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Elektriske hovedkomponenter i vindmøller – påvirkninger, kompatibilitet og specifikationer

PSO Project 010087 "EMC Wind"

Final Report

December 2013

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Index - Final Report

1. Project details

Project title	Elektriske hovedkomponenter i vindmøller – påvirkninger, kompatibilitet og specifikationer
Project identification	PSO F&U project 010087
Name of the programme which has funded the project (ForskVE, ForskNG or ForskEL)	ForskEL
Name and address of the enterprises/institution responsible for the project	CEE, DTU Electrical Engineering Elektrovej 325 DK-2800 Kgs. Lyngby
CVR (central business register)	DK30060946
Date for submission	30. December 2013 - Summary report was submitted 16. September 2013, the content of which is updated and included in this final report. - Final account submitted 27. november

2. Executive summary

PSO project 010087 on Electric Main Components in Wind Turbines – Exposure - Compatibility – Specifications was conducted in the period of 2008-04-01 to 2013-04-14 as cooperation between universities – power utilities and several industrial parts in Denmark.

The 3 main topics of the EMC Wind project were: Wind turbine environment – Compatibility – Component specifications. The technical tasks to be fulfilled under each issue where treated and solved by different participants (see also: organization) and covered the following challenges:

2.1 Topic 1: Wind turbine environment

This first task involving all participants was finalized by means of the Technical Report "Wind Turbine Electrical Equipment, Electrical and Non-electrical Environment" published the 16. November 2011. Contributions were given by 6 authors including an iterative feedback process with the whole project group. A comprehensive overview was given on relevant knowledge, relations, standards and regulations within the area of the wind-turbine environment and suggestions were made on new environmental ‘classes’, which better could reflect the special environment wind turbine components are exposed to, as compared to standard electrical applications.

The outcome of this work was presented at several arrangements in Denmark (like by the Danish Wind Association) and was forwarded to working group 06 under Dansk Standard S588 (Wind Turbines) and to IEC TC88 (Wind turbines) as background material for further work.

2.2 Topic 2: Compatibility

This task was solved mainly by means of the Ph.D. project 'Compatibility of electrical main components in wind turbines'. The project with ph.d.-student Andrzej Holdyk has been finalized, the thesis was handed in December 2013 and was carried out very satisfactorily. Since compatibility means that the affecting part and the exposed part can interact with each other without problems, the title of the ph.d.-thesis will be the more correct 'Interactions of electrical main components in wind farms', which means the scope includes wind farms as well and not just wind turbines. The title also expresses 2 important aspects a) what is the exposure, in this case overvoltage/resonance, of the component and b) is this exposure critical? The latter question usually cannot be answered directly, since it depends on the actual situation. But the project delivers methods on how to, systematically, investigate different constellations, in order to reveal the one, which gives the highest exposure as a necessary measure to decide about compatibility. This includes not only different components (see task 'component specifications'), but also wind farm layout plus the real conditions. The latter is an important aspect, since critical resonances can be found in most networks, but the most likely exposures needs to be included as well in order to identify only critical situations, which actually might occur. Methods were developed and applied to quantify this risk.

2.3 Topic 3: Component specifications

This last task turned out to be essential for the outcome of the compatibility investigations. Necessary and sufficient component equivalents had to be found, especially for cables and transformers. Considerable efforts were done to measure the components characteristics in a frequency range from 50 Hz to almost 5 MHz. Here, sparring with a ph.d.-project on transients in wind farms was very fruitful. Since compatibility had to be investigated in both time and frequency domain, it was chosen to model the components in frequency and then apply methods for implementation of these models in time domain programs. In that way, frequency response analyses (FRA) were proved as being sufficient for the following compatibility considerations. Cooperation with experts at Sintef, Norway contributed to make this part work. Focus was on transformers and cables, but the importance of suitable breaker models became clear as well, in particular regarding very fast transients to be looked at in the future. Other components included where capacity banks and suitable equivalents for the adjacent grid. In the turbine end, investigations were made on how to include generator/converter and it was chosen not to investigate different types, since the method itself on interaction needed highest priority. Additional component models like advanced converter equivalents always can be included, if needed for the electrical conditions inside the turbine.

2.4 Organisation:

Under the first task on wind turbine environment, the project group consisted of the following participants:

> DTU Elektro - Risø DTU - DONG Energy – Delta – ABB – Vattenfall – Siemens Wind – Codan – Siemens - AAU

With the following participants:

Matthew Henriksen (DTU Elektro)
Joachim Holbøll (DTU Elektro)
Rasmus Schmidt Olsen (DTU Elektro)
Braulio Barahona (Risø DTU, changed to DTU Wind Energy)
Ivan Arana (DONG Energy)
Poul E. Sørensen (Risø DTU, changed to DTU Wind Energy)
Andrzej Holdyk (DTU for Sofie Leweson)
Arne Hejde Nielsen (DTU)
Asger Jensen (DONG Energy)
Claus Schleiter (Delta)
Erik Koldby (ABB)
Jan Jørgensen (Vattenfall)
Kenneth Pedersen (Siemens)
Truels Kjer (Codan)
Peter Weinreich-Jensen (Siemens)
Zhe Chen (Aalborg)
Nicolaos Antonio Cutululis (Risø DTU, changed to DTU Wind Energy)

The environmental part being finalized in 2011 meant that a number of participants would not contribute anymore and in task 2 (compatibility) and 3 (component specifications) the following members participated:

> DTU Elektro - Risø DTU - DONG Energy –ABB – Siemens Wind – Siemens - AAU

Since these tasks where mainly carried out by means of the ph.d.-project a supervisor group was formed with the following key persons:

Joachim Holbøll (DTU Elektro, main supervisor)
Asger Jensen (DONG Energy)
Erik Koldby (ABB)

A large number of student projects and some ph.d.-projects were related to EMC wind and contributed indirectly (see references).

Contract period originally was 2008-04 to 2011-12. Due to the sudden leave of ph.d.-student Sofie Leweson in 2009 after one year, a new ph.d.-student had to be found and the 15-04-2010 Andrzej Holdyk started as new ph.d-student, the study to be ended 14-04-2013. Energinet.DK kindly accepted to extend the project period until this day.

Since the amount of simulation work was higher than expected, Andrzej Holdyk was employed at DTU Elektro for another 2½ months as research assistant in order to finalize the work, which he did. The 2½ months employment was covered by DTU.

2.5 Publications

All relevant technical findings were published at conferences, journals and in the technical report from 2011 and the ph.d.-thesis from 2013.

Due to the broad character of the project and the involvement of many external parts in particular in the first years, a portefolio of publications at different levels was generated directly under the project, while some other projects and publications more indirectly supported the work. Hereof can be mentioned:

a) One PhD project with Andrzej Holdyk was directly funded by the project, the thesis was handed in in december 2013. Another ph.d. with Ivan Arana Aristi on transient in offshore wind farms was finalized in 2011 resulting in a very extensive thesis.

b) More than 11 Conference were generated.

c) 1 journal paper is published, 2 are under preparation

d) Several student projects at master and bachelor level leading to reports supporting the final project results (see references).

It also should be mentioned that Andrzej Holdyk was active member of the Cigré group JWG A2/C4.39 'Electrical Transient Interaction between Transformers and the Power System.' A technical report is about to be published from this group in 2014.

3. Project results

The project resulted in a large number of finding which for easiest readability here are arranged according to the 3 main topics of the project.

The following text and the figures are mainly based on the publications documented under references and certain overlap with the wording especially in the latest publications cannot be avoided.

3.1 Topic 1: Wind turbine environment

The work resulted in a 104 pages technical report and 2 papers, giving an overview of relevant knowledge, relations, standards and regulations within the area of the wind-turbine environment plus results from new load models suitable for visualization and analysis of the wind turbine specific load profiles. Several suggestions are made both regarding new environmental 'classes', and with respect to the voltage and current related electrical environment.

3.1.1 Non-electrical environment

The environmental conditions were investigated for the main electrical components in wind turbines: generators, power converters, power transformers, and switchgear. The focus has been placed on the standardized environmental requirements of such components.

It has been demonstrated that there is currently a lack of application standards for wind turbine electrical equipment. The existing wind turbine IEC standards do give a detailed description of the operational environment, however this is aimed at describing the external environment. These descriptions imply a very wide range of environment conditions, which in several cases exceed the requirements of the relevant product standards. Nevertheless, there is currently no standardized requirement for a controlled internal environment for wind turbines.

The lack of standardization for wind turbine electrical components is even more pronounced upon comparison with the rail industry, which is a similarly unique application. IEC Technical Committee 9 has created several standards which apply specifically to electrical main components aboard rolling stock, including one set of standards which is dedicated to the operational environment. An additional standard called EN50125 de-scribes the rolling stock operational environment through environmental severity classes, and also by directly mentioning several unique conditions which have the potential to be problematic if they are not considered. A similar document for the wind turbine environment would be very useful in raising awareness regarding specific, possibly harmful situations.

While climatic parameters such as temperature and humidity are probably the most commonly considered environmental factors, it’s true that the comprehensive environment concerns a great deal more. Aspects such as chemical content of the atmosphere, vibrations, and the presence of dust or sand are also very important. Furthermore these factors occur in different severities and combinations based on the geographic location. If not properly dealt with, the operational environment can shorten the lifetime of an electrical component, or even lead to catastrophic component failure.

Many of these factors are at least mentioned in the documents IEC 61400-1 and 61400-3, but currently there is no clear description of the severity levels. The present report has explored the usage of the IEC 60721 series of documents, which present a powerful method of giving a complete environmental description. With these documents the operational environment can be tailored in order to quantify the difference between operating in, for example The North Sea or rural Texas. Accordingly, the project participants have put together a set of suggested environmental descriptions as shown in Table 1.

Description	**Class combination (Nacelle)**	**Class combination (Tower)**
Onshore, rural	3K6/3Z2/3B1/ 3C1/3S1/3M3	3K6/3Z2/3B1/ 3C1/3S1/3M2
Onshore, desert	3K6/3Z2/3B1/ 3C1/3S3/3M3	3K6/3Z2/3B1/ 3C1/3S3/3M2
Onshore, mountain	3K7/3Z2/3Z12/3B1/ 3C1/3S1/3M3	3K7/3Z2/3Z12/3B1/ 3C1/3S1/3M2
Offshore	3K6/3Z2/3Z7/3B1/	3K6/3Z2/3Z7/3B1/

	3C2/3S1/3M3	3C2/3S1/3M2
Offshore, floating Foundation	3K6/3Z2/3Z7/3B1/ 3C2/3S1/3M5	3K6/3Z2/3Z7/3B1/ 3C2/3S1/3M4
Offshore, cold climate	3K7/3Z2/3Z7/3B1/ 3C2/3S1/3M3	3K7/3Z2/3Z7/3B1/ 3C2/3S1/3M2
Controlled internal climate	3K2/3Z2/3B1/ 3C1/3M3	3K2/3Z2/3B1/ 3C1/3M2

Table 1: Suggestions for wind turbine environmental class combinations made by the authors of this report, making use of IEC 60721-3-3

The letters mentioned here cover different kinds of mechanic, climatic, chemical and thermal environment with different severities as indicated by the number after the letter. This suggestion can of course be modified/extended to other types of environments, in case extreme harsh conditions can be expected to occur.

3.1.2 Electrical environment

In addition to this non electrical exposure of wind turbines and wind turbine components, the electrical environment also needs to be considered. Power fluctuations, current harmonics, and transient overvoltages are noted to be of significance, and IEC standards have been examined to see how they have been dealt with to date and own investigations and suggestions for characterizing the environment were made.

In saying that the electrical environment is unique in the wind turbine environment, several aspects are being considered:

- Power fluctuations
- Harmonic currents
- Overvoltages

Starting with power fluctuations, in a large number of earlier investigations power analyses on WT under different conditions have been reported. In the present work it was found that there are currently no loading classes that directly describe the loading conditions of wind turbines, but there are some flexible classes reported in IEC 60034-1 and 60146-1-1 which could potentially be tailored to suit equipment intended for use with the loading conditions typical of wind turbine equipment. It was also found that the load variations typically are rapid and sometimes of high magnitude.

The following definition is made on how to describe these variations as shown in fig. 1.

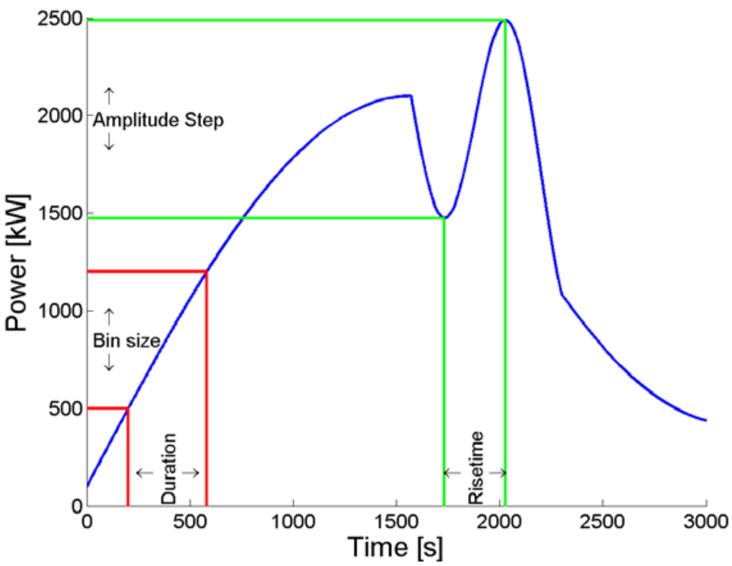
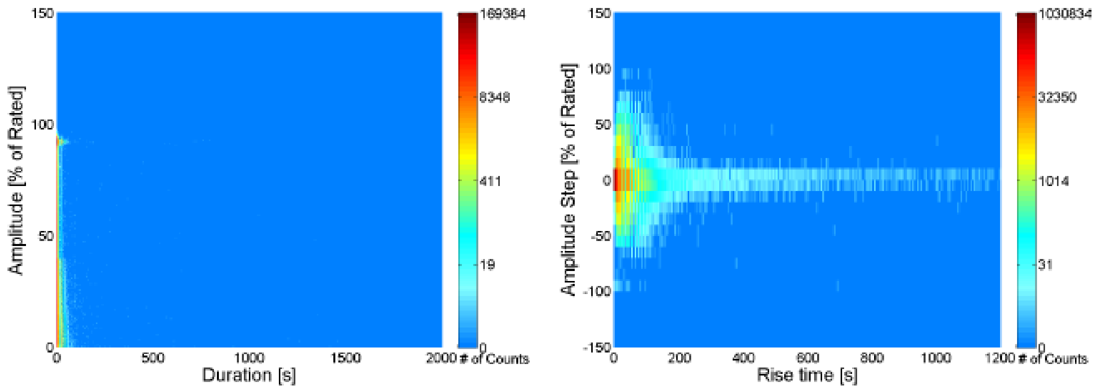


Fig. 1: Graphical interpretation of definitions used in describing parameters for load characterization.

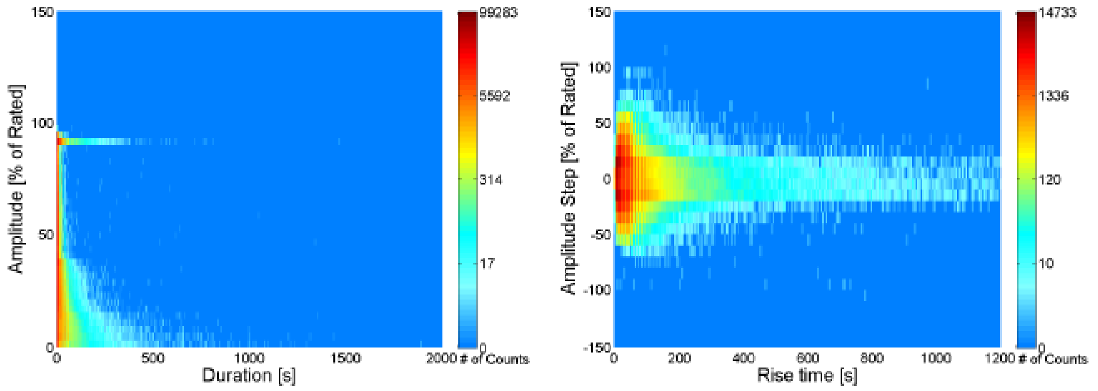
Based on these definitions the following way to characterize loads and variations are made. Figure 2 shows an example from onshore wind turbines, the Overgaard 2 wind farm. It is very clear that the suggested visualization of the load profile allows for easy characterization regarding in particular the fluctuating character and the fast slopes of the variations, which are to form a heavy exposure of components with accelerated aging as a consequence.

This gives a background for both utilities, wind turbine owners and manufacturers to describe the expected load variations and the requirements to the wind turbine specifications and it's components.



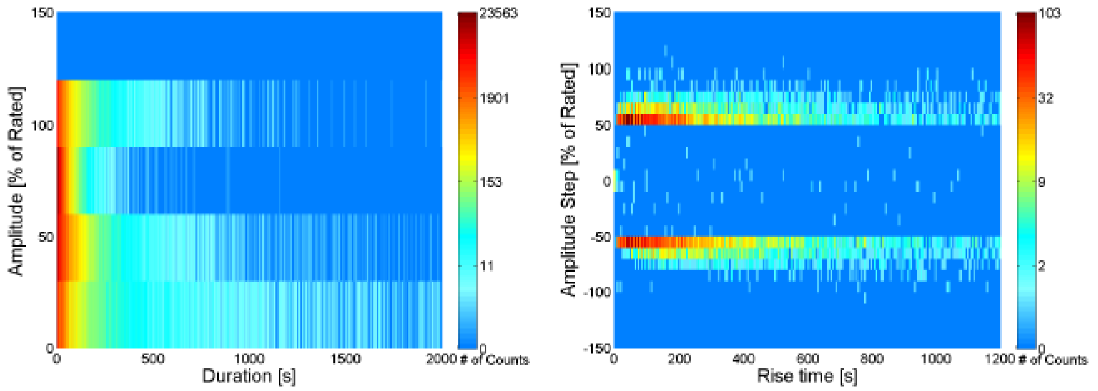
a. Bin size 0.5%.

b. Threshold value 0.5%.



c. Bin size 3%.

d. Threshold value 5%.



e. Bin size 30%.

f. Threshold value 50%.

Fig. 2: Load conditions of the transformer of wind turbine 033 at Overgaard 2 wind farm. Left column of figures contains the static analysis and the right column contains the transient analysis.

It was our intention to compare this typical behaviour with similar load patterns from normally’ loaded transformers in the distribution grid. Unfortunately, none of the project participants was able to find measurements from 10/0.4 transformers with a sufficient time resolution. In most cases distribution transformer load monitoring is done with 10 min. intervals, which is not sufficient for comparison with the fast varying load of wind turbine transformers.

Regarding harmonics, several examples of current harmonics from wind turbines have been provided in this work. The IEC draft 60076-16 does well to mention that harmonic currents should be considered, and also the method of derating a transformer for non-sinusoidal currents is provided.

While a major concern of the wind farm is maintaining an acceptable harmonic level at the point of common coupling, harmonics also have implications for the equipment in each individual wind turbine. Harmonic currents typically in a frequency range up to few kHz, create excess losses, consuming a share of the thermal capacity of the cables and other components.

As an example, here are shown results for the Horns Rev offshore wind farm with Vestas V80 wind turbines, which are rated for 2MW. The generators for these wind turbines are doubly-fed induction. This topology uses a partial power converter which feeds the rotor with variable frequency currents in order to allow a range of variable rotor speed, while keeping the stator synchronized with the grid. Figure 3 shows the results from 321 hours of measurements (10 minute average values, at the high side of the wind turbine transformer).

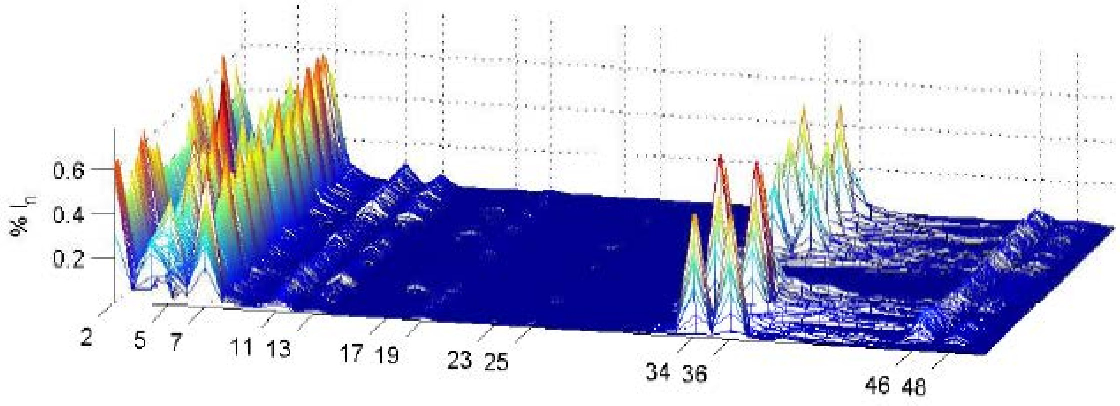


Fig. 3: Harmonic current measurements from Horns Rev offshore wind farm.

Overvoltages, as the last type of electrical exposure are treated extensively in the next chapter, covering the aspect of compatibility.

3.2 Topic 2: Compatibility

The need for knowledge about compatibility between components in a power system is directly related to the complexity of the system. This is need is reflected in the creation of several international research groups investigating the topic. Focus has often been put on electromagnetic transients, harmonics and interaction between components and the power system and especially on the interaction and resonance between the transformer,-cables and the circuit breaker. These phenomena are also important in offshore wind farms, where the specific and often complex structure of the collection grid can cause resonances between cables and transformers, which might lead to potentially harmful over voltages / currents. The question of compatibility includes a comparison between these over voltages and currents and the levels acceptable for each component. In the project it was not possible to define acceptance levels for the very specific transient voltages and currents that occur. But tools were developed to systematically investigate and quantify the voltages and currents, that might occur in real situations. Thereafter, compatibility can easily be decided upon when knowing the critical levels as provided by the manufacturers. Similarily, the results can be used for necessary criteria when ordering components.

This task about compatibility was solved mainly by means of the Ph.D. project ‘Compatibility of electrical main components in wind turbines’. The project with ph.d.-student Andrzej Holdyk has been finalized, the thesis was handed in December 2013, 3 months after the date the steering group agreed upon, but the quality of the work carried out and of the thesis is very satisfactory. As pointed out before, since compatibility means that the affecting part and the exposed part can interact with each other without problems, the title of the ph.d.-thesis is the more correct ‘Interactions of electrical main components in wind farms’, which means the scope includes wind farms as well and not just wind turbines. In accordance to the previous discussion about compatibility, the title also expresses focus on what is the exposure, in this case overvoltage/resonance, as necessary for determination on compatibility.

3.2.1 The approach

It is important to distinguish between investigations on specific situations, like a specific wind turbine or park design and more systematic analyses covering different situations, in order to reveal critical constellations. In the PSO funded project, the following aspects were covered:

The models:

1. Specific WT and component models (see under component specifications)
2. Specific Wind farm layouts
3. Variable layouts with parametric variations

The tools:

A. Time domain modelling, mainly in ATP and PSCAD in some student projects, giving the voltages and currents to occur in different situations

B. Frequency analysis of both components and wind farms, giving admittances matrices, and/or voltage ratios, followed by comparison with the resulting voltage spectra hereby identifying critical resonances.

3.2.2 Resonance

Applying tool A, time domain simulations reveal possible over voltages directly. But critical situations often occur when resonances in the system containing components with inductances and capacitances are excited, e.g. by applying a step signal, or a transient in general. Then the system will oscillate with a certain frequency, known as natural frequency. If a signal is supplied to the system and a frequency contained in this signal is corresponding to the natural frequency of the system, then a resonance condition occurs. During resonance, a high amplification of voltages or currents in the grid can occur due to energy exchange between electric and magnetic fields in the system.

In principle, for resonance, two or more natural frequencies need to be present. This means that a network must contain at least two adjacent parts having similar resonance frequency. The two network parts must have large differences in characteristic impedance, i.e. characteristic impedance of one network has to be much larger than characteristic impedance of the other one. These conditions are valid in case of cable-transformer interaction, when the transient originates from waveform reflections in the cable, generating oscillations, the frequency of which corresponds to one of resonance frequencies of a transformer (see also under ‘component specifications’). These conditions should be investigated during the design stage of large offshore wind farms as modern, large offshore wind farms contain a large amount of wind turbines connected by submarine cables. The total length of collection grid cables can exceed 200 km and due to space requirements and seabed conditions, the collection grids can form complicated topologies.

We will now focus on variation of different parameters, so-called parametric variations, in a wind farm in order to demonstrate the applicability of the developed tool.

3.2.3 A wind farm

The chosen wind farm layout includes both simple radials and branched structures, the latter generating additional points of discontinuity, resulting in additional resonance frequencies.

The interaction between the cable system in an offshore wind farm (OWF), the so-called collection grid and the transformers is shown in an example of a simple OWF containing four turbines in a single radial, as shown in the figure 4. The system voltage of the collection grid is 10kV, though for better understanding, the following considerations are based on pu values.

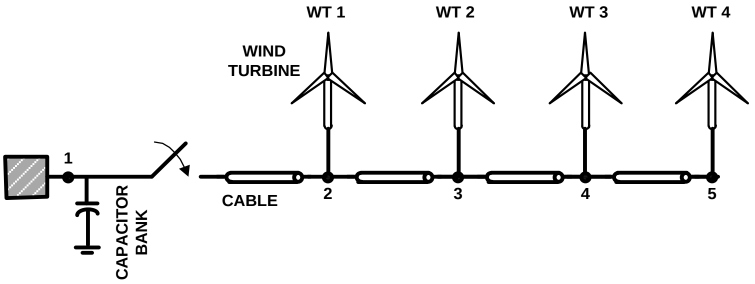


Fig. 4: Simplified diagram of a fictitious, small offshore wind farm.

The fictitious wind farm comprises a capacitor bank modelled as a lumped capacitance, an R/L ratio modelling the impedance of the external grid and a transformer, four sections of a 50 mm2 submarine cable and four wind turbines represented by a wide band transformer model based on admittance matrix measurements. Each of the four cable sections is 400 m long and the LV terminals of the transformers in the turbines are left open.

After closing the breaker, a voltage wave starts to propagate into the radial. The characteristic impedance of a transformer is much larger than the characteristic impedance of a cable, therefore, the waveform is hardly reflected from the turbines but propagates to the last turbine in a radial. It is assumed that the T-connection between cables and WT-transformers takes place right at the transformer and not through a longer cable inside the turbine as the drawing might indicate. Also at the last turbine (node 5), the WT transformer act as an open circuit, therefore the wave is reflected from the last turbine and doubles it’s amplitude. At the breaker end, the reflected waves meet the capacitor bank in parallel with the external grid connection, causing further reflection back into the system. This travelling wave phenomenon will result in voltage oscillations of a frequency related to the propagation speed of the cable and its length.

3.2.4 Variation 1: Influences of wind turbines

The first step is to investigate the influence of wind turbines being connected or not under energizing the radial. In figure 5 are shown the oscillating voltages in the 3 phases at the last turbine (node 5).

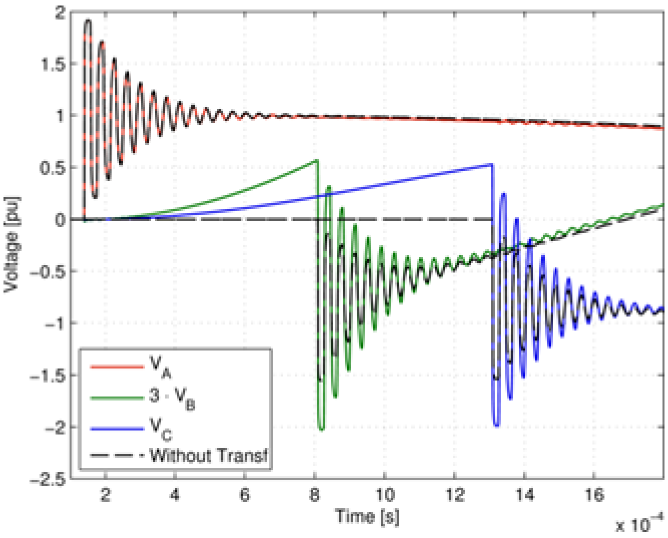


Fig. 5: Voltages at phase A, B and C at terminals of the last wind turbine in a radial (see Figure 4) during energization. Black traces show the case where no transformers are present in the radial – only cable is energized.

The black traces in figure 5 show a case when only cable is energized, namely there are no turbines in a radial, and the voltages are measured at the end of the cable. Comparison between voltages during energization of a radial with- and without the transformers (or wind turbines) show that transformers have insignificant influence on the frequency of oscillations due to travelling wave phenomenon in the radial.

If the frequency of voltage oscillations at MV side coincides with the resonance frequency of a wind turbine transformer, then the transformer resonance in voltage ratio will be excited (see also under ‘component specifications’). That might result in high amplification of the voltage at the LV side.

3.2.5 Variation 2: Cable length

The consequences of variation of the cable length are shown in figure 6. Here the length of the cable was chosen to be 62 m per section resulting in oscillations of approximately 178 kHz which corresponds roughly with one of the first resonance frequencies in the voltage ratio between MV and LV sides of the chosen transformers.

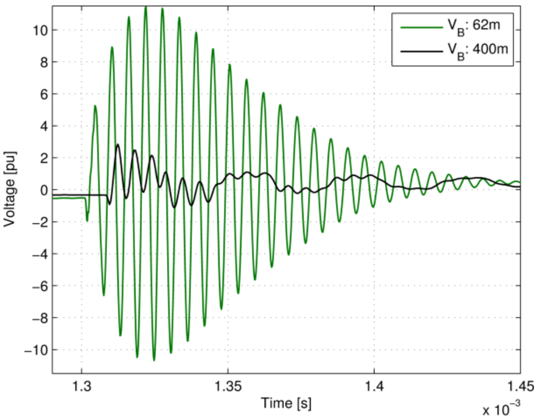


Fig. 6: Comparison of the voltage at the LV side of WT4 transformer for two lengths of collection grid cable section: 62m and 400m.

It can be seen that the highest magnitude of the resonant overvoltage is 11.44 p.u. of the LV side when the cable length is 62m and the LV side of the transformer is left open. It should also be mentioned that the transformer coupling of course has influence on such a result.

So far the considerations on compatibility/interaction were based on simulations of possible overvoltages in order to identify critical situations. These simulations are pretty time and computer capacity consuming. It was therefore obvious to investigate resonances in frequency domain and to apply tool B, Frequency analysis of wind farms, giving admittances matrices, and/or voltage ratios, followed by comparison with the resulting voltage spectra.

This type of investigations requires driving-point admittance sweeps and the waveform characteristics. Figure 7 shows a comparison of resonance frequencies in the driving-point admittance at wind turbine 4 and the power spectral density (PSD) of a surge waveform present during energization of the whole radial.

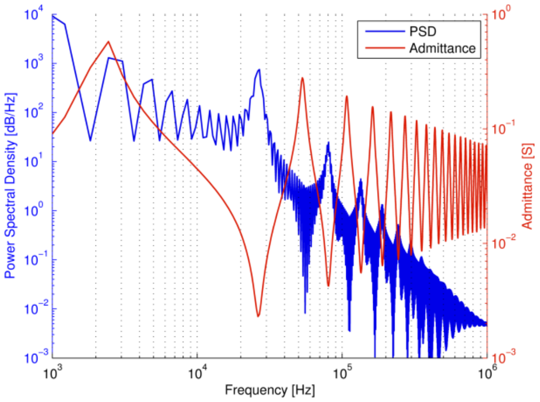


Fig. 7: Comparison of resonance frequencies in driving-point admittance at WT4 and the power spectral density (PSD) of a surge waveform present at the turbine during energization of the whole radial.

It is obvious that in this case, very clear influences of resonances in the cable system on the power content of the surge waveform are visible. This confirms that investigations of grid admittances is a suitable first step for critical peak identification.

3.2.6 Variation 3: Measuring point

Since the basic idea with the EMC wind project is to identify critical situations and the critical point in a wind farm initially is not known, in principle all measuring point needs to be looked at. Figure 8 therefore shows the PSD of surge voltage waveforms at all wind turbines during energization of the radial.

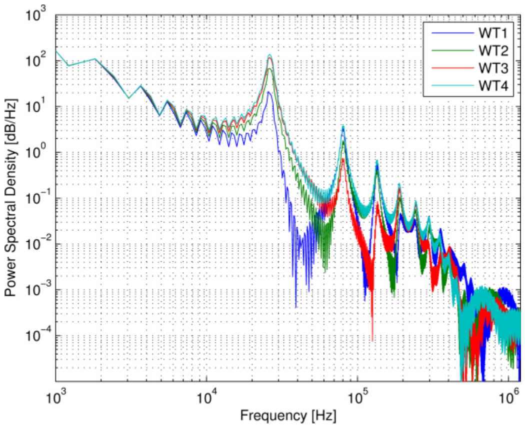


Fig. 8: PSD of surge voltage waveforms along of the radial.

Again, it is clearly seen that the voltage oscillations due to reflections in the cable system of the farm have significant impact on voltage waveforms present at the terminals of all wind turbines. In this simple example the frequency of voltage oscillations is the same at each of the turbine; however the magnitude is different, depending on the exact location of the turbine.

3.2.7 Variation 4: Topology

It is now shown, how the topology of the collection grid of offshore wind farms influences the occurrence of electrical resonances in medium- and high-frequency region.

Here is a situation where a cable in a string joins two or more other cables, as shown in figure 9, as occurs in large OWF, where, due to e.g. limited space, it is no longer possible to place all turbines in straight radials.

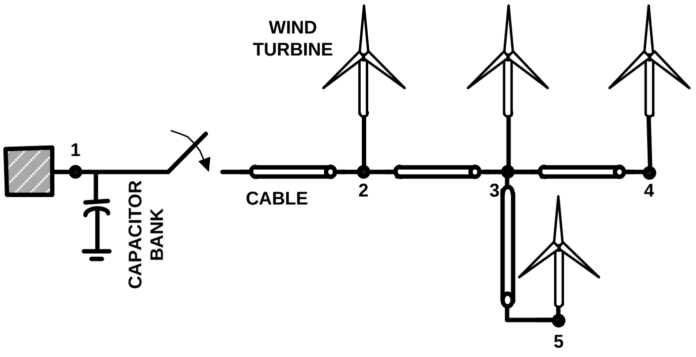


Fig. 9: Simplified diagram of a fictitious offshore wind farm with a string of turbines containing a branch, where two parallel cables of different length connect the last turbines.

In figure 10 is shown the influence of this more complex topology to the driving point admittance.

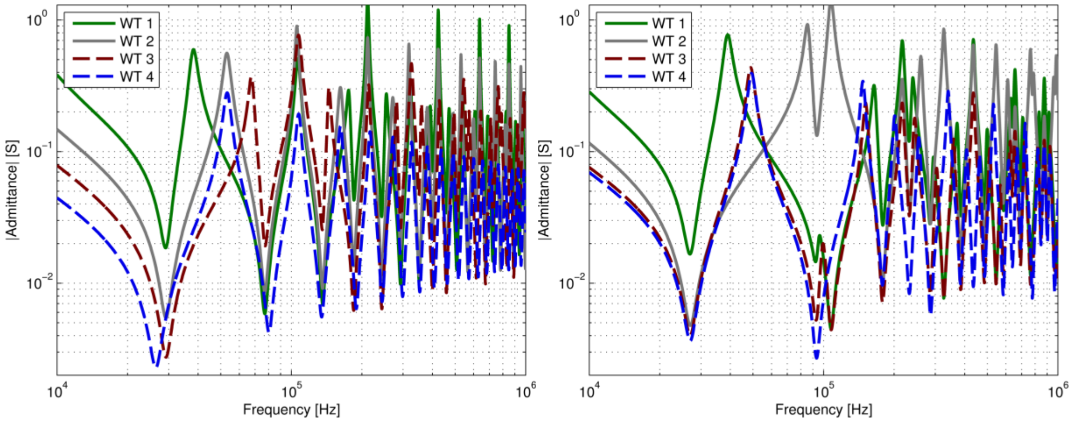


Fig 10: Driving-point admittance. Left: wind farm radial with varying cable cross sections.
Right: wind farm radial with branch

The influence of the branched situation is very clear, leading to more complex behaviour as compared to the more ‘cable-like’ behaviour without branches.

3.2.8 Variation 5: Continuous parametric variations

In the descriptions above, specific situations where investigated. In order to achieve the complete picture, parameters should be varied continuously an in the following is shown an example on how this can be done, here as varying cable lengths.

Figure 11 shows resonances and anti-resonance frequencies in a system with varying cable lengths. The frequencies are dependent on the length of a cable section and will decrease with the increase of the cable length.

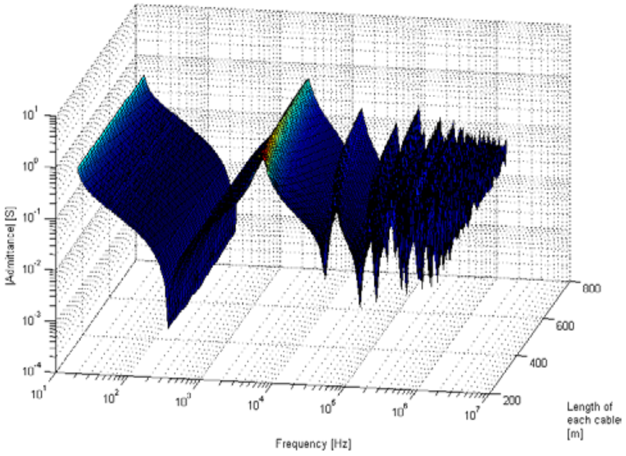


Fig. 11: Frequency sweep of driving point admittance at the first turbine (node 1) for different lengths of collection grid cable sections

It has to be emphasized that this kind of variations is very time consuming. In particular, when variation of other parameters is to be included, discrete variation should be considered instead.

3.2.9 *What has dominating influence?*

In order to give a general characterization of the frequency dependent admittances in the farm, an overview is given in figure 12, showing an example of how it is possible to characterize most admittance peaks in a wind farm and relate them to specific components, saying, which is the dominating component for this particular peak.

Peak	1p	2p	3p	4p	5p	6p	7p	8p
Frequency range (ELF-EHF)	ULF	ULF	ULF	VLF	VLF	VLF	VLF	LF
ƒ / kHz	0.33	0.715	2.75	6.8	13.12	16.98	24.66	56.23
Resonance / anti-resonance	anti	anti	anti	res	res	res	res	res
Dominant components	WT transformer and cables	grid impedance	substation components	cable lengths	cable lengths	cable lengths	cable lengths	cable lengths
Dependent on	Most components	C bank and X/R ratio	Meas. location	Meas. location	Meas. location	Meas. location	Meas. location	Meas. location
Description	First peak	Second peak	Third peak	WT1 peak	WT4 peak	WT5 peak	WT6 peak	WT7 peak

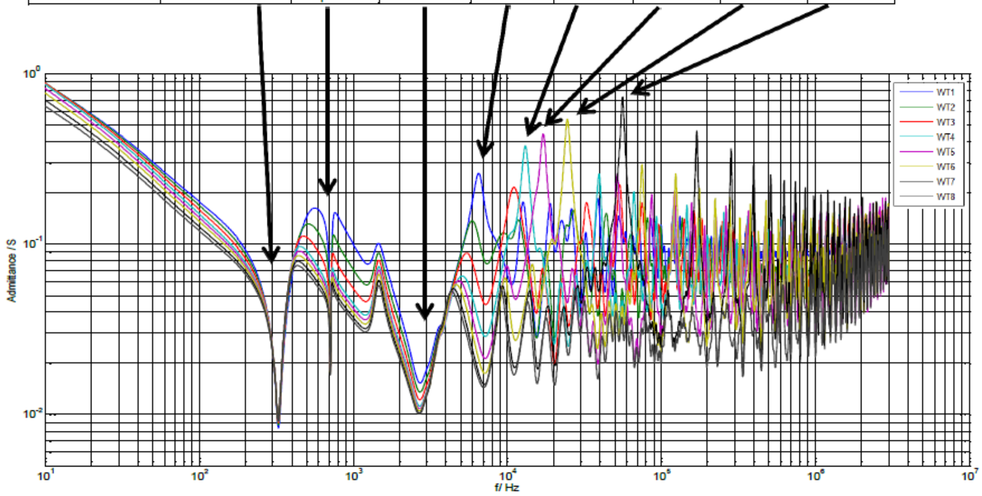


Fig.12: Admittance peaks from all wind turbines in a wind farm and characterization and component dependency.

This picture is showing a very strong tool to be used in the process of wind farm designing, when avoiding critical resonances and overvoltages is in focus.

3.3 Topic 3: Component specifications

For the compatibility investigations, it was necessary to identify component equivalents, especially for cables and transformers. Breakers as the transient generating component were investigated and mainly considered as being ideal, which means re-strike, pre-strike phenomena and chopping current was not included. Capacitor banks included in the model are considered as being purely capacitive in the frequency range of interest here. Another component included was a suitable equivalent for the adjacent grid. In the turbine end, investigations were made on how to include generator/converter and it was chosen not to investigate different types, since the method itself on interaction needed highest priority. Additional component models like advanced converter equivalents always can be included, if needed for the electrical conditions inside the turbine.

A proper representation of electrical components for simulation studies requires using models valid for the frequency range of interest, as wide frequency band models of electrical power components are still uncommon.

For cables and transformers, considerable efforts were done to measure the characteristics in a frequency range from 50 Hz to almost 5 MHz. It was chosen to model the components in frequency and then apply methods for implementation of these models in time domain programs. Frequency response analyses were applied and considerable efforts were put into improving the outcome.

3.3.1 Cables

Cables were modelled as a travelling wave type, taking into account the frequency dependency of all cables' parameters. As can be seen in fig. 13, the measured self-admittance of cable phases shows characteristic repetitive resonance frequencies in the higher frequency range.

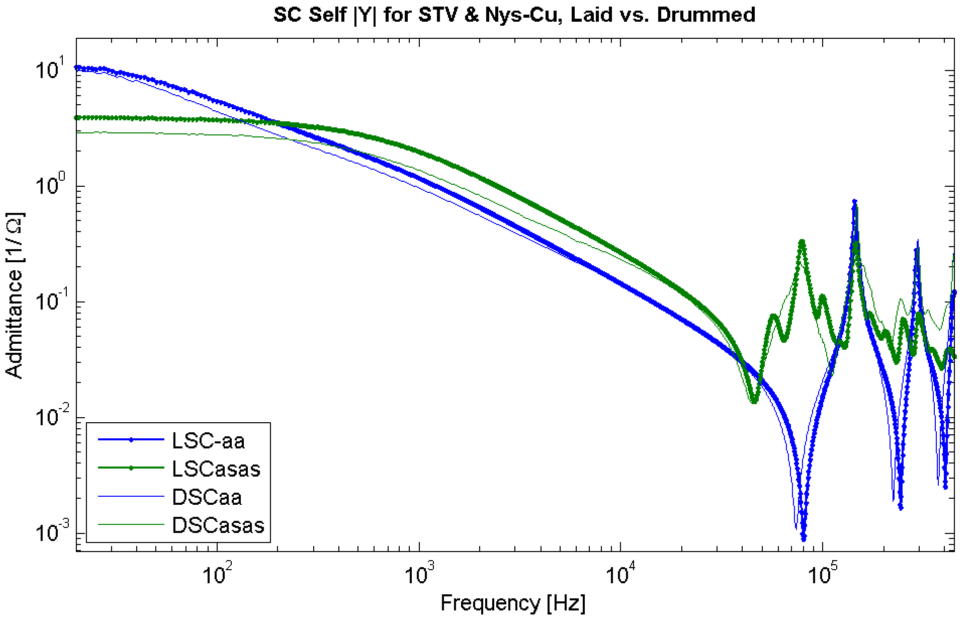


Fig. 13: Measured short circuit self-admittance for 2 copper conductor cables contain typical resonances. The blue line shows the self-admittance of with the characteristic repetitive resonance frequencies in the higher frequency range.

An interesting detail demonstrated in figure 13. is the difference between the frequency response of drummed and laid cables. This means that for cable modelling, the response preferably should be measured on laid cables, in order to get the most correct results.

Regarding modelling, either the measured frequency response can be converted to a suitable model, or the built-in models in the software, like ATP can be used. Electromagnetic transient (EMT) -type programs offer a variety of cable models that can be used depending on the exact type of studies one performs. As mentioned, in most of transient simulations, cables should be modelled as travelling waves including frequency dependency of all cable's parameters. The models often require parameters manipulation to obtain good fitting, however, mostly due to lack of cable cross-bonding, it was found that our model was sufficient accurate to represent transients due to energization of radials in offshore wind farms.

3.3.2 Transformers

Regarding the transformer, a representation has to be chosen including leakage inductances, winding resistances and winding capacitances. Considering the frequency range of the present investigations, up to about 1 MHz, a lumped representation of the transformer characteristics was deemed sufficient.

The simplest transformer model for transient studies of frequencies above 10-20 kHz, is a lumped representation of leakage inductance and winding resistance together with a lumped representation of transformer capacitances. Usually, the winding capacitances should be represented as capacitances from each terminal to ground as well as capacitances between terminals on different sides of transformer. This model has been widely used for EMT studies with often good results.

When the internal voltage distribution, voltage between turns or windings is of interest, a so-called white-box or white model can be used. Creation of such a model requires detailed knowledge of transformer construction, which is often proprietary of transformers' manufacturers. Many references can be found in literature showing different modeling techniques used for successful development of white-box transformer models, as e.g. Multi Transmission Line modeling (MTL) or lumped RLC network.

High frequency transformer models using lumped capacitances to represent properly the surge impedance of a transformer are not able to model the wide band voltage ratio of the transformer accurately. If interaction studies between components are of interest, including proper representation of frequency dependent voltage ratio, and when the transformer construction details are unknown, then a black-box model can be used. For the work in EMC Wind, mainly black box modelling was used and found to be sufficient, based on measurements of the short circuit admittance matrix of transformers. Traditionally, specialized high accuracy laboratory equipment is used to perform admittance matrix measurements, however, it was shown that simple sFRA devices can also be used for that purpose with sufficient level of accuracy.

A frequency dependent admittance matrix, is a way to describe characterizing a transformers behaviour under different conditions. The elements in the admittance matrix will typically change characteristic from being inductive at low frequencies to capacitive at high frequencies. Figure 14 illustrates this behaviour.

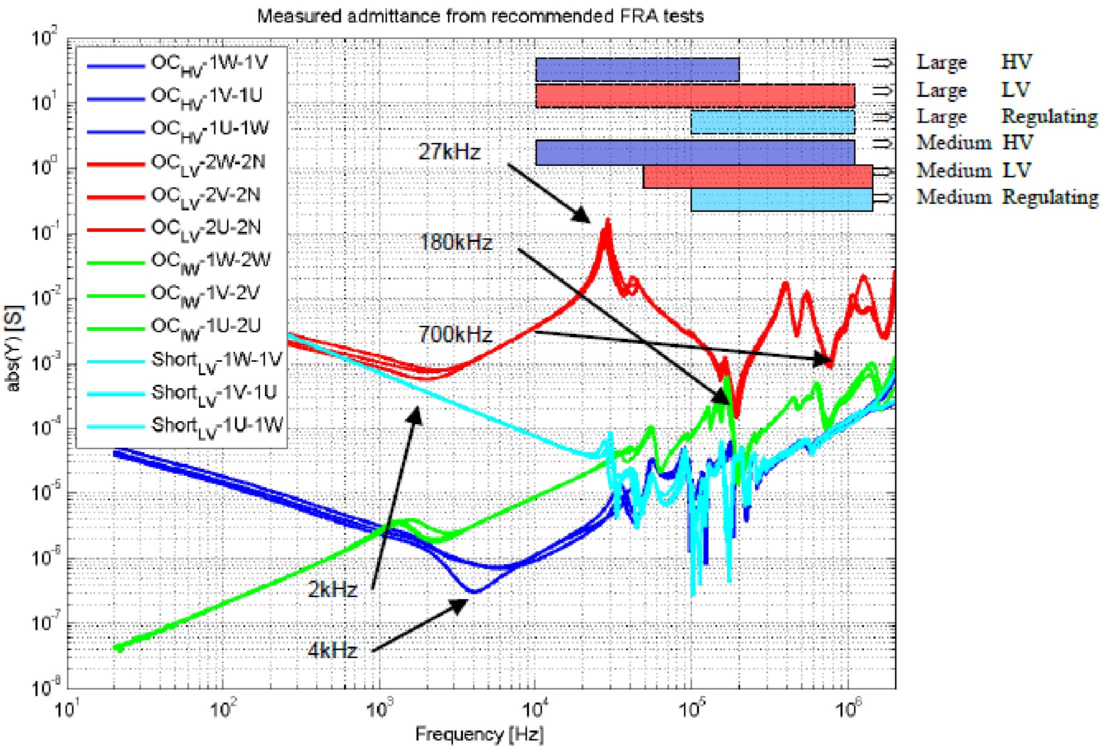


Fig. 14: Measured admittance from FRA-test on a 100kVA transformer. The elements in the admittance matrix are grouped according to comparable behaviour.

In the figure clearly can be seen the shift to capacitive behaviour with frequency. The elements in the admittance matrix are grouped according to comparable behaviour, which means that it is not necessary to measure all elements in a transformer admittance matrix in order to get a complete picture.

The next question is how the broad band characteristics of different transformers will be as compared to each other. Intense studies were done on different transformer types and some results are shown in the following figure.

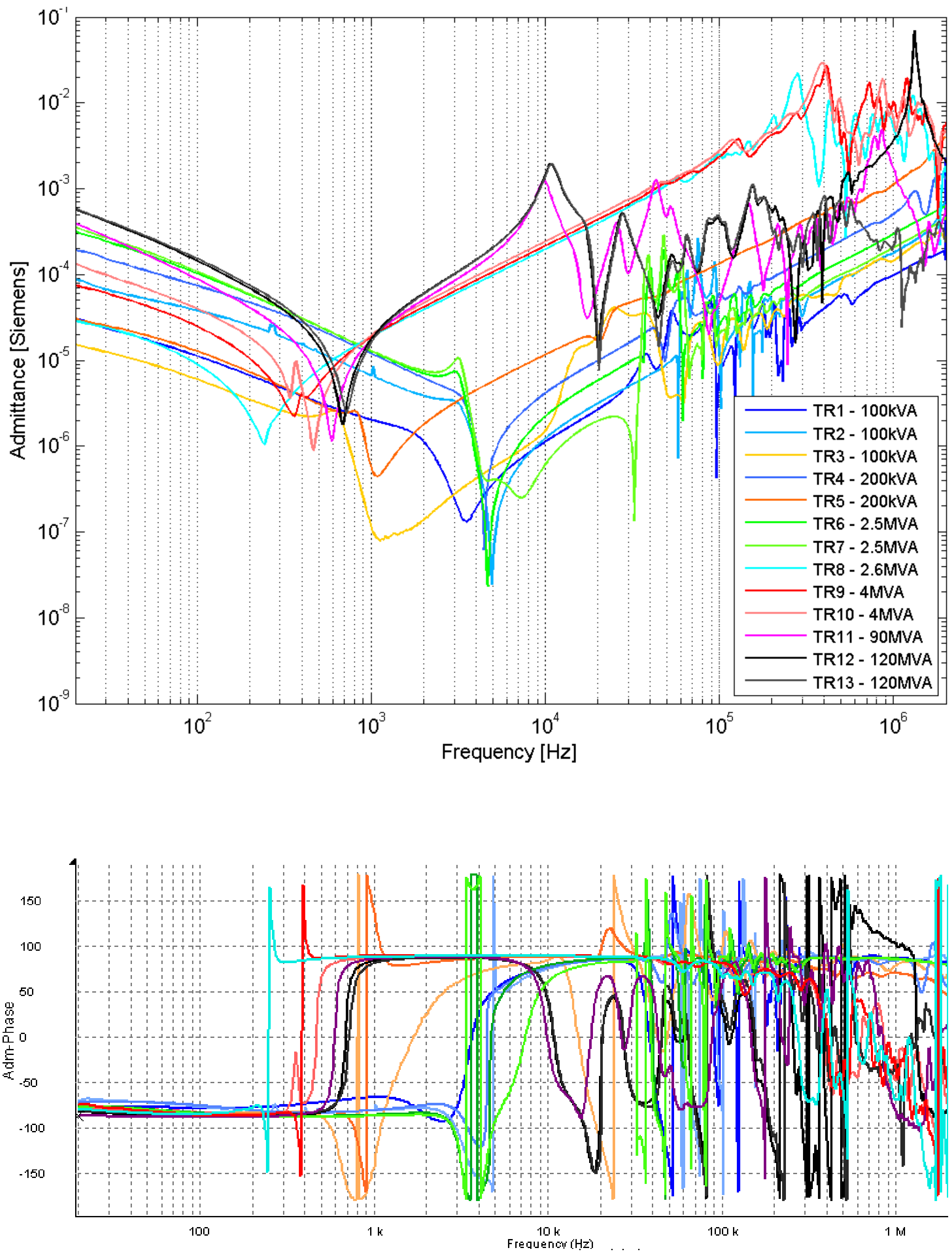


Fig. 15: Transformer admittances: Broad band characteristics of different types of transformers. The upper diagram shows the magnitude and the lower diagram shows the phase angle of the admittance. Shift from inductive to capacitive behaviour and numerous resonances can clearly be seen.

The results showed occurrence of resonances and anti-resonances as being dependent on the voltage rating, cooling type, and transformer size. This indicates that prediction of resonances, anti-resonances and the related voltage spikes could be based on a few and simple informations about the transformer, a very useful approach for practical modelling and simulations including power transformers.

It is interesting here that although winding structure properly also has an influence on the trend of the FRA result, the influence of this structure presumably are interlinked with the voltage ration and size. As a consequence, there is a possibility that knowledge to the internal structure of the transformer, which in most cases is confidential, might not be necessary for the modelling.

Another way of describing transformer characteristics is by means of the voltage ratio. This approach is of course consistence with the approach based on the admittance matrix. Figure 16 shows the positive sequence voltage ratio calculated from the measured admittance matrix of a 100 kVA, 10/0.69 kV transformer over a broad frequency range,.

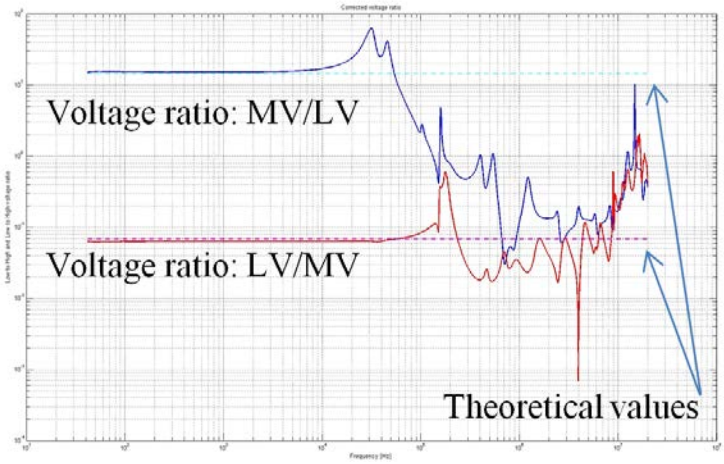


Fig. 16: Positive sequence voltage ratio calculated from admittance matrix measurements of a 100 kVA, 10/0.69 kV transformer. The dashed lines are indicating the theoretic low frequent values.

The ‘normal’ transformer voltage ratio at low frequencies can clearly be seen to change at frequencies above 10 KHz, with the first resonance peak at about 30 KHz.

4. Utilization of project results

In this chapter is shortly described utilization and the utilization potential of the results, mainly with reference to the former chapter.

4.1 Topic 1: Wind turbine environment

The work resulted in a 104 pages technical report and 3 papers, giving an overview of relevant knowledge, relations, standards and regulations within the area of the wind-turbine environment. Several suggestions are made both regarding new environmental 'classes', and the voltage and current related electrical environment.

Since both electrical and non-electrical exposure of components are covered, the report forms a valuable in the designing phase of both wind turbines and wind farms.

For wind turbine owners, the tools allows for specification of the requirements for the specific application to the manufacturers.

For manufacturers, the tool quantifies the exposure of the components from the environment, depending on the specifications given by the customers.

Even with standardization not being including in the present work, it should be mentioned that the report has been forwarded to Dansk Standard where it formed basis for further work under S-588 Wind turbines, working group 06. Furthermore, within IEC TC 88 Wind turbines, the results where available in connection with revision of the 61400-1 standard.

4.2 Topic 2: Compatibility

This topic must be considered as one of the 'hot' topics, not just within wind turbine applications, but within power engineering in general.

8 papers, 1 journal paper were written plus 2 more journal papers are to come.

The tools developed under this topic allow for future investigations of critical constellations in connection not only with wind farms, but also many other complex electrical power system. Parametric variations allow for systematic investigations on the consequences of using different types of components, different sizes, topologies and what else can have influence on the electrical behaviour of the system. Since time domain simulations in many cases can be avoided or at least be reduced to the final step, parametric variations can be done within a reasonable time range. Though, it is still recommended to limit the number of variations to selected discrete values in order to make the investigations realistic.

In the present report, parametric variation was shown as the final, most comprehensive method. Not treated in detail is the large number of other tools being implemented and tested in order to reach the goal of compatibility/interaction investigations. Methods like vector fitting, sensitivity analysis, step response, frequency domain severity factor are just few, which also can be utilized in numerous other applications.

The methods are recommended to be used in the process of wind turbine and wind farm design, saying at comparable early stages of establishing wind power plants.

4.3 Topic 3: Component specifications

Specifications for power components are usually limited to the power frequency of 50Hz. As documented in this report, is it highly relevant to consider high frequent behaviour of offshore wind turbines and farms, a) due to the complexity and b) the dynamic operation of such a grid. An immediate utilization of the results is taking place at Dong Energy, where the models developed in the former and the present ph.d.-project (Aristi and Holdyk) are used in connection with wind farm planning. Next obvious step would be to recommend broad band specifications from component manufacturers. Here, transformers should be mentioned as the most relevant case, since, as has been shown in the report, the construction details of the transformer have considerable influence on it's electrical behaviour. Alternatively, the customer can assess the characteristics by means of measurements. In that connection, FRA-equipment used in the present work is a very useful tool. The apparatus is operated at low voltage level, though, which means that phenomena like core saturation are not included.

Regarding cables, good results can be achieved by means of EMTP-built in models. However, for more complex cable types like 3-phase submarine cables, additional modelling efforts and verification of the results could be necessary.

In addition to the use of FRA-results for transient simulations, the characteristics can be used as fingerprints of the transformer condition. An FRA-test done right after manufacturing the component and again after installation on-site can contribute to reveal damages having occurred under transport and installation of the component. In that sense the method acts as a non-destructive diagnostic tool.

It also should be mentioned that in the period 14. August to end of October 2012, Andrzej was guest researcher at Sintef in Trondheim. Here he worked with one of the very leading experts within component modelling, Björn Gustafson. The work was linked to the cooperation with project partner DONG Energy, which at the moment is ongoing.

5. Project conclusion and perspective

PSO project 010087 on Electric Main Components in Wind Turbines – Exposure - Compatibility – Specifications was conducted in the period of 2008-04-01 to 2013-04-14 as cooperation between universities – power utilities and several industrial parts in Denmark.

The 3 main tasks of the EMC Wind project were: Wind turbine environment – Compatibility – Component specifications. The technical tasks to be fulfilled under each issue where treated and solved by different participants (see also: organization) and covered the following challenges:

It can be concluded that tasks where fulfilled.

Regarding the wind turbine environment, full documentation was delivered for the non-electrical environment. For the electrical environment, several methods were developed and presented for load and harmonic characterization. The tools can directly be used by users and manufacturers for specifying requirements to wind turbine components.

Regarding compatibility, extensive investigations were done on possible approaches and new methods were presented for characterizing component and wind turbine interaction. Clear relations were shown between the time requiring time domain simulations and analyses in frequency domain. The results show the influence of specific parameters being varied depending on the farm layout. In particular, cable lengths and transformer broad band characteristics turned out to have significant impact on the results. Based on these findings, parametric variations now are possible, even for complex systems. No attempts however were made to compare with component specific maximum voltages, since these usually are not available for frequencies other than 50 Hz. Another possible future continuation of the work could be a look at breaking events including breaker properties. Also interaction of collection grid and HVDC converters could be relevant for future investigations. The methods demonstrated here, can generally be used in the process of wind turbine and wind farm design and are suitable to identify critical constellations.

Regarding component specifications, broad band transformer and cable equivalents were established in the frequency range up to 1MHz, in order to cover the necessary requirements in connection with compatibility investigations. Clear relations between component characteristics and wind farm behaviour were identified, emphasizing the necessity for extended component specifications. Also it was shown that commercial available FRA equipment can be used for component characterization. This gives valuable information not only for mentioned applications, but also as a general tool in connection with component quality control and diagnostics

The project leader wants to thank for the PSO-funding and Energinet.dk for cooperation and for making this project possible.

6. Annual export of electricity (only ForskVE)

Not applicable for this ForskEL project

7. Updating Financial Appendix and submitting the final report

The final financial overview is given in following table:

Project Number	**10087**			
Title (automatic)	Elektriske hovedkomponenter i vindmøller			
	Budget	Financing (including feed-in tarif)		
	Total (DDKx1000)	**Other (DDKx1000)**	**Internal (DDKx1000)**	**PSO funding (DDKx1000)**
Contract sum	6 696.0	-	2 676.0	4 020.0
Supplementary grant 1			-	
Supplementary grant 2			-	
Total	**6 696.0**	**-**	**2 676.0**	**4 020.0**
Accumulated costs (sum of periods)	5 433.8	-	1 961.1	3 472.7
Residual sum / residual commitment	**1 262.2**	**-**	**714.9**	**547.3**

Net expenses realised during the periods (sum of periods)

	Total (DDKx1000)	**Other (DDKx1000)**	**Internal (DDKx1000)**	**PSO funding (DDKx1000)**
Before 2. half 2008	-	-	-	-
2. half 2008	1 081.6	-	761.4	320.2
1. half 2009	808.1	-	485.0	323.1
2. half 2009	438.6	-	238.4	200.1
1. half 2010	437.1	-	160.6	276.5
2. half 2010	503.2	-	100.0	403.1
1. half 2011	661.9	-	90.3	571.5
2. half 2011	493.8	-	58.8	434.9
1. half 2012	388.4	-	45.3	343.1
2. half 2012	472.9	-	21.1	451.7
1. half 2013	148.3	-	-	148.3
Accumulated costs	**5 433.8**	**-**	**1 961.1**	**3 472.7**

It can be concluded that the project goals have been reached well below the budget, though with slightly increased funding percentage of 63.91% instead of 60% in the budget, caused by the early leave of the first ph.d. candidate after one year.

In the following can be found our remarks (in Danish) to the balance, by DTU's project economist Torben Sejten as sent to Energinet.dk the 27. November 2013.

The following text is similar to a mail from Torben Sejten to Energinet.dk 27. november 2013

Bemærk venligst, at vi under udarbejdelsen af slutregnskabet har konstateret tilfælde af fejlrapporteringer i tidligere perioder. De konstaterede fejl har vi så vidt muligt inkluderet i rapporteringsskemaet for periode ”1. half 2013”, hvilket er årsagen til, at der heri optræder negative poster.

I 2 tilfælde har vi dog været nødsaget til at foretage rettelsen direkte i rapporteringsskemaet for de pågældende tidligere perioder, nemlig for ”1. half 2009” og ”2. half 2009”. Årsagen hertil er at fejlene skyldes manglende udfyldelse i rapporteringsskemaet af OH% eller PSO%. Da disse Excel skemaer er låst, har vi ikke kunnet medtage rettelserne på anden måde.

Sammen med rapporteringsskemaerne medsendes også til din orientering en oversigt, der viser sammenhængen i den akkumulerede projektøkonomi fra den seneste rapportering for periode ”2. half 2012” og frem til slutregnskabet ved udgangen af periode ”1. half 2013”.

Udover dette bedes du være opmærksom på følgende:

I regnskabet for periode ”1. half 2013” er medtaget udgifter som er påløbet efter projektets udløbsdato d.14. april 2013. Disse udgifter, der beløber sig til i alt kr. 24.329,73 eksklusive overhead, er rejseudgifter vedrørende konferencer, som har faglig relation til projektet.
Der er for periode ”1. half 2013” ikke nogen udgifter fra de øvrige projektpartnere.
Projektets samlede PSO funding i forhold til de samlede akkumulerede omkostninger medfører en støtteprocent på 63,91 mod den budgetterede støtteprocent på 60. Årsagen hertil er omstændighederne i starten af projektforløbet, hvor den første ph.d.-studerende sprang fra efter 1 år. Dette er tidligere oplyst i statusrapporterne, og du har d. 25. marts 2013 forholdt dig til dette spørgsmål i dit svar på mail fra Casper Sembach af d. 13. marts 2013.

Jeg vil sørge for, at Appendix P også bliver uploaded på sagen på Forskel.dk.

Du er velkommen til at kontakte mig, såfremt du har spørgsmål eller bemærkninger til slutregnskabet.

Med venlig hilsen
Torben Sejten
Vikarierende projektøkonom

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8. Figure source list

The following figure sources refer to the reference chapter. The letters in front of the number mean: T- Technical report, C – Conference or Journal, P – Ph.D. thesis, S – Student project

Figure 1, 2, 3: *T1)*
Figure 4 -10: *T12)*
Figure 11: *Abstract to T12)*
Figure 12: C8)
Figure 13: *S2)*
Figure 14: P2)
Figure 15: S1)
Figure 16: *T12)*

9. References

The following scientific publications where produced under the project

9.1 Technical reports

1) Matthew Henriksen, Joachim Holbøll, ”Wind Turbine Electrical Main Components, Electrical and Non-electrical Environment”, Report from PSO project 010087, Techn. University of Denmark, Electrical Engineering, 102 pages, 2011.

2) Cigré Working Group C4.307, "Resonance and ferroresonance in power networks," Cigré, Tech. Rep. Brochure 569, Feb 2014 (A. Holdyk contributed).

9.2 Conference contributions and journal papers

1) Holdyk, A., Holboell, J., Jensen, A., “Implementation of Cable Models for Studies of Compatibility of Electric Components in Wind Farms“, Jicable 2011, 20-23 June 2011.

2) Holdyk, A., Holboell, J., Arana, I., “Compatibility Between Electric Components in Wind Farms “,’10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms’, Aarhus, Denmark, 25-26 October 2011

3) Henriksen, Matthew Lee ; Koldby, Erik ; Holbøll, Joachim ; Holdyk, Andrzej, ”Environmental Severity Classes for Main Electrical Components in Offshore Wind Turbine”, ’10th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms’, Aarhus, Denmark, 25-26 October 2011.

4) Rasmus Schmidt Olsen, Joachim Holboell, Asger Jensen “Analysis of load conditions of wind turbine components”, EWEA Offshore 2011, Amsterdam.

5) J. Holboell, M. Henriksen, R.Olsen, A. Jensen, E. Koldby, “Electrical and Non-Electrical Environment of Wind Turbine Main Components”, Cigré Symposium, Paris 2012

6) Holdyk, A., Holboell, J, Arana,I., Jensen, A., “Switching Operation Simulations in a Large Offshore Wind Farm with Use of Parametric Variation and Frequency Domain Severity Factor“, UPEC 2012, 4-7 September 2012.

7) Kocewiak, Łukasz Hubert ; Arana Aristi, Iván ; Hjerrild, Jesper ; Sørensen, Troels ; Bak, Claus Leth ; Holbøll, Joachim, ”EMC of harmonic and transient measurement equipment in offshore wind farms”, Energy Procedia , Deep Sea Offshore Wind R&D Seminar, Trondheim, 2012

8) V. Kersiulis, A. Holdyk, J. Holboell, I. Arana,‘ Sensitivity of Nodal Admittances in an Offshore Wind Power Plant to Parametric Variations in the Collection Grid’, Proceedings of the 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems. 2012

9) A. Holdyk and J. Holboell, "Implementation of the parametric variation method in an EMTP program," in International Conference on Power System Transients, IPST, Vancouver, BC, Canada, 2013, pp. http://www.ipst.org/techpapers.htm.

10) A. Holdyk, I. Arana, J. Holboell, ‘Wide band characterization of wind turbine reactors’, IPST, Vancouver 2013

11) A. Holdyk, B. Gustavsen, I. Arana, J. Holboell, ‘Wide Band Modeling of Power Transformers Using Commercial sFRA Equipment’, IEEE Transactions on Power Delivery, 2013

12) A. Holdyk, J. Holboell, E. Koldby, A. Jensen, ‘Influence of an offshore wind farm’s layout on electrical resonances’, Cigré Symposium, Paris 2014 (submitted)

In addition is planned for 2014 submission of the 2 IEEE journal papers:

13) A. Holdyk, "Validation of EMTP/ATP and PSCAD models of switching operation in the collection grid of Burbo Bank offshore wind farm," IEEE Transactions on Power Delivery, 2014

14) A. Holdyk, J. Holboell, “Natural frequencies in Offshore Wind Farms”, IEEE Transactions on Power Delivery, 2014

9.3 Ph.D. theses

1) Holdyk, ‘Interactions of electrical main components in wind farms’, Ph.D.-thesis, Technical University of Denmark, 2013.

2) Ivan Arana Aristi, ‘Overvoltages and protection in offshore wind power grids’, Ph.D.-thesis, Technical University of Denmark, 2012. (Related topic conducted in parallel to EMC wind)

9.4 Student projects (bachelor and master level)

Selected results from the following master theses are directly included in this report:

1) A. S. Bengtsson, ‘Comparison of recommended FRA measurements in different type, rating and size transformers, M.Sc. Thesis, Technical University of Denmark, 2012.

2) C. Karlshøj Madsen, 'Resonances in MV Cable and Transformer Systems for Simulation of Switching Transients in PSCAD', M.Sc. Thesis, Technical University of Denmark, 2010.

3) V. Kersiulis, 'Sensitivity of electrical conditions in offshore wind farms to parametric variations in collection grid cables, simulated in ATP-EMTP', M.Sc. Thesis, Technical University of Denmark, 2012.

In addition, the following student projects have contributed to the work:

1) Analyse af elektriske og klimatiske omgivelser i vindmøller ,22. jun 09 - 30. sep 09
2) Sammenligning af kabelækvivalenter i tids- og frekvensdomæne ,3. aug 09 - 30. sep 09
3) Udviklingsprojekt til bestemmelse af transformers admittancematrix under laboratorieforhold ,17. aug 09 - 2. okt 09
4) Transformerindkoblingsstrømme under varierende koblingsforløb i en 11kV-station ,5. okt 09 - 18. dec 09
5) Analyse af vindmøllekomponenters belastningsforhold under termisk, mekanisk og miljømæssig stress ,4. jan 10 - 30. jun 10
6) Bestemmelse af MV-transformers admittansmatrix ved hjælp af Frax 101 Frequency Response Analyzer ,2. jan 12 - 22. jan 12
7) Principper og målemetoder for karakterisering af multiterminal-komponenter ved hjælp af lineære systemer ,30. jan 12 - 17. feb 12
8) Transienter i Offshore HVDC Systemer - Modellering og Simulering ,30. jan 12 - 13. aug 12
9) Black box modellering af højspændingstransformere bestemt ved frekvens- og spændingsafhængige knudepunkts-admittansmatricer ,20. feb 12 - 31. aug 12
10) Analyse og modellering af elektromagnetisk interaktion ,3. sep 12 - 20. dec 12
11) Transienter i HVDC transmissionsnet for offshore vindmølleparker ,11. feb 13 - 30. aug 13