LIGHTNING-PROOF WIND TURBINES

Danish consultancy Global Lightning Protection Services A/S is using electromagnetic simulation to calculate the magnetic fields and current distribution created when lightning strikes a wind turbine in order to optimize protection for internal electronics.

By **JENNIFER HAND**

Søren Find Madsen of Global Lightning Protection Services A/S in front of a wind turbine at a test site in northern Spain.

FOR A STRUCTURE standing 150 m high on an elevated site chosen for its exposure to wind, the big concern is not if lightning strikes but when. The number of such direct lightning attachments has risen dramatically in the past decade, along with the increased size of wind turbines and the trend toward placing them in harsh environments, particularly offshore.

Topology and geography dictate the incidence of lightning, creating large regional differences with notable hot spots of activity. Some extreme wind turbine sites experience 10 strikes a day, with lightning typically attaching to one of the blades. In such situations, both the current flowing through the turbine and the magnetic field created by it can interfere with the electronic equipment in the nacelle, the housing that covers the drive components in a wind turbine.

For manufacturers and operators, electromagnetic compatibility is a key consideration, given the potential cost of repair, replacement, and downtime. The big question for engineers is where to best position the panels that shield the control systems and cables connecting the panels so that exposure to the lightning current and the associated magnetic field is minimized. Indeed, lightning protection has become a requirement under the standards set by the International Electrotechnical Commission (IEC 61400-24, as revised in 2010) and Germanischer Lloyd Industrial Services (GL: 2010).

Under these two standards, it is also mandatory to document the effectiveness of the installed lightning protection system. GL: 2010 requires that a lightning protection zone be clearly established; IEC 61400-24 specifies that numerical modeling is an acceptable means of verification.

» *EVALUATING FLOW AND VOLTAGE*

SØREN FIND MADSEN of Global Lightning Protection Services A/S (previously Highvoltage.dk ApS) explains that in order to verify protection, engineers most frequently draw on results obtained from extensive physical testing of subcomponents like blades and external sensors, tests of entire systems like nacelles or control systems, or field experience. None of these approaches can give a completely accurate picture of risks and consequences, and all are expensive and time-consuming. It can, for example cost 400,000–500,000 Euros for a full range of laboratory tests on an entire nacelle. It is more cost effective to model the impact numerically as a first iteration. “Clients seek advice from us at the design stage, when they have to decide on the type and extent of lightning protection,” says Madsen. “That decision is a complex one that needs to take into account numerous variables, such as the type and angle of lightning incidence and the likely route that currents will take.”

It is, for example, possible to use simple linear algebra to resolve the distribution of a DC current injected through a

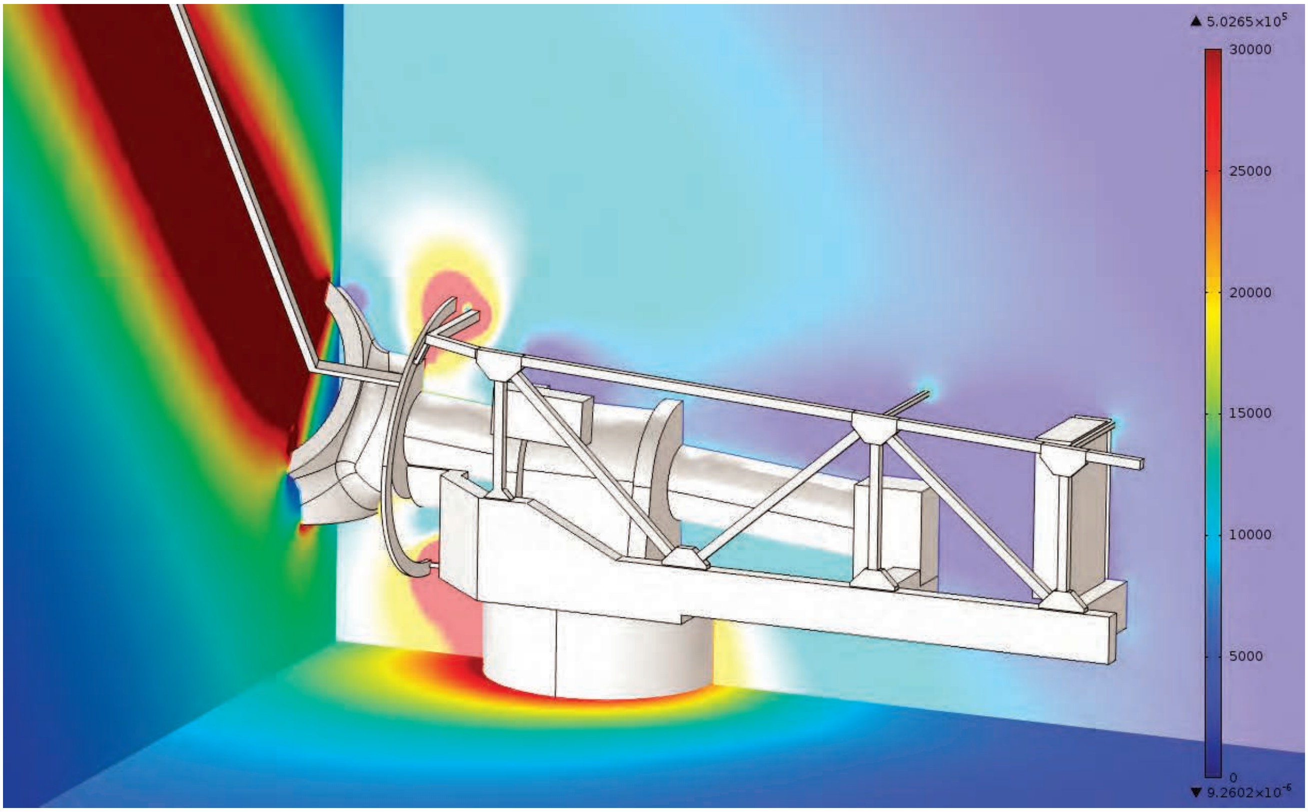

FIGURE 1: Illustration of the magnetic field after a 200 kA @ 25 kHz lightning strike strikes one of the blades.

complex structure because the current will be distributed according to the resistance of each potential route. The current and voltage do not change in time, so there are no mutual couplings in which the current flowing in one conductor induces a voltage on another. On the other hand, AC or transient currents will create mutual couplings, and numerical methods are required to solve the Maxwell equations throughout the structure.

"We find that finite element method (FEM) modeling using COMSOL Multiphysics is enabling us to define couplings and determine the direct and indirect effects (injected and induced current) on shielded cables," Madsen says "Along with the transfer impedance of the shielded cables, we can evaluate the voltages to be experienced at either end of shielded cables and select appropriate surge protection or a sufficient level of shielding."

» PREPARATION OF A CAD MODEL FOR SIMULATION

THE FIRST STEP is to precondition a 3-D CAD model of the wind turbine's structural components. According to Madsen, "Because 3-D CAD models include such a high level of detail, the FEM modeling environment discretization process would become a bottleneck. In order to model the magnetic field in an entire wind turbine nacelle, we have to simplify the geometry. We are aiming to retain enough detail for a realistic representation yet limit the number of nodes in the computation process so that the numerical solver can actually find a solution."

The CAD model is therefore imported into SpaceClaim® Engineer (from SpaceClaim Corp., Concord, Mass.), where it can be easily edited. "We remove small details, such as bolts, nuts and edges; irrelevant material, for example fibreglass and plastic; and unnecessary information, as in manufacturing labels," says Madsen. "We can keep a higher level of detail around any areas of particular concern, and finally we use COMSOL's LiveLink™ for SpaceClaim® to transfer the 3-D geometry of the turbine nacelle into COMSOL Multiphysics." The next step is to create an analysis volume around the turbine as a means of defining where the magnetic field is distributed.

» WAVEFORMS WITHIN A WIDE SPECTRUM

LIGHTNING PROTECTION standards show probability density functions governing the relevant lightning

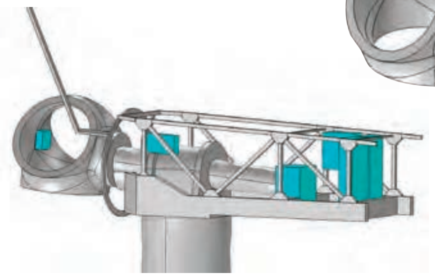

FIGURE 2: Control panels can be added to investigate the magnetic field at specific positions within the nacelle.

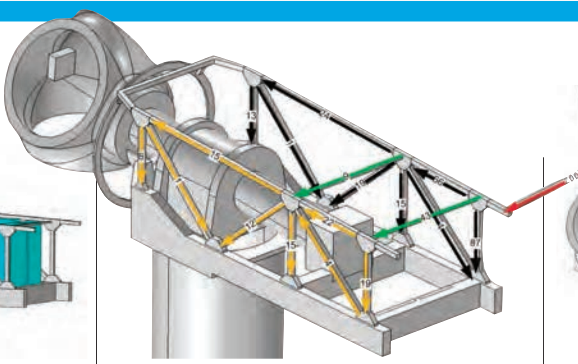

FIGURE 3: Calculated current distribution within the nacelle during a 200-kA lightning strike to the rear right corner of the nacelle. (All numbers refer to kA.)

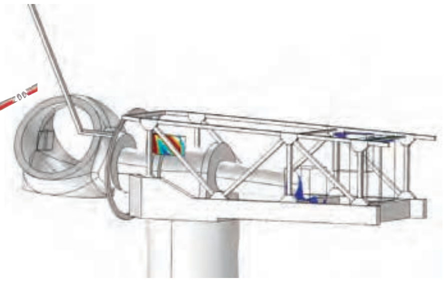

FIGURE 4: Isosurface plot of the magnetic field at the desired positions of the panels. The result is used to determine the shielding requirements for the panels and the installations.

parameters and the frequency characteristic of typical lightning current waveforms. From these curves, three characteristic components of a lightning strike can be derived. They are the first short stroke current, the subsequent short stroke current, and the long stroke current. In natural lightning all possible combinations occur; however, these must be considered individually when modeling voltage drops during the interception of a lightning strike.

Another issue is that the frequency response of a lightning current measurement spans a wide spectrum, from nearly DC to a frequency reaching a few MHz, and these differences must be considered. The skin effect has to be defined, as this will play a major role in current distribution when materials with high permeability and conductivity, such as iron, are considered. For simple calculations of voltage drops along the conductors, it can be assumed that the entire current flows in the cross-sectional area limited by the outer boundary and skin depth. Using the impedance boundary condition within COMSOL Multiphysics, it is possible to treat the solid structure of the nacelle as boundaries, account for the skin effect, and define a 2-D mesh on the geometry surface instead of meshing the whole structure in 3-D. This simplification enables complex geometries to be solved without affecting the results of the numerical simulation.

"In COMSOL we run a series of scenarios where realistic lightning current pulses are injected into the air termination systems," says Madsen. "We can vary the lightning attachment points and waveforms to calculate current amplitudes, map the magnetic field within and around the nacelle structure (see Figure 1), and highlight the distribution and duration of current in the structural components. We can easily focus on areas of specific interest (see Figure 2) so that designers can evaluate the minimum distance of sensitive equipment from current-carrying structural components. If a panel is to be mounted on one of two iron bars within the nacelle, the iron bar conducting the least amount of current can be selected (see Figure 3)."

» *SOLID RESULTS FEED THE DESIGN*

GLOBAL LIGHTNING Protection Services A/S is using such results to inform clients about shielding requirements (see Figure 4). With solid data, clients no longer have to rely solely on the somewhat subjective analysis suggested by the IEC standards. In some cases, this leads to a more rigid and stringent design; in others, it allows for more flexibility. In one such example, a design was being prepared for installation in both high- and low-risk lightning locations.

"One option would have been to make two types of blades, one for each environment," explains Madsen. "But it is obviously more cost effective to design and manufacture one design. However, there is a tendency to design to the higher-risk location, for safety reasons. We assisted one particular client with the selection of panels required in accordance with the worst-case scenario. We also followed up with physical tests, which confirmed the numerical modeling. Out of an overall development period of several years, it took about three months to produce reliable results indicating that it was safe to reduce the number of shielding panels on the turbine. This created massive savings, as thousands of units were to be manufactured."

Madsen concludes by commenting on the positive feedback Global Lightning Protection Services A/S has received from customers, which include industry leaders in China, Denmark, and Japan. "They are very impressed with the results we are producing and can see the value of verifying proposed lightning protection at the design stage, when it is still relatively easy and cost effective to make amendments. We certainly expect numerical modeling to play an increasing role in lightning protection." ◎