



A New Cost-Effective Wind Farm Structure with HVDC Link Preserving Technical Advantages of Advanced offshore Wind Farms

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Abstract— In this paper a review of common wind turbine systems and wind farm configurations with AC and DC links is presented first, and then a new structure based on HVDC local grid is proposed and compared to the existing structures to show its effectiveness with respect to the older ones. The most important feature of the new structure is its lower cost, while it preserves controllability of the most flexible configurations like DFIG-based wind farms or wind farms with PMSG generators and back-to-back converters. The other feature of the proposed structure is its high efficiency, which is due to the use of direct driven multi-pole synchronous generators.

Keywords- Wind farm structure, Cost effective wind turbine, Direct driven wind turbine-generator, HVDC transmission.

I. INTRODUCTION

Wind turbines are arguably the most developed sources of renewable electrical energy with ratings of several MW. In recent years, many power conversion techniques have been developed for integrating with wind turbines. The use of power electronic converters allows variable speed operation of the wind turbine, which in return, makes maximum power extraction of the turbine possible for different wind speeds, and attenuates the mechanical stress that the turbine blades and towers are subjected to [2], [4].

As the wind industry develops, there is more interest in building large wind farms further offshore. For example, ambitious energy planning in Denmark has scheduled a level of 50% wind energy penetration in the year 2030—mainly covered by large offshore wind farms. This offshore wind farms might have distances of more than 100 km to the nearest grid connection point. In such a case the charging reactive power associated with the AC transmission cable capacitance will be significant and cannot be easily handled. Therefore, it may be necessary to use HVDC links instead of HVAC [2], [3].

On the other hand, the latest semiconductor technology development has provided modern HVDC transmission systems with fully controllable converters, based on forced commutated semiconductor switches. HVDC technologies are mainly interesting for power transmission over longer distances. The DC cable is less expensive than an AC transmission cable with the same capacity, but the cost of converter stations make the complete HVDC link more expensive than the corresponding AC link, if the transmission distance is below a certain threshold [5].

In this paper, common wind turbine systems are briefly reviewed in Sec. II. Different configurations of wind farms are then discussed in Sec. III. In Section IV a new cost effective wind farm structure based on HVDC link is proposed which is suitable for offshore wind farms. Also, some advantages of the new structure are discussed in these sections. Finally, in Section V the proposed structure is compared with some common structures of wind farms.

II. TYPES OF WIND TURBINE SYSTEMS

Since early days of exploitation of wind energy for electricity generation till now, different types of wind turbine systems have been designed and used. Early systems were constant speed types, i.e. the wind turbine-generator speed was relatively constant, regardless of wind speed variations. But the need for higher efficiency wind turbines required the generators vary in a wide range, depending on the wind speed, in order to implement Maximum Power Point Tracking (MPPT) feature. Shortcomings of the constant speed wind turbines led to development of variable speed types which are being used at new wind farms. A brief review of common wind turbine structures is presented in the following, for the sake of better introducing the new structure.

A. Multi stage gearbox- squirrel cage induction generator- constant speed wind turbine

This wind turbine system, as shown in Fig.1, includes a squirrel cage induction generator (SCIG) directly connected to the AC grid. In spite of torque variations and by the use of a multi-stage gearbox, the SCIG keeps an almost constant speed (variation of 1-2%) and the input power of the system is limited aerodynamically either by stall, active stall or by pitch angle control of the wind turbine [3]. Fixed speed wind turbines were mostly manufactured until late 1990s with power levels of below 1.5 MW [1].

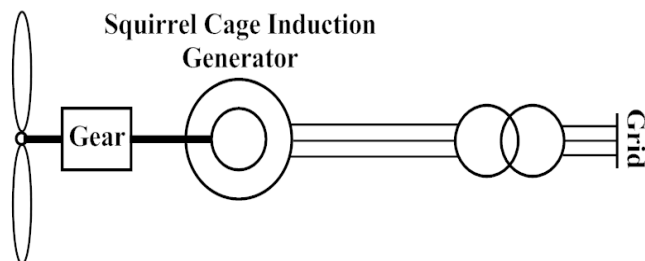


Figure 1. Multi stage gearbox- squirrel cage induction generator- constant speed wind turbine

B. Multi stage gearbox- doubly fed induction generator- wind turbine

Since the late 1990s manufacturers have changed to this type with power levels starting from 1.5 MW. In this system, Fig. 2, the 4-quadrant converter between the generator rotor and the grid is approximately 20~30% of the rated power of wind turbine and is responsible for speed variation and maximum power point tracking [1].

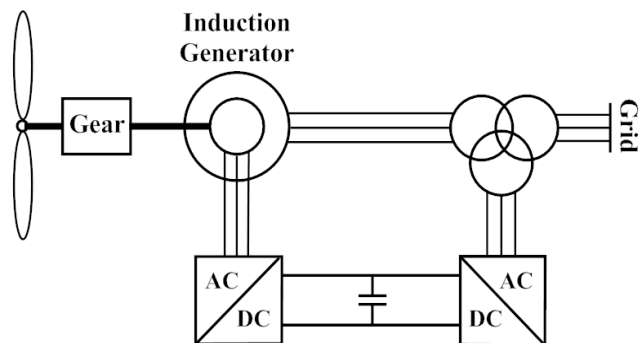


Figure 2. Multi stage gearbox- doubly fed induction generator-wind turbine

DFIG has been considered as an economic solution for large, variable-speed wind turbines in spite of its disadvantage of having a brush-slip arrangement. Using this system, speed variation of 60% around synchronous speed may be obtained by the use of a power converter with 30% of nominal wind turbine power [2], [3].

C. Direct driven or single stage gearbox- synchronous generator- wind turbine

Different parts of this scheme are shown in Fig. 3. The generator-side AC/DC voltage source converter is controlled through MPPT such that for each wind speed, optimum rotor speed and maximum electrical power is obtained. In contrast,

the grid-side inverter controls the line currents so that the DC-link voltage of the converter is regulated. The back-to-back converter is of full rated power, i.e. equal to that of the synchronous generator.

In this system the gearbox can be eliminated by employing a high pole number, low-speed synchronous generator. Since 1991 this type of wind turbines has been considered to eliminate gearbox failures and to reduce maintenance problems. But for increasing power levels and decreasing speeds the direct driven turbine system becomes larger and more expensive. By the use of a single-stage gearbox, smaller-size synchronous generators can be used for the same wind turbine rating. This system, as compared to direct-driven system, has a significant reduction in generator cost and an increase in generator efficiency [1]. However, addition of gearbox will introduce losses and will reduce the overall reliability of system, and therefore, the direct driven system might be preferred.

Synchronous generator of this wind turbine might be excited either electrically or with permanent magnets. Permanent magnet excitation is generally favored in smaller scale turbine designs, since it yields higher efficiency and smaller wind turbine generator diameter, and also, it does not require any external excitation system. On the other hand, as the industry moves to larger scale designs, economics of large volumes of permanent magnet material has limited application of Permanent Magnet Synchronous Generators (PMSGs) in such designs [4].

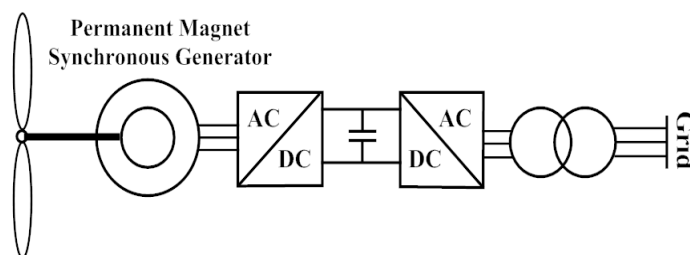


Figure 3. Direct driven- synchronous generator- wind turbine

An example of electrically excited system is TWT1650 wind turbine with a direct driven generator of 1800 kW rating, designed by M. Torres group. First prototype of this wind turbine began operation at Cabanillas wind farm (Spain) in August 2001 [7]. Also, Enercon and Lagerwey are other examples of wind turbine manufacturers that have used direct-driven wound rotor synchronous generators [5].

A major cost benefit in using synchronous generator is the fact that a diode bridge rectifier may be used at the generator terminals since no magnetizing current is needed to be absorbed from the grid. In this case, the generator speed is controlled through the DC-link voltage where a DC/DC converter can be used to gain more flexible system [4].

III. COMMON WIND FARM CONFIGURATIONS

Although different configurations have been used in wind farms, but the variety of them is not that much. Different configurations differ in the nature of wind farm's local network, i.e. AC or DC, and the way they are connected to the AC grid.

Accordingly, wind farm configurations can be grouped as follows.

A. Wind farms with AC local network and direct connection to the grid

In this type of wind farms, as shown in Fig. 4, wind turbines are connected to a common AC local network within the farm, in order to collect and transfer the generated power into the main grid. Usually the local network is coupled to the main grid through transformers, which match voltage levels of the two sides. It is obvious that in this configuration the local network has the same frequency as the main grid.

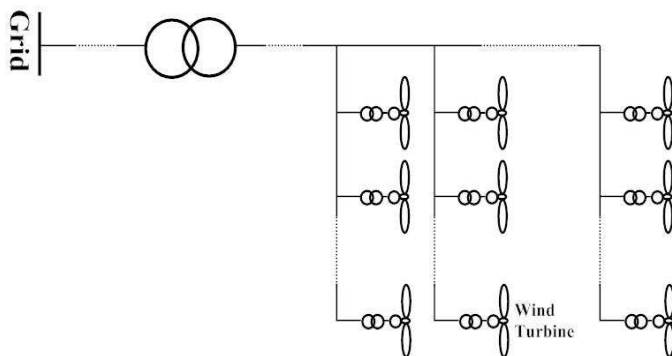


Figure 4. Wind farm with AC local network and direct connection to the grid

Configuration of most wind farms is of this type, however, it is recently preferred to use HVDC links in some cases like offshore wind farms, to benefit from advantages of HVDC.

B. Wind farms with AC local network and connection to the grid through an HVDC link

In this configuration the AC local network is connected to the power grid through an HVDC link, as shown in Fig. 5.

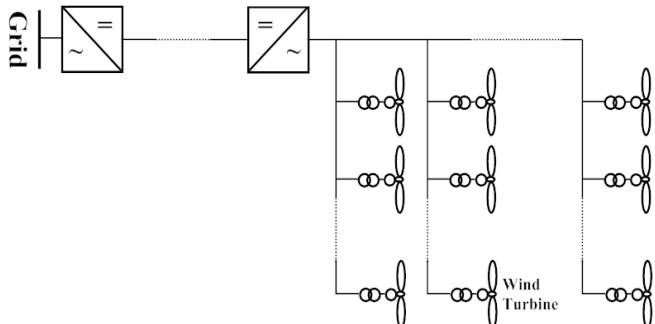


Figure 5. Wind farm with AC local network and connection to the grid through an HVDC link

In principle, all wind turbines designed for connection to AC grid can be used in this configuration, including fixed speed wind turbines with directly connected induction generators; provided that voltage source converters (VSCs) are used for the HVDC terminals. Depending on the type of WT, then, some of the advantages of using power converters in the wind turbines are vanished. In this configuration, it is possible to control the frequency of the local network in order to improve the aerodynamic efficiency in the same way as for

wind turbines with individual power converters. The frequency control must set the frequency to an optimum value considering optimum speed of all individual wind turbines in the farm, because the wind speed is different from one wind turbine to another. Therefore, the aerodynamic efficiency will be higher than fixed speed WTs, but lower than WTs with individual power converters. Another problem with the common frequency control, which is probably more important, is that it cannot be used to reduce mechanical stresses on the drive train as individual WT power converters can [5].

C. Wind farms with DC local network

Another way of using HVDC is to have a local DC network, as shown in Fig. 6. In this configuration each wind turbine is directly connected to the HVDC local network. Also, HVDC is used to transmit the generated power to the grid connection point, where a DC/AC converter rated at full capacity of wind farm is installed.

One variant of this configuration is to have constant voltage DC link and to control each wind turbine through its own forced commutated converter, so that it operates at the individual optimal speed [3].

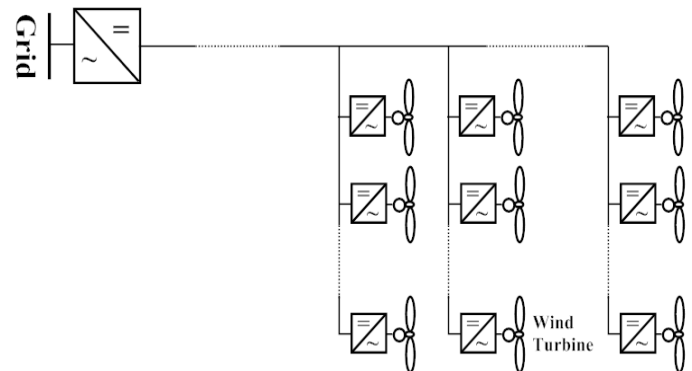


Figure 6. Wind farm with individual wind turbines connected to HVDC link

Another method is to use diode bridge rectifiers as individual wind turbine AC/DC converters and to control the wind farm through voltage magnitude of the DC link, like common frequency control discussed in configuration B of this section. As an example of this approach, ABB has proposed a new Windformer concept with individual diode rectifier AC/DC converters for wind turbines (Nielsen 2000). The generators are of synchronous type, because they must provide the magnetic field themselves. ABB proposes a multi pole (gearless), high voltage permanent magnet generator, which can be connected directly to the rectifier without a transformer. In this case there is no provision for frequency control to reduce mechanical stresses on the drive trains, because the speed control is based on control of the common DC link voltage magnitude. A more critical aspect of this wind farm is whether it will be stable with the required blade pitch angles. Both the steady state stability and the dynamic stability must be studied. The system is very complicated, with speed dependent aerodynamic loads and generator AC impedances in the individual wind turbines, and only one common DC voltage, which must be controlled with compromise between all the turbines [5].

This configuration along with configuration B is suitable for offshore wind farms which are too far from the nearest costal grid connection point at coast. In such cases, due to the large reactive power compensation requirements, use of AC transmission cables between wind farm and the grid is almost impossible.

IV. A NEW CONCEPT FOR WIND FARM CONFIGURATION

In offshore wind farms far away from coastline that HVDC transmission is the only choice, using AC local network for wind farm, as in Fig. 5, seems not optimum. Since one AC/DC conversion is needed at the wind farm side of HVDC transmission link; and should the wind turbines be of variable speed type, another AC/DC/AC conversion has been done by each WT's converter to perform MPPT and inject the generated power to the AC local network. Although for DFIG-based wind turbines the latter conversion has fractional rated power of WT. Thus, one of these conversion steps seems unnecessary. In other words choosing DC local network, which is a part of HVDC transmission link, as shown in Fig.6, results in the fewest AD/DC conversions possible and will be more cost effective for offshore wind farms.

As of the choice between variable voltage HVDC link or constant voltage one for the wind farm, it must be taken into account that having direct control on each wind turbine can have significant advantages over group control of wind turbines. Therefore, it is preferred to have a constant voltage HVDC local network with its grid-side DC/AC converter responsible for keeping the voltage constant, and to deploy a means of direct control on individual wind turbines. Up to now, this control has been gained by the use of full-rated forced commutated converters at the terminal of wind turbine generators (usually PMSG) to connect them to the HVDC network. In the following a new solution is suggested that preserves advantages of the above structure, and reduces the wind farm cost significantly.

The last point about this structure is that because of DC nature of the local network and transmission link, not only big capacitance of network cables are not a problem, but also this big capacitance can be used as a great energy storage bank during transients to maintain stable operation of wind farm. For example, it can help solving the ride through problem of wind farm when grid faults occur.

In the proposed configuration, each WT is connected to the local DC network through a diode bridge rectifier. Therefore, the wind turbine generators cannot absorb their magnetization current directly from the local network. This suggests that the wind turbine generators must be PMSGs with self excitation or Wound Rotor Synchronous Generators (WRSGs) with external excitation source. Since it is preferred to have direct control on each wind turbine rather than controlling a group of them simultaneously, use of PMSGs is inappropriate and the wind turbine generators must be of WRSG type. On the other hand, considering this structure for the wind turbines, the synchronous generators excitations can be seen as a means of direct control on each wind turbine at the cost of a small low cost DC/DC converter fed through HVDC local network. Thus, the suggested structure comprises WRSGs which are connected to the HVDC local network through step up transformers (if needed) and diode bridge rectifiers. Excitation systems of these

WRSGs consist of DC/DC controllable converters connected to the HVDC local network. These converters have ratings equal to the excitation circuit of WRSGs and thus are much smaller and cheaper than the converters used in wind turbines with PMSGs and back-to-back converters or DFIG based wind turbines. Yet, this small converter provides the same control level as the above-mentioned high end wind turbines and can be used for performing MPPT on each wind turbine and to reduce drive train mechanical stress. The proposed structure for the wind turbine system is shown schematically in Fig. 7.

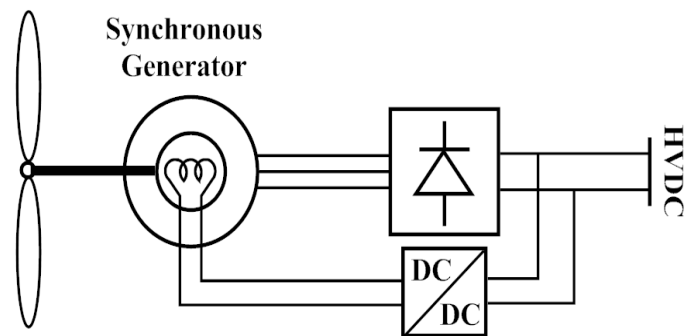


Figure 7. The new wind turbine system for HVDC transmission of wind farm generation

The other WT systems possible with HVDC local network are PMSGs or induction generators with full-rated VSC rectifiers at their output. Among these two, PMSGs are preferred since they can be chosen of high-pole direct driven types. However PMSG for larger scale wind turbines considered nowadays is costly [4]. Besides, this structure requires more expensive converters compared to new structure, both in terms of the type and ratings of the converters.

As the last point, note that the wind turbine generators of the proposed structure can be high pole number-direct driven WRSGs with improved overall efficiency or single stage gearbox driven WRSGs with smaller size and reduced cost. Also, if the use of brush-slip arrangement for excitation circuit of the generators reduces the system reliability, the generators can simply equipped with the widely used brushless AC excitation system.

V. COMPARISON OF THE NEW CONFIGURATION WITH OTHER TYPES

The first comparison is done between the new structure and synchronous generator-based wind turbines with AC local network. The main advantage of the proposed structure is that the full rated forced commutated rectifier of the generator's back-to-back converter is replaced with a much cheaper diode bridge rectifier, and the wind turbine control is done through a DC/DC converter with much smaller rating and cost. Also, AC network-side inverters of the generators back-to-back converters are eliminated and the DC/AC conversion is done by the grid-side converter of HVDC link. In addition, AC local network is replaced by HVDC, an immediate advantage of which is that in the case of offshore wind farms, reactive compensation and capacitive over voltages of the local network would not be an issue anymore. Further, this high capacitance can be used to improve dynamic behavior of the farm during grid transients or wind fluctuations. The same advantages apply

compared to DFIG-based wind turbine-AC local network wind farm; added that low reliability gearbox can be eliminated in the proposed structure.

The other comparison considers the new structure and ABB's Nielsen 2000 wind farm [5] which was discussed briefly in Section III. The new structure has full control on each wind turbine rather than controlling them collectively through HVDC voltage magnitude, and therefore suggests improved aerodynamic efficiency, fewer stability problems and reduced mechanical stresses on the turbine drive trains. The other difference between the two wind farms is that costly PMSGs are replaced with WRSGs. Instead, only a low-cost DC/DC converter of excitation system rating is added to each wind turbine. Thus, in spite of higher performance indices, the overall cost of the proposed wind farm could be even lower than the Nielsen 2000 design.

The last comparison considers one of the most recent offshore wind farm structures suggested in [8]. This structure, as shown in Fig.8, consists of PMSG based wind turbines equipped with Magnetic Energy Recovery Switch (MERS), transformer and diode rectifier. All wind turbines in the wind farm are connected in series to a single Current Source Inverter (CSI) through DC link. CSI is installed at a coastal point close to the farm. Each MERS consists of four reverse conductive semi-conductor switches and a dc-capacitor. By shifting the gate signal of the switches, the equivalent capacity can be adjusted. This behavior of MERS is thus regarded as a variable series capacitor that can provide a limited control on each wind turbine.

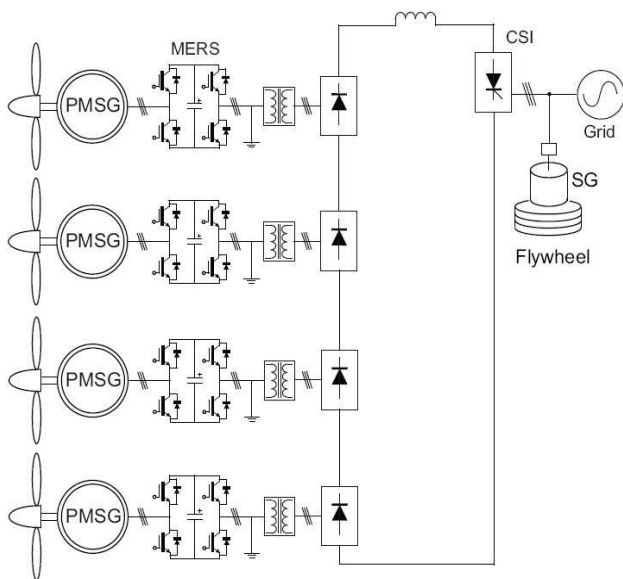


Figure 8. The offshore wind farm structure suggested in [8]

The overall control of the structure is such that, in order to achieve the MPPT operation, CSI takes charge of global control according to the average wind speed of all wind

turbines and MERSs take care of local controls according to the locational wind speeds. However, considering the limited controllability of MERSs, it is concluded that higher number of wind turbines in the wind farm will make accurate MPPT impossible. Comparing this structure with the new structure proposed in this paper, it is evident that the new structure suggests guaranteed MPPT control on each wind turbine with lower cost. In fact, the new structure has replaced three MERSs with nominal current rating of each wind turbine with one DC/DC converter of much lower rating for the generator excitation circuit. Furthermore more costly PMSGs are replaced with brushless excitation WRSGs.

VI. CONCLUSION

In this paper a new structure is proposed for offshore wind farms which is optimized for HVDC transmission of wind farms output power. The main idea behind the new structure is to have an HVDC local network and transmission link for wind farm, and to use electrical excitation of WRSG-wind turbines to control them instead of controlling their terminal currents through costly voltage source converters. Excitation systems are also fed through the HVDC local network. According to the comparisons presented in sections IV and V, this structure can yield a significant cost reduction for offshore wind farms far away from the coast, maintaining main advantages and controllability features of the most advanced wind farms.

Quantitative analysis of the proposed structure, and investigating its applicability for land based wind farms is underway by the authors, and will be presented in near future.

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