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Current distribution and magnetic fields in complex structures using Comsol Multiphysics

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Abstract: The present paper presents numerical calculations of the magnetic fields and the current distribution within a wind turbine nacelle. The results are used by control system engineers designing panels and cables, who must ensure that the immunity of the equipment complies with the environment within the turbine.

Since the release of the International standard concerning lightning protection of wind turbines, IEC 61400-24 [1], it has become mandatory to document the effectiveness of the installed lightning protection system. In this respect, numerical modelling of magnetic fields and current distribution is a natural part of establishing the zoning concept, also required in the GL2010 [2].

The computations have been conducted on an arbitrary turbine, to illustrate which kinds of results that can be obtained.

Keywords: Magnetic fields, wind turbines, lightning protection, AC/DC module.

1. Introduction

When complex structures like wind turbines are struck by lightning, the associated current distribution and magnetic fields might interfere with the electronic equipment within the turbine. If no precautions towards the immunity are considered, the consequence might be that the turbine stops its production or gets damaged.

Therefore lightning protection of wind turbines has become mandatory according to the IEC standard IEC 61400-24 [1], and the protection must typically fulfil the requirements for the Lightning Protection Level 1 parameters (LPL1).

One of the early steps in all branches of design engineering is modelling of the physical behaviour. Modelling - and in this case numerical modelling - is a fairly inexpensive way of gaining knowledge of the system, otherwise only available during extensive testing or field experience. According to IEC 61400-24 [1] modelling can even be used as mean of verification when the validity of the numerical tool has been verified.

The first step is to precondition a 3D CAD drawing of the structural components before it is loaded into the numerical software based on the FEM method. The different sub domains and boundary conditions are established, and the numerical tricks to enable a computation on such a complicated structure are presented.

Secondly the impact in terms of the lightning attachment points and the lightning current waveforms are defined, and the computations of the magnetic fields and the current distribution with the structural components can be conducted.

The magnetic field distribution is used to estimate the necessary shielding of panels and cables, and the current distribution to foresee current amplitudes in shielded cables etc.

2. Numerical modelling

When a DC current is injected through a complex structure with several different paths, the current will be distributed according to the resistances of the different paths. There do not exist any mutual couplings of neither inductive nor capacitive nature since the currents or voltages are not time dependant. The solution of the current distribution is then strait forward, and can be performed using simple linear algebra.

By injection of AC currents or transient currents, the dI/dt of the AC current or the dU/dt of the AC voltage will introduce mutual couplings, such that the current flowing in one conductor might induce a voltage on another conductor, or vice versa. In this case the mutual couplings must be identified. It can be done analytically on very simple structures (two parallel wires, two wires of infinite length crossing at a fixed angle, etc.), but when it comes to real physical structures, numerical methods are required.

The numerical codes typically used are based on the FDTD (Finite Difference Time Domain) or the FEM (Finite Element Method). In both cases, the structure geometry is subdivided into a finite number of elements, and Maxwell Equations are then solved for each element respecting the mutual boundary conditions.

In order to model the magnetic field in an entire wind turbine nacelle, simplification of the geometry has been necessary. By starting with the detailed CAD drawing, the compromise is to define a geometry that is detailed enough for a realistic representation, and still simple enough to enable the numerical solver to find a solution.

2.1. 3D CAD drawing

All modern structures are designed and engineered using CAD tools, improved for visualization and modelling. Considering the level of detail presented in such models, the number of elements during a discretization within the FEM environment approaches infinity. Therefore an important first step is to evaluate which details are necessary for achieving the correct results, and which details that can be omitted without compromising the final solution.

Problems of relatively simple nature (Electro statics, conduction of DC currents, etc.) do not require the full Maxwell Equations, such that even detailed models can be evaluated. Considering transient currents in high permeable materials, like the present simulations, the equations used for solving the problem contain far more parameters. In such cases, some simplification of the structure must be done either by considering 2D symmetries, or simplifying the 3D geometry.

The preconditioning of the geometric model is performed in the CAD tool Space Claim [3]. For the numerical simulations of magnetic fields and current distribution within the overall construction, several details can be removed from the original model like bolts, nuts, small edges etc. If specific areas of the model are of more concern (around panels or sensors), the model can be of higher detail here.

2.2. Current waveforms

To model voltage drops during the interception of a lightning strike, the different components of the lightning strike must be considered individually. In the international standards for lightning protection, probability density functions governing the peak amplitude and the frequency response are shown. From these curves, four characteristic current components for a Level 1 stroke are derived.

1. The first positive return stroke, a 200kA current pulse with a rise time of 10µs and a decay time of 350µs. In the frequency domain, this waveform is simulated by an oscillating waveform exhibiting a frequency of 25kHz.
2. The first negative return stroke, a 100kA current pulse with a rise time of 1µs and a decay time of 100µs. In the frequency domain, this waveform is simulated by an oscillating waveform exhibiting a frequency of 250kHz.
3. The subsequent return stroke, a 50kA current pulse with a rise time of 0.25µs and a decay time of 100µs. In the frequency domain, this waveform is simulated by an oscillating waveform exhibiting a peak frequency of 1MHz.
4. The continuing current, a DC current pulse of amplitude 200-800A and duration of up to a second.

In natural lightning, all possible combinations do occur, but for verification of lightning protection systems (simulation and testing) these four individual components apply. In the case of determining the maximum magnetic fields within the nacelle, the first and the subsequent return strokes are of most concern.

2.3 Materials and skin depths

The materials used in the modelling are defined by the following physical constants:

Table 1: Fonts Physical constants used in the modeling

Property	Air	Iron
Electrical conductivity ζ [S/m]	0	10^7
Relative permeability µr	1	200
Relative permittivity εr	1	1

Where all values are estimated based on tabulated values for standard materials.

As commented earlier, the frequency response of a lightning current measurement would be very wide in its spectrum and contain current components from nearly DC up to a few MHz. These differences must be considered when optimizing a numerical model as the case in this research.

Considering Iron as the current conductor (defined above), the skin effect will play a major role for the current distribution. The current density is in reality an exponential decaying function of the distance from the surface of the conductor having the largest current densities at the boundary of the conductor and the smallest densities at the centre.

For practical use, a term skin depth is defined, indicating the depth from the conductor surface where the current density has declined to 1/e=36.8% of its original value. For simple calculations of voltage drops along conductors it can be assumed that the entire current flows in the cross sectional area limited by the outer boundary and the skin depth. The following equation defines the skin depth where 'f' is the frequency, 'μ_0' is the vacuum permeability, 'μ_r' is the relative permeability of the conductor and 'ζ' is the conductivity.

$$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_0 \cdot \mu_r \cdot \sigma}}$$

The skin depth 'δ' is often used to compute the effective conductor cross sectional area, and is therefore a good basis for estimating the effective resistance of the conductor at high frequencies.

For Iron, the skin depth at the frequencies relevant for first and subsequent return stroke simulations (>10kHz) is less than 0.11mm. The vast majority of the current will therefore flow very close to the structure surfaces, and the numerical model treats the solid structure of the nacelle as thin boundaries, using the Impedance Boundary Condition of Comsol Multiphysics [4].

The bulk materials are defined as stated above, but Comsol Multiphysics then accounts for the skin effect, and defines a 2D mesh on the geometry surface instead of meshing the entire structure in 3D. This simplification enables solving of more complex geometries in Comsol Multiphysics without impacting the result of the numerical simulation.

3. Case story

To visualize the capabilities with such numerical simulations, the following case story presents the calculations of magnetic fields and current distribution within an arbitrary nacelle structure. Initially the geometric model is described as it appears in the CAD tool, and secondly the different conditions are defined within the FEM environment.

3.1. Precondition in Space Claim Engineer

Since the structure considered in this paper is an arbitrary wind turbine nacelle, there does not exist any detailed model in a CAD environment. However, as mentioned previously, the first step for an analysis on a real structure is to decide the different levels of details in the regions of interest.

In general lightning protection, positioning of the air termination systems is one of the initial steps. These points on a wind turbine nacelle will typically be integrated parts of the structure, or externally placed Franklin rods, metallic rings around instrumentation, etc., besides the three blades on the HUB. The air termination system is firmly connected to the nacelle main structure, either directly or via suitable down conductors. Once the current enters the nacelle main structure, the impedances in this geometry will define the current distribution.

In the present case story, all details besides the nacelle structural components have been disregarded. A typical simulation would consider several different attachment points, by injecting the lightning current into different places at the nacelle. The present model however, only considers the situation when the blade is struck in an angle of 45° with horizontal, Figure 1.

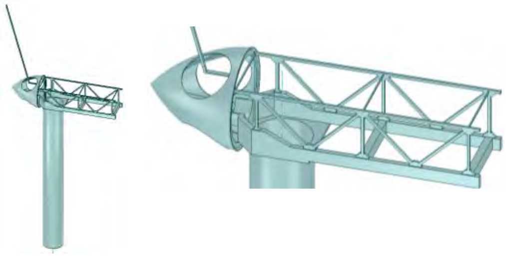

Figure 1. The configuration where the turbine is struck on a blade pointing to the left with an angle of 45° with horizontal. The line extending from the HUB is simulating the blade down conductor.

Once the CAD drawing has been altered to the level of detail seen on Figure 1, the model can be imported into the FEM environment.

3.2. Comsol Multiphysics

Comsol Multiphysics has previously featured a CAD import module, which should make importing STEP and IGES file formats a simple formality. However, this has never been the case for real engineering structures, so again the benefits of using Space Claim is worth mentioning. Lately a Live link between Space Claim and Comsol Multiphysics has been launched, making the de-featuring and import much easier.

When the geometry of the turbine nacelle is imported, the next step is to create an analysis volume surrounding the turbine. The analysis volume is the media (air) in which the magnetic field is distributed, and must be large enough to avoid excessive impact from the outer boundaries. For the present case a volume of 50mx50mx50m has been considered sufficient.

3.2.1. Model parameters

The physical model selected for the project is the 'Magnetic and Electric Fields (mef)', solved in the frequency domain with the standard solver FGMRES. The two configurations considered for the first and subsequent stroke currents are 200kA@25kHz and 50kA@1MHz. In both cases the quasi static approach is found adequate, since the maximum geometry size of 50m is well below the wavelength of a 1MHz wave (300m).

Subdomain. Two different subdomains exist; the nacelle structural components and the surrounding air. Due to the skin effect, the model can disregard the interior parts of the metal structure by deactivating the subdomain of the turbine and enabling the impedance boundary condition on the structure surfaces.

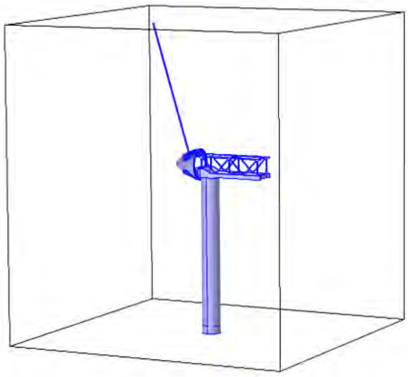

Figure 2. Illustration of the subdomains containing the nacelle structural components. The box shaped wireframe indicates the analysis volume.

In some cases the numerical solver has difficulties in converging, where the conductivity of air can be increased to 10 or 100, still orders of magnitude lower than that of the nacelle structure. The remaining parameters for the subdomains are listed in Table 1.

Boundary. Several different boundary conditions apply. When the sub domain of the nacelle structure has been deactivated, the impedance boundary condition can be selected. This boundary condition chosen for the entire nacelle structure disregards the volume of the structure and assumes that all current is flowing on the structure surfaces. The electric properties of the materials are listed in Table 1.

The boundary of the analysis volume is defined as magnetic insulation, ensuring a minimum impact of the magnetic field distribution.

Edge. All edges are default defined by an edge current of 0A. To inject the lightning current into the wind turbine nacelle, the edges in the intersection between the lightning channel and the analysis volume is defined by a certain potential $V_{lightning}$, whereas the edge of the tower base at its intersection with the analysis volume is defined by a potential V=0, see Figure 3.

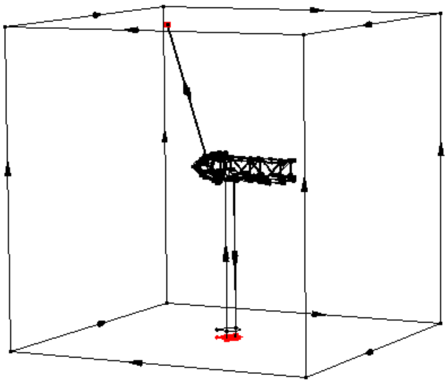

Figure 3. $V_{lightning}$ is applied at the edges in the intersection between the lightning channel and the analysis volume, whereas V=0 is applied at the edges in the intersection between the tower and the analysis volume

Once the different conditions are defined, the first simulation is conducted. The initial purpose is to define $V_{lightning}$ so that the overall lightning current, calculated using edge integration along the interface between the tower and the analysis volume, becomes correct. When coherent values of $V_{lightning}$ and the total current is found, $V_{lightning}$ can be adjusted linearly to match the desired total current amplitude of ex. 200kA.

With the desired combination of the total current and frequency is found, the results are obtained by calculating the current amplitudes in each of the structures in concern, and mapping the magnetic fields in the area of interest.

3.2.2. Output

The currents are calculated by one of two means:

Line integration. If it is possible to define an edge perpendicular to the length of the structure in concern, the current in the structure can be found by performing an integration of the surface current density along this edge. The parameter integrated along the edges is: 'mef.normJs' [A].

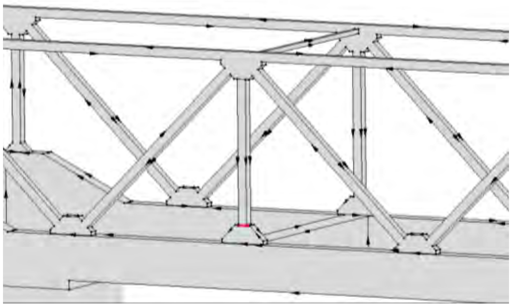

Figure 4. Illustration of edge integration

Surface integration. The second option, which is found more accurate, is an integration of the current density along the entire surface of the structure, and then divide the result with the length of the structure. Intentionally the results would be the same as with the line integration, but since the entire surface contains a larger amount of discrete elements than the edges perpendicular to the length, the results are more consistent using surface integration.

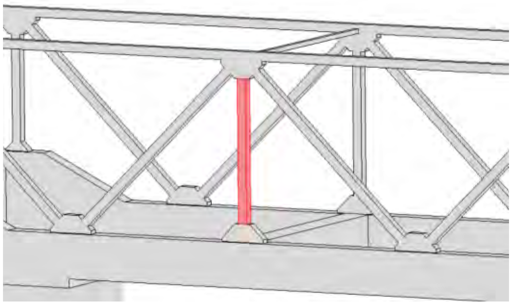

Figure 5. Illustration of surface integration.

The parameter integrated along the surfaces is: 'mef.normJs' [A·m], and finally divided by the length of the structure.

4. Results

The result consists of two parts, the magnetic field distribution within the surroundings of the nacelle structure (internal and external) and the current distribution in the structural components.

4.1. Magnetic fields

The magnetic field distribution found by the present simulation is used to specify the necessary shielding of panels and installations, to comply with the zoning concept of the wind turbine.

A typical result is seen on Figure 6, where 200kA@25kHz is injected into the blade tip. The plot shows two slice plots of the magnetic field. For simplicity, the colouring of the plot is limited to a maximum of 30kA/m.

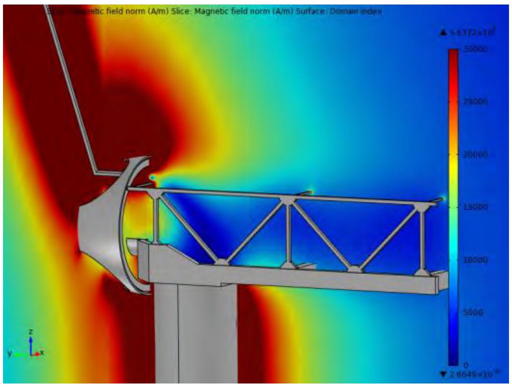

Figure 6. Illustration of the magnetic field at 200kA@25kHz lightning strike on one of the blades. The solution is plotted in two orthogonal planes.

In IEC 61400-24 [1] and GL2010 [2] it is required that manufacturers establish a lightning zoning concept for the wind turbine. This means that the manufacturer has to consider the installation and the protection principles installed and define which of the lightning protection zones that applies to the different parts of the turbine.

The highest zone is the LPZ0A, where structures are exposed to direct attachment and the full lightning current. Secondly there is LPZ0B where no direct attachment occurs and only the impact from the passage of the full lightning current and un-attenuated magnetic fields shall be considered. The remaining zones LPZ1 and LPZ2 defines limited values of the lightning parameters, i.e. the conducted voltage and current surges and the magnetic field.

By using Comsol Multiphysics to calculate the actual environment instead of relying on the subjective analysis of the design engineer, a more rigid and stringent design is optained.

If certain areas are of specific interest, i.e. at the positions of panels within the nacelle, the magnetic fields can be defined on the boundary or inside such panels as well, Figure 7 and Figure 8.

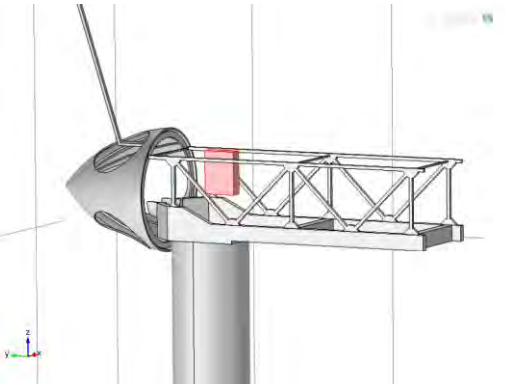

Figure 7. A control panel is added to investigate the magnetic field at its specific position within the nacelle

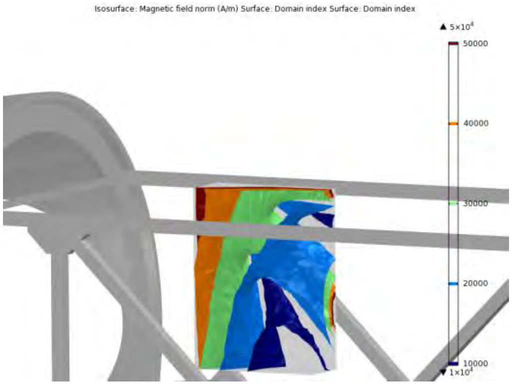

Figure 8. Isosurface plot of the magnetic field at the desired position of the panel. The result is used for determine the shielding requirements for the panel and the installations.

On Figure 8 it is seen how the maximum magnetic field at the surface of the panel attain values of 50kA/m due to the proximity of the structural bars behind the panel and the lightning channel carrying 200kA. Based on these results, the panel can either be moved to a different and less exposed region of the nacelle, or might be selected with an attenuation of 30dB or even 40dB. With 30dB attenuation the maximum magnetic field within the panel will decrease to app. 1600A/m, whereas 40dB attenuation will reduce the magnetic field to 500A/m. In both cases the equipment within the panel is selected according to these levels.

The use of the zoning concept is an engineering approach of designing adequate lightning protection. Similar to the EGM methods of defining lightning attachment points on various structures, the methodology is good due to its simplicity and ease of application. However, as numerical tools become more and more developed, it is believed that the use of these becomes more common.

4.2. Current distribution

The current distribution within the structural components considered in this model, can be used to assess the current flowing in shielded cables etc. Initially the information also enables designers to evaluate the minimum distance of sensitive equipment to current carrying structural components. If a panel is to be mounted on one of two iron bars within the nacelle, the choice can depend on the iron bar conducting the least amount of current and hence surrounded by the minimum magnetic field.

The current distribution within the nacelle for the 200kA lightning strike to one of the blades is seen on Figure 9.

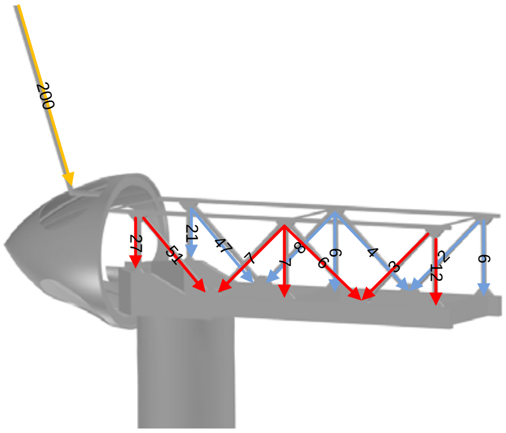

Figure 9. Calculated current distribution within the nacelle during a 200 kA lightning strike to one of the blades. All numbers are in kA.

The current values can be used to assess the impact on connections between different structural components, but the main idea is to enable a calculation of the current flowing in cables adjacent to the structures. Such models combined with the transfer impedances of shielded cables would end up with an evaluation of the voltages to be experienced in either end of shielded cables, and hence a basis for the selection of appropriate surge protection or additional shielding.

Current in shielded cables adjacent to current carrying structural components is presently being investigated thoroughly, and will be a topic for a future publication.

5. Conclusion

During lightning strikes to structures like wind turbines, the magnetic fields and the current distribution within the structure are an important issue for designing effective lightning protection. The magnetic field might interfere with the safe operation of control systems, and therefore define the environment for panels, sensors, etc. The current distribution in the main structure will affect the current coupled directly and induced into shielded cables traced along the structures, and will together with the transfer impedance of these installations form the bases for selection of correct surge protection devices.

The present research has defined some tools to achieve this information, and it is definitely expected that numerical modelling of such phenomena is an important part of tomorrows lightning protection.

8. References

1. IEC 61400-24 Ed. 1.0: Wind turbines – Part 24: Lightning Protection, July 2010.

2. Germanischer Lloyd: Guideline for Certification of Wind Turbines, July 1st 2010.

3. Space Claim, CAD tool used for preconditioning 3D CAD models before import into FEM analysis software, http://spaceclaim.com.

4. Comsol Multiphysics, commercially available FEM software, http://comsol.com.