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ABSTRACT

THIS paper presents three topics which are important for better performance of future wind farms. The topics are investigated in three coordinated Ph.D. projects ongoing at the Technical University of Denmark (DTU), Aalborg University (AAU) and DONG Energy. The objective of all projects is to improve the understanding of the main electrical components in wind farms, based on available information, measurement data and simulation tools.

The aim of these projects is to obtain validated models of wind turbine (WT) generators, WT converters, WT transformers, submarine cables, circuit breakers and wind farm transformers, and to develop a methodology on how to select appropriate equipment for the power system, control system and protection system.

I. INTRODUCTION

Three coordinated Ph.D. projects have recently started at DTU, AAU and DONG Energy. The main aim of the three of Ph.D. projects is to improve the understanding of the main electrical components in wind farms. Two of the Ph.D. projects focus specifically to offshore wind farms and full-scale converter wind turbines (WTs), while the other focus on the electrical main components WTs in general.

The Ph.D. project "Overvoltages and Protection in Offshore Wind Power Grids" focus on the transient and temporary overvoltages known to appear in the collection grid of offshore wind farms. The academic and industrial partners of this project are DTU, DONG Energy and Siemens Wind Power.

The Ph.D. project "Harmonics in Large Offshore Wind Farms" will provide in-depth knowledge of all relevant aspects related to harmonics in offshore wind farms. The academic and industrial partners of this project are AAU and DONG Energy.

The Ph.D. project "Electrical Main Components in Wind Turbines" focus on electrical compatibility between the main electrical components of WTs and their compatibility with the surrounding environment. The academic and industrial partners of this project are DTU, DONG Energy, Vattenfall, DTU-Risø, AAU, ABB, Siemens, DELTA, Siemens Wind Power and CODAN.

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Overvoltages and Protection in Offshore Wind Power Grids

So far, there have been successful applications of large offshore wind farms in Denmark and the UK. However, the failure rate experienced for certain components in offshore wind farms is too high and several research projects focus on different aspects relating to this, for example a recently completed DONG Energy Industrial Ph.D. project by N. Barberis Negra [1]. Overvoltages are a possible cause of some component failures experienced in offshore wind farms incl. failures to WT transformers at Middelgrunden and Horns Rev 1 [2]. The present project will focus on overvoltages in offshore wind farms especially related to the cable collection grid – i.e. on the mechanisms causing overvoltages. The approach will be development of validated models for computer tools for simulating and assessing the severity of overvoltages, and on mitigation by insulation coordination.

Large offshore wind farms (OWFs) are based on extensive MV submarine cable collection networks connecting tens to hundreds of usually identical WTs placed in regular patterns with certain interspacing and connected to a transformer station which in large wind farms is usually also placed offshore at which the voltage is raised to high voltage for transmission via a submarine export cable to a connection point in the public power system on land. Such arrangements are unusual as compared to a typical expansion of a power system in several ways such as: the lateral sizes of the systems, the large number of identical sub systems: generators, power converters, transformers, and switchgears in the WTs and collection network cable network; and also unusual compared to other power system´s operating conditions and environmental constrains.

The wind farm transformer station is often connected via a single export cable to a connection point to the public power grid on land up to more than hundred kilometres from the offshore wind farm. This is also highly unusual.

Transient- and temporary overvoltage studies and system protection studies are usually performed during the development of extensions of the electric power systems. The detail to which such studies are conducted depends on the simulation tools and resources available, and the reliability of the results depend on the tools used as well as the trustworthiness of models and input parameters representing the components of the system. DONG Energy have previously conducted overvoltage studies for the Danish offshore wind farms Nysted and Middelgrunden, however in both cases the

usefulness of the studies were limited by the uncertainties that had to be attributed to the models and therefore to the results. This problem was also demonstrated in a recent M.Sc. project [3] that compared two commercial simulations tools against measurement, and confirmed that insufficiently accurate models, input parameters and limitations of the simulation tools lead to significant uncertainties of results.

This Industrial Ph.D. project is focused on investigating how best to perform such studies for offshore wind farms taking into account the new and unusual conditions typical of offshore wind farms mentioned above, and with the specific aim to improve methods and models to be used for these studies and thereby achieve the necessary higher reliability of offshore wind farms as large power generation units in electrical power systems.

Regarding the modelling of MV and HV equipment for transient overvoltage studies / insulation coordination, there is fair amount of information and guidelines available in the literature about circuit breakers, transformers, cables, surge arrestors etc.; this however tend to be mainly theoretical information, and in practice the information about these components is typically not available in sufficient detail for accurate insulation coordination studies [4]. Furthermore, commercial simulation tools tend either to have limited facilities for this type of studies or require very specialized training and experience. In short, the credibility of this type of studies relies on the quality of the models and information that the user can get hold of, and even then, it depends on the simulation tools and the user's skills. This creates additional concern and further work is necessary to design the collection grid of wind farm with the high reliability, needed for offshore wind farms. The following sections will briefly describe how some components can be modelled for transient overvoltage studies.

Vacuum circuit breakers (VCB) are often used in offshore wind farms as primary switchgear components, hence it is important to be able to accurately represent this component. Recent research has shown the importance of the representation of VCBs in the simulations of wind farms [5],[19] and the simulation tools currently available to DONG Energy evidently does not have sufficiently accurate models for this component to replicate switching overvoltages measured in wind farms [18]. For the VCB different models do exists and they all take into account arc thermal instabilities. However there is no universal precise arc model. The generic model of VCBs incorporates stochastic properties of different phenomena that take place in the breaker opening and closing process [6]. The different properties that are generally considered are the random nature of the arcing time, current chopping ability, the dielectric strength between contacts, and the quenching capabilities of the high frequency current at zero crossing [7]. In [8] a procedure to estimate the VCB parameters based on measurements has been developed with good accuracy, as well as interesting conclusions regarding the magnitude and rise time of surges. However such more accurate models are in practice not available for the commercial VCBs employed in wind farms, as it is either generic/theoretical models or kept confidential by the VCB manufacturer. This therefore creates a need for developing sufficiently accurate open models for the VCBs actually used in wind farms and for validating them against measurements.

Each WT is connected to the MV submarine cable collection grid through a step-up transformer, which must be modelled sufficiently accurately for transient studies, since fast and very fast transients are a known cause of transformer damages. A detailed transformer transient model can be employed to design the proper insulation [9]. Transformer modelling methods can be classified as Gray Box and Black Box models. The Gray Box models can be used by the transformer designer to study the resonance behaviour of transformer windings and the distribution of electrical stresses along the transformer windings. The Black Box models are necessary for the insulation coordination of power system and can be employed to evaluate the current and voltage wave shapes at the terminals of the transformer. The Black Box models are normally based on the results from measurements in time and/or frequency domains. Gustavsen has developed a procedure to measure the frequency dependent admittance matrix of the transformer [10], and then create a synthesized electrical network [11] using the vector fitting technique [12]. However, such models are in practice not available from the transformer manufacturer and sufficiently accurate models therefore have to be developed and validated against measurements.

The cables in the collection grid of offshore wind farms are solid dielectric cables with cross-linked polyethylene (XLPE) insulation. For transient studies the cables should be modelled in EMT programs that can accurately represent the frequency dependence of the cables. These models require certain information: the series impedance matrix Z and the shunt admittance matrix Y. These parameters are calculated automatically by the cable constants routines within the program, using cable geometry and material properties as input parameters. The calculation of Z and Y from the geometry and the material properties follows similar procedures for all cable constant routines. However there are still challenges regarding the impedance calculation based on computing surface impedance and transfer impedance of cylindrical metallic shields, as well as regarding calculation of the self and mutual ground impedances [13]. Again such models are in practice not available from the cable manufacturer and therefore have to be developed and validated against measurements.

Metal oxide surge arresters (MOSA) are widely used as protective devices against switching and lightning overvoltages in power systems. Switching surge studies could be performed by representing the MOSA only with their non-linear V-I characteristics. However, MOSA have dynamic characteristics and have to be modelled differently for low frequency, slow front, fast front and very fast front transients;

as explained and discussed in [14]. Some characteristics, referred to as frequency-dependent and temperature-dependent, might be required in more sophisticated models than the simple static non-linear resistance. Again such models are in practice not available from the MOSA manufacturer and therefore have to be developed and validated against measurements.

The temporary overvoltages in the collection grid of offshore wind farms is gaining attention from wind farm owners and WT manufacturers due to the large amount of sensitive power electronics in frequency converter WTs. The transmission system operators are also interested in temporary overvoltages, since high overvoltages are experienced when disconnecting in the grid connection system for offshore wind farms while the WTs are operating [14]. However, at the planning stage of a wind farm, the system designer has at best only a limited digital model from the WT manufacturer available to estimate the worst possible temporary overvoltage.

Overvoltages as high as 2p.u. in Horns Rev 1, on the west coast of Denmark, have been observed when the main-circuit breaker tripped the wind farm cable at the on-land connection point and left the wind farm in isolated operation with the cable and the wind farm transformer [15]. Although such events are rare, this represents a risk of damaging the equipment. The Danish transmission system operator, Energinet.dk, performed investigations of such overvoltage in connection with the planning of the new offshore wind farm Horns Rev 2. These investigations have shown that the temporary overvoltage levels are influenced by many parameters, including operational characteristics of the WTs prior to the disconnection, protection systems, control and the accuracy of the representation of the cable and the transformers in the relevant frequency range [16].

The WTs have evolved from the first models with direct connected induction machines, to complicated systems with new advanced equipment and capabilities. As mentioned before, the wind farm developers have only limited digital models of the WTs from the WT manufacturers, available for conducting the appropriate design studies. Such dynamic WT models are based on a generic design of a variable-speed WT employing either a doubly fed variable speed generator or a full-scale converter where the WT generator is grid connected through a frequency converter system, which feeds the generated active and reactive power into the power grid at the power system frequency. The application of a frequency converter system comprises two AC/DC converters and a DC-link. The DC-link decouples the generator and grid frequency, so that the WT rotor speed always can be optimized to the actual wind speed conditions. The combination of variable-speed operation and pitch blade-angle control improves power output optimization of the WT rotor and reduces noise. In high-speed wind, the pitch control is used to limit the power output to the rated WT power.

Work with implementation and validation of dynamic WT models are of increasing importance for wind farm developers and transmission system operators, since the offshore wind power installations increase in size and complexity and the dynamic simulation tools become an indispensable part of transient overvoltage stability and insulation coordination studies related to the incorporation of wind power into power grids

WT manufacturers have developed dynamic simulation model of their WTs, as requested by transmission system operators and wind farm developers. Siemens Wind Power has published the dynamic model validation results for a certified fault-ride through tests (Low voltage ride through). The validation has shown good agreement between the measurements and the dynamic results gained from the WT [17]. The successful validation gives credibility to the WT model for transient power system stability studies. However, there is a corresponding need for accurate and validated modelling of WTs in connection with overvoltages, which so far have not received nearly as much interest as low voltage ride through.

As mentioned above, there has been extensive work done regarding the modelling of transformer, cables, circuit breakers, surge arresters and WTs for different studies; however no work has been done so far on gathering this information and apply it to create general guidelines for overvoltage protection studies in offshore wind farms. Doing this in this Industrial Ph.D. project, will eventually help to develop a more reliable and robust electric network from the planning stage to the operation of the wind power plant.

Regarding the available measurements to create validated models, DONG Energy has access to GPS synchronized high frequency measurements of switching events realized at three different locations in two different large offshore wind farms: Nysted Offshore Wind Farm and Burbo Bank Offshore Wind Farm, as well as long term time series and power quality measurements registered at 44.5kHz [18]. The measurement system was developed and the measurements performed within the project entitled “Voltage conditions and transient phenomena in medium voltage grids of modern wind farms”, PSO-F&U Projekt nr. 2005-1-6345.

These measurements will be used in this Industrial Ph.D. project, and further measurements are planned after completion of other offshore wind farms. These measurements are important because it makes possible to validate the capabilities of the simulation tools for transient and temporary overvoltage simulations against actual measurements. Moreover, the measurements will be used for validation and improvement of components models. Based on existing component models and the available information about the wind farm electrical components, more detailed models of cables, transformers, switchgears and protective equipment will be developed and implemented in short circuit studies, insulation coordination studies, islanding operation studies and

protective relaying studies.

Most of the research of this Ph.D. project will be based on simulation tools and high frequency measurements in offshore wind farms, where the capabilities of the simulation tools will be tested and analyzed in order to find the optimum solution to protect the wind power plant. The main premise here is to regard the protection system design used today, as insufficient for accurate overvoltage estimation, based on ambiguous simulation tools and models. The new protection schemes will be implemented digitally based on the validated models, operational experience, technical capabilities of the real system, available protection equipment, and if necessary additional components. Finally, recommendation will be created regarding the simulation tool's capabilities and the actual overvoltages in the system

Harmonics in Large Offshore Wind Farms

Nowadays, variable-speed WTs are grid friendly machines in most power quality respects. The power electronic devices with advanced semiconductor technology and advanced control methods that are used in WTs for transferring power from the generator to the grid can meet with the most demanding grid requirements seen today. However there are issues with regards to the power quality, voltage stability, transmission losses, and reliability that need to be addressed and improved in order to exploit the potential and advantages that large offshore wind farms (OWFs) have as important elements in the efforts to reach renewable energy targets while maintaining a stable and robust power system.

Harmonics generated by the grid side power converters may be of concern in networks where harmonic resonance conditions may exist in large OWFs with a widespread submarine MV cable network connected to the transmission system by long HV cables.

Submarine power cables, unlike underground land cables, need to be heavily armoured and are consequently complicated structures, having many concentric layers of different materials. Inductive coupling across the material boundaries contribute to the overall cable impedance, and these complex relationships consequently affect the level of voltage and current waveform distortion and amplification due to possible resonances, as the electrical characteristic of cables in the frequency domain is dependent on their geometrical arrangement and material layer structures [32]. In particular power cables have a relatively larger shunt capacitance compared to overhead lines which make them able to participate more in resonant scenarios. Consequently, it becomes necessary to study the different categories of resonance problems in more detail; in particular for OWFs connected to the transmission system with large MV submarine cable systems and long HV cables [33]. An electrical transmission system can magnify harmonic voltages or harmonic currents that happen to be at, or near to, a resonance frequency [31].

This issue becomes quite complicated and makes accurate harmonic analysis of OWFs much more complex, involving advanced models for all system components, including the external HV network with consumer loads connected which present the greatest uncertainties.

In the case of small onshore dispersed wind farms (WFs) connected to the distribution network, performing sophisticated harmonic load flow studies is not a usual practice due to the large number of such installations. For large OWFs where the total capacity is in the range of hundreds of MW, harmonic load flow analysis becomes an important issue.

WT performance is a critical issue in light of increasingly stringent grid connection requirements. These days, modern wind farms provide a sophisticated set of grid code friendly features. This is achieved by using sophisticated WF control systems for integrating external control signals, measurements, the control systems of the individual wind turbines, and centralised units such as park transformers, SVCs etc.

The full-scale converter WTs concept is an important technical advantage to reduce constraints as far as the fulfilment of grid codes requirements is concerned. Technology provided by most of WT manufacturers can support the grid through reactive power supply, and it can be operated similar to a conventional power plant. Additionally, with the reactive power feature, the WTs in the MW power capacity range can generate reactive power even when the wind is not blowing, which can be exploited for providing reactive power to the system and for fast response voltage stabilization, which otherwise would have to be provided by other units in the system.

Stochastic aspects of WT harmonic emission have to be applied for WFs with power converters, and it is known that probabilistic techniques are helpful for evaluating the harmonic emission of a wind farm [28, 29]. This is also aligned with the statistical approach adopted in the IEC 61000 series of electromagnetic compatibility (EMC) standards, where harmonic emission assessment refers to 95% non-exceeding probability values on the whole measurement period.

The total harmonic emissions of a WF depend on the statistical characteristics of the individual WT harmonic current or voltage vectors. The probability distribution functions of their magnitudes and phase angles may prove very helpful in detailed harmonic studies.

The number of WTs with full-scale converters used in large OWFs is rapidly increasing. More and more WT manufacturers such as General Electric (GE), Siemens, Vestas, and Gamesa use back-to-back converters in their flagship products. As mention before, at present, these WTs are mainly connected through a widespread MV cable network with practically no consumption and connected to the transmission system by long HV cables. This represents new challenges to the industry in relation to understanding the nature,

propagation, and effects of harmonics.

Today's WTs with a power greater than 2MW [20] are mainly variable speed turbines. For offshore applications, where low maintenance requirements are essential, a WT with a permanent magnet excited generator is widely considered to be the promising solution, in which case a full-scale back-to-back converter has to be applied. The conversion efficiency of this system is very competitive, especially in partial load operation.

Compared to a conventional system with a doubly-fed induction generator, the efficiency in the partial load range is remarkably higher, resulting in increased revenues for wind power producers. This and many other advantages contribute full scale power converters in WTs to have a bright future. For example, an extremely important issue is that during extreme grid faults, the full-rating power converter can provide 100% reactive current [21] to support the grid which is required by many European grid codes today.

While WTs up to 5MW are already produced in series, WTs with higher power levels are either under development or at the prototype stage. Most of the next generation WTs are expected to be applied in large WFs situated either offshore or in regions with low population density. Higher power WTs in the range higher than 5MW are expected in the future. The OWFs are seen as power generation plants. In case of a grid frequency drop for example, the WTs have to maintain the power level to support the grid. Another important demand is that the WT must stay in operation in case of reclosing operations which are carried out in the event of short circuit problems in the grid.

Inside large OWFs, the future turbines face new control requirements, as grid code requirements might be stricter, and as advanced control in power converters allows for the implementation of advanced functions to improve OWFs performance as large generators connected to the grid. For instance, harmonic damping might be required by grid codes in order to improve the power quality.

The output of the converter is connected through a grid filter to a step-up transformer which adjusts to the higher voltage of the collection cable system. An important challenge in the converter and filter design is to meet the harmonic emission requirements according to IEC and IEEE standards [22, 23].

In order to meet these requirements with the chosen converter topology and an optimally sized filter, the approach of optimised pulse patterns is used. This technique enables the converter to eliminate low and high order harmonics. Sometimes, to improve the grid converter harmonic emission spectrum, the passive grid filter is involved to eliminate the remaining higher order harmonics. Therefore, the wind power converter is operated with an optimised pulse pattern on the grid side. Different modulations used by manufacturers imply different harmonic spectra of the power converters.

Modelling strategies for harmonic sources and network components for various widely used approaches to power system harmonic analysis are sometimes insufficient. It has been observed that different modelling techniques give different results. That is why measurement data processing and model validation play a crucial role. Simulation techniques in the frequency, time, and harmonic domains and modelling of the WTs as harmonic sources sometimes should be extended and accuracy for different cases assessed. Various phenomena related to harmonics need to be investigated, explained, and compared with measurements. It is necessary to find methods to achieve better agreement between theory and experimental/practical results.

It has been observed that resonances may be excited by a relatively small distortion source in the system or by an unbalance situation which has influence on the converter components or applied control strategy. The resulting amplification of the small source by the resonant characteristics of the system can compromise the normal operation or even lead to instability. This phenomenon might appear in case of large OWFs where resonance peaks may appear in a frequency range of up to 2000 Hz. This is investigated by use of a wind farm equivalent model in frequency domain with a power converter as a main harmonic source frequency response simulation.

The objectives of the PhD project are to provide in-depth knowledge of all relevant aspects related to harmonics in offshore wind farms including:

- The voltage source converter as a harmonic source
- Modelling and analysis of WTs and wind farm network elements in relation to harmonics (i.e., the frequency range from DC to 5kHz) in time and frequency domain
- Modelling of WT converters and other wind turbine components in time and frequency domain
- Interaction of offshore wind farms with AC transmission system (other harmonic sources, controllers, etc)
- Dynamic phenomena, ferroresonance, harmonic instability, period doublings, etc
- Operation of VSC with harmonic resonances near its characteristic frequency
- Engineering standards and power quality standards.

The rapidly growing wind power market shows development and application of new technologies of WTs, and for sure, full-scale converter have the green light in WT application. But even in this narrow part of the power electronic industry, every manufacturer introduces different topologies and control scenarios, which show different behaviour and therefore needs to be addressed individually.

As an example the Gamesa G10X WT can be mentioned where parallel connected voltage source converters (VSC) with advanced control are used. The control improves the harmonic spectrum of the converter close to switching frequencies. This change influences the power converter harmonic emission and changes the system impedance because no additional passive filters are needed [34]. This redundancy

also increases the total DC link capacitance level and resonance peaks in the impedance sweep.

On the other hand, in the Enercon E112, the redundancy in power electronic devices exists for grid converters [35]. Therefore, the DC link capacitance will inevitably be lower in comparison to the Gamesa model. Of course the list of differences of WTs and other components in WFs, that influence the harmonic analysis, is much longer.

It is concluded that every WF system configuration should be investigated in cooperation with manufacturers which increases modelling complexity and difficulties. This problem is not only with reference to harmonic analysis, it exists in all branches of modelling. It shows the necessity to extend the requirements for data provided by manufacturers and to describe modelling methods better in standards.

Electrical Main Components in Wind Turbines

This Ph.D. project forms the main part of a PSO project "Electrical Main Components in Wind Turbines – Environment, Compatibility and Specifications". The main focus in the Ph.D. project is on electrical compatibility between the main electrical components of WTs defined as the generator, converters, filters, transformer, cables and breakers and their compatibility with the surrounding environment.

Through simulations of the WT systems, the project will analyse the interaction between the main WTs components, their specific characteristics and the interaction with the electrical grid. Methods and tools for the assessment of the electrical conditions surrounding the components and the influence of the components will be provided in order to formulate guidelines that ensure compatibility.

'Environment' is the subtitle of a task in the PSO project which covers mainly the electrical exposure of the components from the varying load and operational conditions. In cooperation with other research institutes, manufacturers and utilities, this part aims at classification of the component environment, as known from other specific applications than WTs.

Here, focus is especially on load mapping based on analysis of wind conditions at selected sites and by monitoring data analysis mainly with respect to load amplitude, duration, frequency and slope. These data are supplemented by investigations of other exposures to the main components, like overvoltages and climatic and mechanical conditions. In order to be valid as broad as possible, this work should be based on the most common WT constructions and the classification should be as independent of specific component types as possible.

'Compatibility' is the core of the Ph.D. project and covers development of tools for investigation of the internal WT components interaction and their compatibility with the surrounding grid. Such investigations require thorough knowledge of

- the component's broad band characteristics,
- the WT electric circuit,
- the surrounding grid,
- operational aspects.

Since the aim is a systematic approach to reveal critical component combinations, it is important to simplify component models by characterization through a number of parameters. This number has to be sufficient to cover the typical properties, like pronounced resonance frequencies. The simplified component models then are included in typical WT electrical circuit models. Numerical simulations show the electrical behaviour under systematic parameter variations, by means of which critical combinations can be uncovered. The exposure of the components from both wind and grid side is a necessary part of the simulations, which means that, in order to describe these two interfaces, the simplified approach should be used as well. For the same reason operational aspects like switching operations have to be included.

It is obvious that in this kind of investigations, the number of parameters to be varied should be limited, in order to ensure realistic simulation times. On the other hand, it is important to include all necessary parameters and for that reason the last part of this project deals with the component specifications.

The projects third subtitle, 'specifications', means mapping of necessary and sufficient component specifications. Here 'necessary' is in the sense of specifications that enable us to establish broad band simulation models, which can reveal critical combinations under all operational conditions. 'Sufficient' is in the sense of limiting the number of details in the specifications to realistic values. As an example can be mentioned that broad band transformer models [10], even up to the MHz range, now are considered as necessary. But how many details are sufficient in the frequency spectrum to show critical behaviour in the actual configuration?

It should be clear that the three subtopics in the 'Electrical Main Components in Wind Turbines' project are closely linked to each other and cooperation between research institutes, manufacturers and utilities is necessary. The research results will apply to design of WTs and wind farms by providing the basis for common guidelines for electrical component procurement, wind farm planning and design, and risk analysis of selected electrical systems.

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