for wind applications

There is a clear trend in the multi-megawatt wind turbines towards variable speed systems. Several manufacturers change from constant speed to variable speed for the large turbines. There are nowadays two important variable speed systems and for comparison one constant speed system, namely :

- the doubly-fed asynchronous generator with partial inverter coupling (system f)
- the synchronous direct drive generator with full inverter coupling (system j,k,l)
- gearbox with two stator induction generator (system a)

It is not yet clear what is the winning system. We do not expect important developments in drive systems with doubly-fed induction generator. We do expect important developments in direct-drive generators. The first development is the application of permanent magnets, because this results in a higher energy yield (2-4%) and an important reduction of the active mass of the generator (factor 2). The objection that permanent magnets are too expensive is loosing value because prices of the magnets are decreasing dramatically. A drawback of using permanent magnets is that the excitation can not be controlled. Besides, we expect that generators with higher power densities can be developed for direct drive wind turbines. For example with transverse flux machines, it seems to be possible to double the power density once more.

Tab. 1 Qualitative comparison of generator technologies

Technology	Reliability	Maintenance	Energy Extraction	Power Quality	Cost	Size
Gearbox with 2 – Stator induction generator	*Average* + Squirrel cage IG - Gearbox	*Average* + No brushes - Gearbox needs oil & filter replacement	*Least* - 2 Constant speeds	*Least* - "Shadow effect" causes strong current fluctuations	*Best* + High-speed IG + No Converter - Gearbox	*Best* + Height approx. 1 m + Light
Gearbox with Doubly-fed induction generator	*Least* - Gearbox - Wound-Rotor IG - Brushes on IG	*Least* - Gearbox needs oil & filter replacement - Brushes on IG	*Average* + Partly variable-speed	*Best* + Variable speed lowers current fluctuations - Conv. harmonics must be filtered out	*Average* + High-speed IG + Converter rated only 10% to 25 % - Gearbox	*Average* + Height approx. 1 m + Light - Converter requires additional space
Direct-Drive Generator	*Best* + No Gearbox + PM version has no brushes - Wound rotor version has brushes	*Best* + No Gearbox + PM version has no brushes - Wound rotor version has brushes	*Best* + Fully variable-speed	*Best* + Variable speed lowers current fluctuations - Converter harmonics must be filtered out	*Least* + No gearbox Low-speed generator -Converter rated 100%	*Least* - Height between 3.2m to 7.6m - Heavy

Balance of Torque and Power

In steady state the electromagnetic torque developed by the generator should balance the load torque. At a certain wind speed the operational point will be at the point of intersection of the generator and turbines characteristic. At higher speed the turbine will slow down and at lower speed it will speed up according to (7):

$$J\frac{d\omega}{dt} = T_{shaft} / n - T_{em} \quad (7)$$

Here J is the effective inertia of wind rotor and generator, n is the gearbox ratio, T_{shaft} is the torque developed by the wind rotor and T_{em} is the electro mechanic torque developed by the generator. Note that for a loss free gearbox the product of torque and speed on the slow shaft is equal to the product of torque and speed at the high-speed shaft. Also the mechanical input power of a generator should balance the output power and losses in steady state (8),(9):

$$P_{mech} = P_{elec} + P_{loss} \quad \text{or} \quad T\,\omega = \sqrt{3}\,U_{gen} I_{gen} \cos\varphi + P_{loss} \quad (8),(9)$$

Here U_{gen} is the line to line generator voltage and I_{gen} is the generator current. The angle φ is the phase angle between voltage and the fundamental of the current. With this equation we can easily calculate the current as a function of power, provided that cos φ is known. At increasing power rating of generators, the nominal voltage has to be increased to avoid excessive currents. Usually the generator voltage level is adapted to the voltage level of available power electronic converters. In Fig. 12 both turbine characteristics and generator characteristics are shown. The static operation point is determined by the point of intersection of two curves. The graph shows how the torque-speed curve of the generator should be located to extract maximum power from the turbine. With increasing wind speed the supply frequency should be increased to shift the operation point to a higher rotational speed.

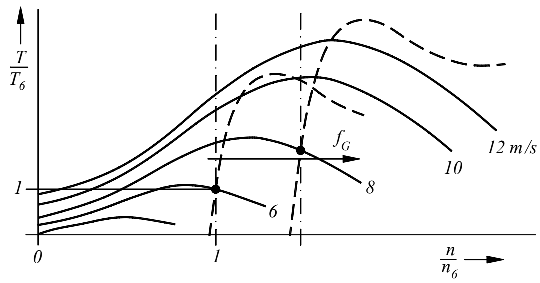


Fig. 12. Generator and turbine characteristics.

Power Electronic Converters

Power electronic converters perform an electronic conversion of voltage and/or frequency to adapt the characteristics of the source to the characteristics of the load. Electrical systems in variable speed turbines have followed the trend of electrical systems for traction and steel mills to apply variable speed devices based on the latest solid state technology. The development of power electronic switches their parameters and costs determine the further development of wind energy and wind parks. The preferred type at this moment is the IGBT (Insulated Gate Bipolar Transistor) and IGCT.

Windparks use the complete scale of power electronic converters. These are diode rectifiers, thyristor rectifier and inverter, AC/AC converters, AC/DC/AC (back to back) converters and DC-DC converters (see part power collection and transmission)

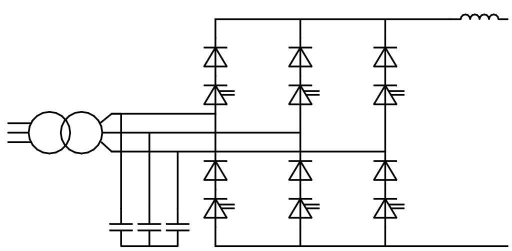


Fig. 13: Schematic of current source inverter

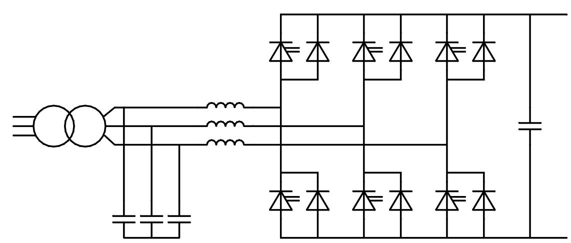


Fig. 14: Schematic of Voltage source inverter

The topologies for connecting a three phase systems are based on two basic configurations:

- Current source inverter (Fig. 13)
- Voltage source inverter (Fig.14)

Operation of a three phase inverter, different modulation principles and design is very well studied subject and therefore is not repeated here. For the high power applications such as windenergy and three level converter and 12 pulse converter will be used as studied next.

Modulation principles

For high power converters such as applications for wind energy and wind parks the switching frequency is usually limited to few hundred Hertz respectively kHz. Higher power means always lower frequency due to the switching losses in the semiconductor switches

The square wave is a basic switching strategy used for high power converters. The Voltage source inverter by the square wave switching operates with switches alternately switching in a phase leg with 180 degrees conduction. The output voltage with block modulation (square wave) can be varied with the use of three level inverter (Fig.15). The first waveform shown Fig.16 is a full 180 degrees square wave obtained by the closing of devices S1 and S2 for 180 degrees and the closing S3 and S4 again for

180 degrees. The second voltage waveform is obtained by turning S1 off and S3 on angle ∀ earlier. This in combination with the diode D5 and D6 clamps the phase voltage to zero with respect to a midpoint 0. This feature allows to obtain variable phase and line voltage.

To improve the harmonic content of a modulated waveform the twelve pulse converter is used. The two six pulse converters are connected in parallel on the same DC bus and work together as a 12 pulse converter. By phase shifting 30 degrees and delta wye connection of the transformer, the combined output voltage has a so called 12 pulse waveform with improved harmonic performance (Fig. 17). The idea of twelve pulse converter was originally used by thyristor rectifiers where with connection as depicted in Fig. 18 from two six pulse rectified voltages a twelve pulse voltage and current with improved harmonic performance is obtained. Since a thyristor rectifier is a current source converter according the principle of duality the shape of the waveforms in Fig 17.b has the AC current (Fig.18).

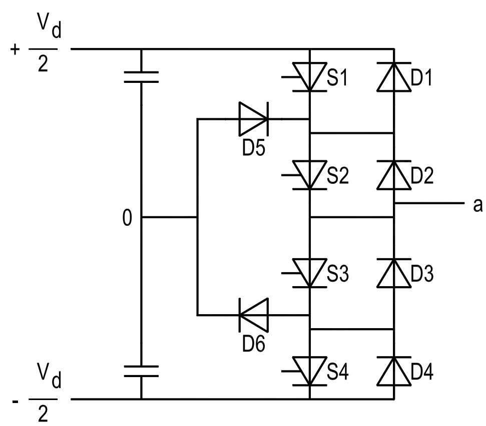


Fig. 15:One phase leg of a three level converter

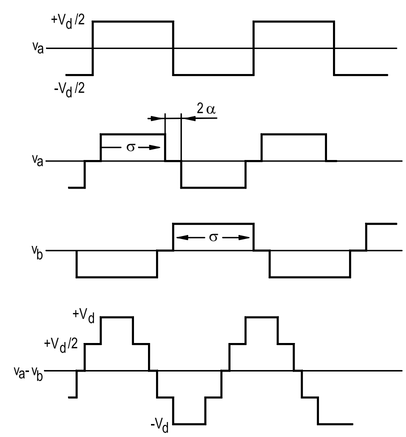


Fig. 16:Voltage of a three level converter

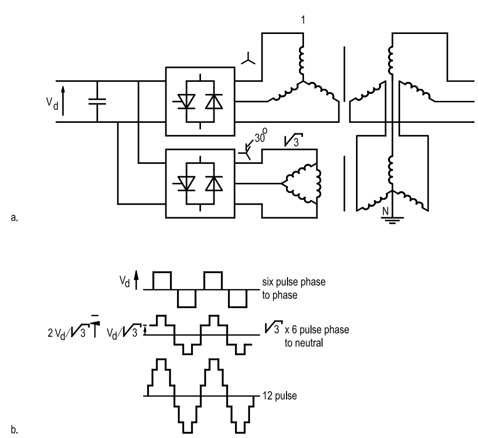


Fig. 17: Twelve pulse converter

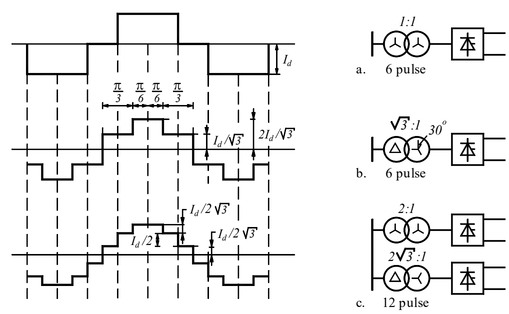


Fig. 18: Twelve pulse converter

HVDC Technology

Besides PWM modulated converters in high power application the line commutated converters (diode rectifier, thyristor rectifier and inverter) are still used. These in principle current source converters (Fig. 13) with phase control (thyristor) or uncontrolled (diode) are conventional and their operation is very well studied in all power electronics books [9]. For the offshore windpark application for connection to shore it is HVDC based on thyristor technology and the latest development HVDC based on IGBT technology. DC transmission in the range of 500 –1000MW is realised for decades with so called HVDC systems (High Voltage DC); the applied voltage is in the range 400-1000 kV. These systems are based on classic thyristor technology and are less suited for off shore wind power station because these HVDC systems require large amounts of space (football field size), they are susceptible to commutation failures when connected to weak grids extensive filtering and power factor correction is required. In the last few years several manufacturers (ABB, Siemens) have started the development of DC transmission systems based on the voltage-source converter topology (HVDC-light, HVDC-plus). These systems are more suited for wind farms because they do not posses the mentioned disadvantages. For the offshore applications plays the footprint an important role by the decision which technology should be applied. In Fig. 19 (ABB) the area's of HVDC systems are compared.

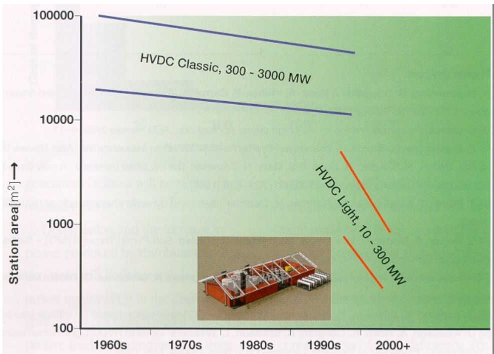


Fig. 19. HVDC systems comparison (ABB)

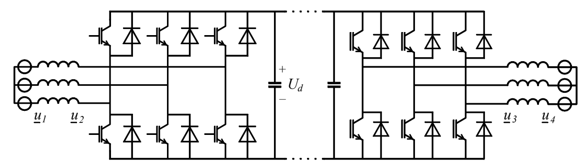


Fig. 20. DC Light (+) system principal circuitry

In Gotland (S) an onshore wind farm has been equipped with DC-light at 80 kV. DC systems are costly and the price is in the range 100-500 €/kW depending on voltage level, technology and requirements. The basic circuitry of a dc-light system consisting of two voltage source converters is shown in Fig. 20. The system is basically identical to a back-to-back converter as used in variable speed turbines.

Power Control of Wind Turbines

Essentially three methods of control speed control, torque control and power control can be used to match the turbine speed with wind speed. With direct grid connected generators basically have speed 'control' is achieved. Torque control and power control are related. In Fig. 21 block diagram is shown that illustrates a method of power control for a variable speed turbine. The control is based on a function that is assumed to be known and that gives the 'extractable' power as a function of wind speed. Because constant λ is assumed this function can be translated to power as a function of rotational speed. The control loop starts with measurement of the rotational speed. Next the generator side converter will be controlled such that power is extracted form the generator according to the function. When the rotational speed is too low for the wind speed, the turbine will accelerate and thus will the controlled power until an equilibrium is obtained. When the turbine meets maximum power the electric power will be limited by the converters. As a result the turbine will speed up above maximum speed and subsequently the pitch angle will be adapted to reduce the aerodynamic power. The capacitor acts as an intermediate energy buffer. The magnitude of line current is controlled on basis of the deviation of the capacitor voltage from the desired value

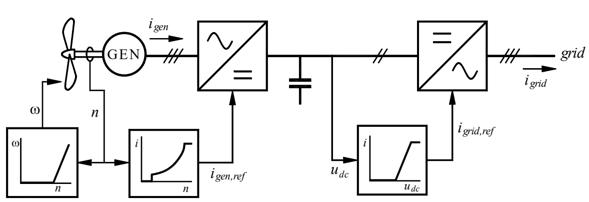


Fig. 21. Power Control for a variable speed turbine

Power Collection and Transmission

To transfer power from individual wind turbines to the onshore grid connection a system for the collection and the transmission of power is required. On shore power is normally transmitted via over head transmission lines, however these cannot be used because of wind, waves and ship traffic. Therefore undersea cables are required despite the fact that they also give rise to new problems and costs. A submarine cable consists amongst other of a conductive core of aluminium or copper, a layer of insulation that can withstand the applied voltage, a conductive shield to conduct capacitive currents, a steel armour and a finally watertight barrier. Because of the presence of the insulation the current carrying capability (ampacity) of the cable is limited because the developed heat cannot be transferred easily through the insulation. In practice the maximum ampacity of cables is 800 to 1000A, depending on soil type, voltage level and type of insulation. The limitation in ampacity means that the voltage level has to be increased if more power has to be transmitted. Tab. 2 gives, as an example, an overview of required voltages levels depending on power level both for ac as well as for dc transmission. The table also gives an indication of the resistive voltage drop per km as a percentage of the rated voltage. This percentage is equal to the loss of efficiency of the power transmission due to the resistive loss in the cable. Apart from resistive losses also dielectric losses occur. From the table it can be concluded that also for efficiency reasons the voltage level has to be increased with increasing power.

Tab. 2. Minimum required cable voltage

Power	Minimum required cable voltage @ 1000A			
	3 phase	DC	Resistive voltage drop	
MW	KV	kV	V/km	%/km (with ac)
4	2	2	50	2,2%
20	12	10	50	0,4%
100	58	50	50	0,1%

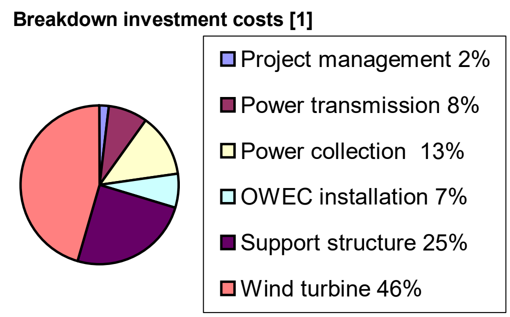


Fig. 22. Breakdown of investment costs

Basic electrical architecture of offshore wind farms - Architectures with AC connection

Several methods to collect the power can be distinguished. One of the standard solutions for the collection and transmission of power from wind farms that are located near the shore is shown in Fig. 23.a, where induction generators that are directly connected to the grid are used. In Fig. 23.b the voltage is stepped up in side the turbine and the power of a string of turbines is collected via a common cable to a common collection node. At that node the power of several strings is collected and the voltage is stepped up again to a higher voltage level and finally transmitted to a substation of grid. For large parks an extra collection level may be required. In Fig. 23.b the power of a star cluster of several turbines is collected to a common collection node. At that point the voltage is stepped up to a higher voltage level and subsequently transmitted to a collection node where the power of several clusters is collected. The differences between a and b concern availability of generators in case of cable failure, the need for additional platforms for a star cluster and the voltage rating of the cables in the cluster. In a string cluster the voltage rating of the cable should be higher than the voltage rating of cables ‘a’ in a star cluster. The power and voltage rating of the substation should be sufficiently high to absorb the wind power. If not the substation may need up grading of the substation which will be very costly.

The necessity of transformers near the turbines depends on the voltage rating of the cable and the voltage rating of the generators. With star clustering a transformer can possibly be left out (as indicated in fig b) if the generator voltage is sufficiently high (say >> 5 kV). With string clustering the transformer can only be left out if the generator voltage is at least several tens of kV because of the limited current rating of cables. With low voltage generators the number of transformers with star clustering can possibly be lower then with string clustering. ABB has presented in 2000 a generator for wind turbines where the windings are realised with high voltage cables; this so called ‘wind former’ is said to be suited for applications with dc-transmission as only a robust diode rectifier is needed to convert the machine voltage to dc. On the other hand the number of platforms with star clustering is higher then with string clustering as each cluster needs its own nodal platform for switch gear and a transformer. Next to star and string clustering there are more cluster types, such as meshed types and octopus. For park with variable speed turbines the standard architecture is comparable to the fixed speed solution. The systems of Fig. 24 consist of traditional variable speed turbines with back-to-back low voltage converters (about 1 kV). In Fig. 24.b medium voltage converters will be required (2 … 10 kV) when the converters are directly connected to the cable. More details about architectures for the electrical system of wind farms can be found in [6].

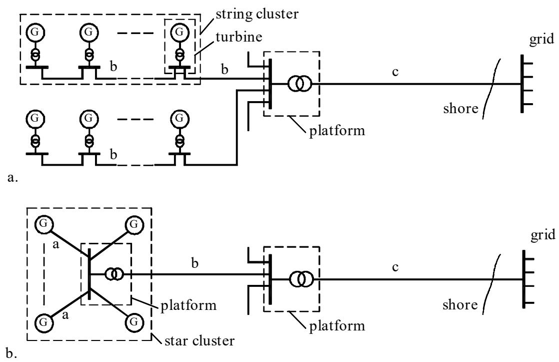


Fig. 23. Constant speed systems C1(a) and C2 (b)

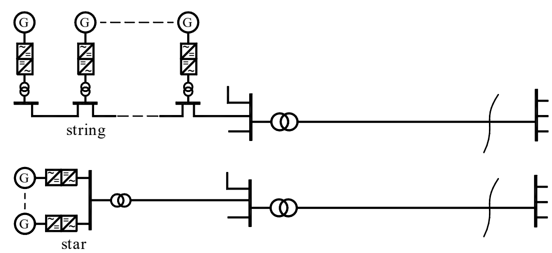
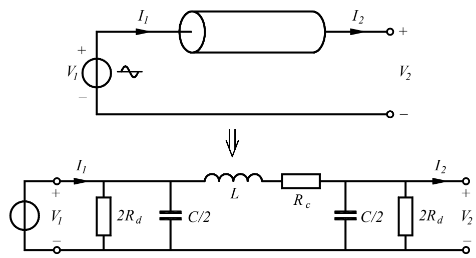


Fig. 24. Individual variable speed systems IV1 and IV2

Limitations of cables

Concerning power transmission several aspects of cables are of importance. It is mainly transmission length and capacitive current and losses and thermal aspects. The thickness of the insulation increases with the voltage rating and should be sufficient to prevent a breakthrough, while the conductor cross section increases with current rating. Fig. 26 shows the losses as a function of current. The maximum current for a certain cross section is determined by the ability to remove heat from the conductor, which is highly obstructed by the presence of the insulation. The ampacity is therefore mainly determined by the thickness of the insulation, the conductivity of the conductor and the thermal properties of the soil in which the cable is buried. For the example in Fig. 26 the maximum amount of heat that can be removed is 18 W/m, which is reached at about 1200 A. Excessive heating will deteriorate the insulation and will lead to accelerated oldering.

For low and medium power the three conductors of a three phase connection are integrated in a single cable. Mostly the centres of the conductors form a triangle, however some manufacturers (e.g. Pirelli) use a flat cable to improve the thermal management. For high-power cables three separate cables are applied, where the cables are laid in the soil with a spacing of about 1m to avoid thermal interaction. depending on soil type, voltage level and type of insulation. The conductive core of the cable has a capacitance to the soil. The total capacitance of the cable is proportional to the total length of the cable. When an open cable is connected to an ac voltage source, a current will flow into the cable according to (10). Here U is the rms voltage, ω is the radial frequency of voltage, C' is the capacitance per meter and l is the length of the cable. With increasing length the capacitive charging current will reach the value of the maximum allowable current of the cable; this length is called the *transmission length* and is roughly 100 –150 km, depending on cable type. For a cable that is connected to a load (the grid) the current in the cable will be the (complex) sum of the load current and the capacitive current. For a short cable the maximum load current is almost equal to the ampacity of the cable. For a longer cable an increasing part of the current carrying capability is used for charging current so that less power can be transferred to the grid. When cable losses are neglected we can write for the total current phasor at the sending end (11).



$$I_C = \frac{U}{\omega C' \ell} \quad (10)$$

$$I_C(j\omega) = \frac{U(j\omega)}{j\omega C' \ell} + I_{grid}(j\omega) \quad (11)$$

Fig. 25. Simple cable model

As an example Fig. 27 shows the current I_{grid} that can be transported to the grid as a function of the cable length for 150kV cable with a conductor cross-section of 1200 mm^2 . Further it is assumed that the power factor at the grid is 1.

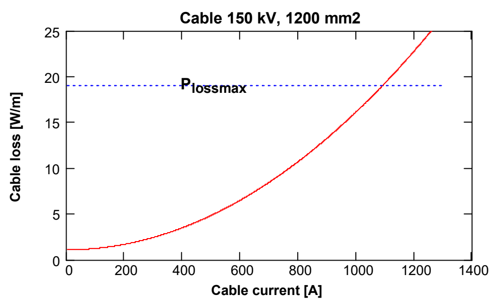


Fig. 26. Losses as a function of current

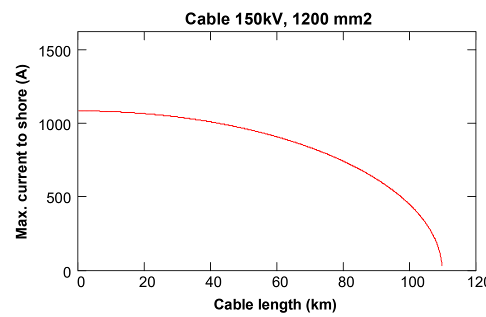


Fig. 27. Maximal transported current versus cable length

The transmission length can be extended by compensation of the capacitive current at both ends of the cables. With optimal compensation the transmission length can be roughly doubled. Note that the current inside the cable is depending on the co-ordinate along the cable as we have a distributed capacitance. As submarine cable are much shorter than the wavelength of the electromagnetic wave at 50 Hz, the simple cable model as shown in Fig. 26 can be applied. This model represent the capacitance, the losses and the inductance of the cable. The resistance R_c represents the conduction losses and the resistance in parallel to the capacitors represent the dielectric losses which occur even at no load. For XLPE (polyethylene) insulation the dielectric losses can be neglected in comparison to the conductor losses, while for paper insulated cable these losses are considerable. Typical values for a 1200 mm2, 150kV XLPE cable are: C= 0.21 uF/km, L=0.37 mH/km, Dielectric loss: 100 W/km. From this data the electrical parameters in the network model can be obtained.Because the current carrying capability of cables is determined by thermal limits, the cables should be laid in the soil with sufficient spacing (about 1m) to avoid additional heating by adjacent cables.

Architectures with DC transmission

a) b)

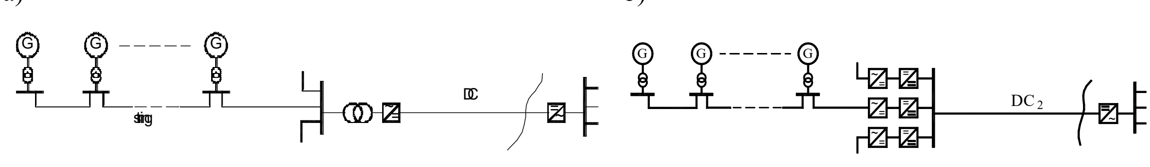


Fig. 28. Park coupled variable speed (a), cluster coupled variable speed (b)

For distances in excess of several tenth of km the power that can be transmitted by the cable is reduced significant due to the charging current of the cable. For long-distance submarine transmission the application of Direct Current is required because for dc the capacitive current is reduced to zero. The maximum distance that can be bridged is only limited by the cable resistance. In Fig. 28 systems are shown where DC is applied for the transmission of electric power. In Fig.28a) a system is shown where the power is transported from the park to the shore via DC. In the second system DC is also used inside the farm. Because the voltage level has to be increased at increasing power level, a DC transformer is included in the system. These high-power electronic dc transformers do not exist yet. At TUDelft/EPP research is performed in this field [8]

Fig. 29 shows a system where several turbines as connected to a common ac/dc converter to limit the number of converters. The frequency of the generators is variable and is controlled such that optimum power is extracted for the string. In this system also back-to-back converters are pulled apart such that dc-transmission is obtained.

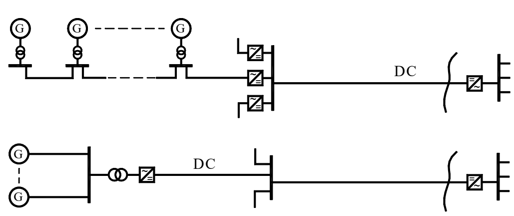


Fig. 29.Cluster coupled variable speed systems CV1 and CV2

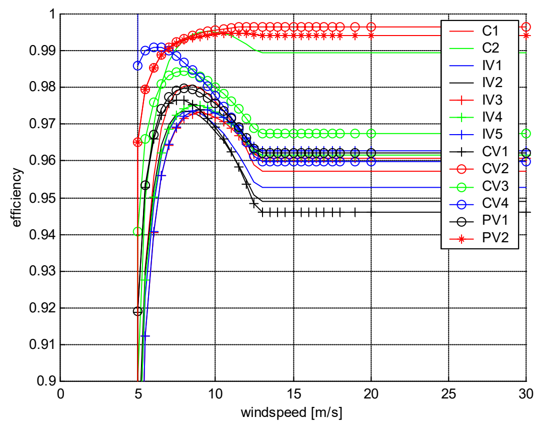


Fig. 30. Efficiency of electrical system of 100MW wind farms, 20km offshore

In a common project of TUDelft/EPP and ECN/Wind a programme is being developed for technical and economic comparison of architectures for offshore wind farms. In [7] the tool EEFARM and models of the components are described. More than 10 different architectures have been compared and analysed for two park sizes (100 and 500MW) and two distances to shore (20 and 60 km).

Tab. 3 Best scoring electrical architectures in dependency of turbine type

Turbine type	Architecture type		Efficiency	Costs	E-Cost per kWh
	Short description	code	%	M€	€/kWh
Constant speed	All ac; string clusters.	C1	97.7	20	0.008
Variable speed	All ac; string clusters.	IV1	95.5	30	0.012
	MVDC farm; AC to shore; strings.	IV3	96.2	66	0.027
Coupled speed	Var.freq.AC in string; HVDC to shore.	CV3	96.2	122	0.052
	Var.freq.AC in farm; HVDC to shore.	PV1	95.8	61	0.025
For all cases: Park size 100MW; cluster size 4 * 5MW; medium voltage level 33 kV; High voltage level 150 kV.					

The losses generally increase with increasing number of power converters, however when these converters are used to enable dc- transmission, the extra losses are to a large extent compensated by a reduction is cable losses. A traditional ac connection proved to have the highest overall annual electrical efficiency and the lowest cost of electrical equipment per kWh for near shore farms with constant speed turbines (Fig. 30). For near-shore farms with variable speed turbines a traditional ac connection also resulted in the lowest cost per kWh, however not in the highest overall efficiency.

The Tab. 3 shows that the traditional constant speed and variable speed systems offer a reasonable efficiency at moderate cost. The system IV3 offer the possibility to increase system efficiency however at higher costs. Systems CV3 (and PV1) might be interesting in the future if the cost of power electronics drops dramatically, because the energy yield of these systems possibly exceed the yield of any other system. It should be emphasized that the comparison does not take into account the extra energy yield due to variable speed operation and the cost differences of the different types of wind turbines itself. Further the electronics for CV3 and PV1 do not exist yet. The costs are estimated and consequently inaccurate. In [7] more information about electrical architectures for offshore wind farms can be found.

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