Lightning Protection Optimization for Large Wind Turbines with Method-of-Moments

Florian Krug, Ralph Teichmann
General Electric - Global Research
Freisinger Landstrasse 50, 85748 Munich, GERMANY

Ulrich Jakobus, Niels Berger
EM Software & Systems GmbH
Otto-Lilienthal-Str. 36, 71034 Böblingen, GERMANY

Hans Steinbigler, Josef Kindersberger
Laboratory for High Voltage Technology and Power Transmission, Technische Universität München
Arcisstr. 21, 80290 München, GERMANY

Abstract: - Electro-magnetic fields adjacent to the lightning current path in wind turbine generators are analyzed. The method of moments is used to analytically describe the transient distributed electro-magnetic field caused by a lightning strike. A simulation tool using the method of moments is presented. The electro-magnetic field distribution during a lightning strike in a wind turbine hub is analyzed in detail. The electro-magnetic field analysis is extended by a statistical lightning risk evaluation for wind turbine generators.

Key-Words: - Lightning protection, Method-of-Moments, Wind turbine, Power System, Risk Analysis, Electro-magnetic Field

1 Introduction
Lightning strike effect on wind turbine generators have recently become a major concern as the number and the height of wind turbines continue to increase. The impact on wind turbines range from disturbances on control electronics, damages to single components, such as blades or electronic components, to fires resulting in a complete loss of the installation. Most of these effects result in undesirable downtimes with its financial implications for the wind turbine operator. Further costs are added if components need to be replaced. Lightning strike risk analyses for common structures are established procedures to identify sensitive areas and determine the probability and severity of damages caused by lightning strikes. Simple methods [3] and more sophisticated procedures [4] were introduced. Specific guidelines and recommendations to assess and mitigate the risk of lightning damage for wind turbine generators [1] [2] were presented by various international technical committees such as IEC or IEA.

These recommendations focus on provision to safely conduct the lightning current thereby avoiding substantial damage. The electro-magnetic implications caused by the large transient lightning currents on control electronic components adjacent to the lightning current path have not yet been discussed. This paper presents an analytical method and a tool suitable for the analysis of direct lightning strike effects on sensitive electronic components in a wind turbine generator. The simulation results for the electric and magnetic field distribution during a lightning strike in a generic hub of a large wind turbine are presented.

2 Risk Analysis
An important initial step of a risk analysis is the estimation of the frequency of direct strikes to the wind turbine. This frequency is mainly a function of the lightning activity at the installation site, the local geographical topology and the dimensions of the turbine. The procedure of the estimation is described in [1] and [2]. It is based on investigations and experiences with common structures up to a height of 60 m. As an example a wind turbine with three rotor blades, a hub height of 100 m and blade length of 38.4 m is used. An offshore location with a distance of more than three times the total height of the turbine to the next turbine is assumed.
The annual average number of direct lightning flashes to the wind turbine can be assessed by the following formula:

\[ N_d = N_g A_d C_d 10^{-6} \]  \hspace{1cm} (1)

where \( N_g \) is the annual average ground flash density \((1/(km^2 \ a))\), \( A_d \) is the average collection area of direct lightning strikes \((m^2)\) and \( C_d \) is the environment factor according to [1]. Data on the annual average ground flash density are given in standards on lightning protection, e.g. in [5]. For example for a offshore installation site near the German North Sea coast \( N_g \) is approximately 0.75 \((1/(km^2 \ a))\) [5]. The average collection area \( A_d \) for a wind turbine placed on a flat ground is calculated to be the area of a circle with a radius of three times the turbine height [1]. For the calculation of \( A_d \) reference [1] recommends the modeling of the turbine as a tall mast with a height equal to the hub height plus one rotor radius:

\[ h = 100 + 38.4 = 138.4 \text{ m} \]  \hspace{1cm} (2)

The average collection area of direct lightning strikes amounts to:

\[ A_d = (3h)^2 \pi = (3 \cdot 138.4)^2 \pi = 54.2 \cdot 10^4 \text{ m}^2 \]  \hspace{1cm} (3)

The assumption that the wind turbines are separated by a distance of more than three times the height of the turbines results in an environment factor \( C_d = 1 \). With the calculated values for \( N_g, A_d \) and \( C_d \) the annual average number of direct lightning flashes to the turbine is given by:

\[ N_d = 0.75 \cdot 54.2 \cdot 10^4 \cdot 10^{-6} = 0.4 \frac{1}{\text{a}} \]  \hspace{1cm} (4)

This means that the wind turbine is hit by a lightning flash in average once within a period of about two and a half year. A more detailed analysis should distinguish between upward and downward lightning flashes. Wind turbine generators with heights similar to this example are exposed to both types of lightning discharges. A tendency to experience a higher number of upward flashes as the turbine height increases has been noted. A need for further data of lightning flashes to wind turbines, e.g. data of lightning flashes to very high structures with moving parts, clearly exists. The estimation of the frequency of direct lightning flashes to the wind turbine is a first step of a risk analysis. The next step is an investigation as to whether the lightning protection system being installed is sufficient. The considerations for this step of the risk analysis are based on the fact that not every lightning flash to the turbine causes damage, depending on the efficiency of the lightning protection system. In [1] a failure of the lightning protection system is called a “critical event”. The permissible number of such critical events \( N_c \) per year can be calculated as follows:

\[ N_c \geq N_d \left(1 - E \right) \]  \hspace{1cm} (5)

with the efficiency \( E \) of the lightning protection system. This efficiency is correlated with the protection level defined in [1]. It can be calculated with the formula:

\[ E \geq 1 - \frac{N_c}{N_d} \]  \hspace{1cm} (6)

For the permissible number of critical events the value \( N_c = 10^{-3} \text{ 1/a} \) is recommended in [1]. Using this value the efficiency of the example wind turbine is:

\[ E \geq 1 - \frac{0.01}{0.4} = 0.997 \]  \hspace{1cm} (6)

In [1] four levels for lightning protection systems are defined in accordance with [3]: level I through level IV. According to [1] for the calculated efficiency \( E \) a protection level I is necessary with the following lightning current parameters: peak current 200 kA, average rate of current rise 200 kA/µs and total charge transfer 300 C. These data are the basis for testing and simulation calculations for the lightning protection system of the wind turbine generator being considered. Further steps of the risk analysis must be carried out for the different areas of the system. Sensitive areas with a high risk of damage are for instance the rotor blades and areas with control systems. Lightning damage statistics show that more than 50% of damages occur in control systems of the wind turbine [6]. A highly sensitive component of the wind power turbine is the pitch control system for the control of the blade angle. It is located within the hub adjacent to the lightning current path. In order to calculate the risk of damage for the components of this pitch control system it is necessary to determine the electromagnetic field distribution inside the hub. This field distribution depends on the lightning current path from the point of impact to the ground and specifically on the lightning current distribution on and near the hub.
3 Numerical Analysis

There are few numerical methods to analyze the electro-magnetic impact of a lightning strike on a certain component within a complex mechanical structure. Each approach has its specific advantages. Time-domain approaches offer the opportunity to incorporate hysteresis effects and to calculate an impulse resonance directly in time-domain. Frequency domain approaches can handle frequency dependent material parameters and can exactly account for the infinite space. In this paper the method of moments shall be introduced to perform these specific calculations to reduce the model to conducting elements only.

3.1 The Method of Moments

The method of moments (MoM) is a current-based numerical technique to first derive the current distribution on a meshed model and to deduce all other quantities (e.g. the nearfield distribution) in a second step. The MoM belongs to the integral equation methods based on the determination and superposition of all field sources. Multiple distributed sources are exciting the set-up and inducing/influencing currents and charges on the metallic structure. The electro-magnetic effects of all sources are superimposed with the original field.

Therefore only metallic structures carrying these sources (currents and charges) have to be considered (see Fig. 1) and structured into discrete elements. Wire structures are meshed into segments and solid structures are meshed into a triangular surface body.

Fig. 1: Scattering of waves with metallic and dielectric bodies.

3.2 The Computer Code FEKO

The program flow of the computer code FEKO [7] shall be used to describe in detail the method of moments.

For each connection between the discrete elements (triangles for surfaces and segments for wires) a basis function has to be defined, which realizes the galvanic contact and describes the current $I_e$ and charge at a given element

$$I_e = \sum_{n=1}^{N_1} \beta_n \cdot g_n. \quad (7)$$

The triangular basis function $g_n$ (linear approximation of the current distribution) for the segment interconnections (nodes) can be seen in Fig. 2. The segments and the expansion coefficients $\beta_n$ are unknown in (7) and have to be determined. There are analogous basis functions and expansion coefficients for the connection between triangles (edges) and between segments with triangles (connection point) as shown in Fig. 3. The RWG (according to Rao-Wilton- Glisson [8]) basis functions are used in this case for the metallic edges.

Fig. 2: Wire segment basis functions and their weighting functions.

Fig. 3: Basis functions for triangular connections (edges) and connection points between segments and triangular patches.

The electro-magnetic problem solver has to evaluate a set of unknowns (representing either the fields or the sources) from a set of linear equations at a given excitation. In the method of moments the set of linear equations is based on a number of boundary conditions (e.g. electric field is perpendicular to perfectly conducting structures, charges can be derived from the currents with the continuity equation) and a number of transformation equations (e.g. Greens function $G(\vec{r}, \vec{r}')$).
which describe the relation between a source element and the field strength or the coupling between two source elements.

\[
E(r') = -\frac{j}{4\pi \omega} \left[ \oint \left( \nabla \cdot \mathbf{J}(r') \right) \cdot \mathbf{G}(r', r'') dA'' + \oint \frac{\partial \mathbf{E}(r'')}{\partial t'} \cdot \mathbf{G}(r', r'') dA'' \right] - j \omega \mu \left[ \int \mathbf{J}(r') \cdot \mathbf{G}(r', r'') dA'' + \int \mathbf{L}(r') \cdot \mathbf{P}(r', r'') dA'' \right] - \frac{1}{4\pi} \nabla \times \int \mathbf{J}(r') \cdot \mathbf{G}(r', r'') dA'' .
\] (8)

These transformation equations (e.g. in (8) with the relation between the scattered electric field and all electric and magnetic line and surface currents) are integral equations. Therefore this method belongs to the integral-equation methods. A harmonic approach is needed to replace the time-derivative by \( j\omega \) with the angular frequency \( \omega \). To enable a set-up and solution of these linear equations the linear equations have to be solved numerically. The resulting expansion coefficients directly give the current and charge distribution on the discrete elements of the structure. This calculation is a solution for a single frequency (time-harmonic continuous-wave (CW) signal) and can be repeated for a number of frequencies to determine the frequency response of the system. This can be called a filter.

### 3.3 Additional Modules of FEKO

The electro-magnetic code FEKO has been selected as the best choice to solve this problem because it combines the three main advantages,

- MoM based solver well fitted to this study with mainly conducting structures only
- Built-in Fourier-Transformation for time domain analysis
- Built-in optimizer for model parameter optimization.

In addition to metallic surfaces, also dielectric bodies or non-perfect materials (e.g. finite conductivity, skin effect etc.) can be considered within the MoM framework. The Fourier-transform and the optimisation feature shall be described in detail below. The discrete Fourier transform or spectrum \( V(l) \) for a time-domain signal \( u(k) \) is given in (9) e.g. at the discrete frequency \( f_l = f_0 \)

\[
V(l) = \sum_{k=0}^{N-1} u(k) e^{-j2\pi k l / N} \forall l
\] (9)

with the basic frequency \( f_0 \). The time-domain function or equivalent signal is given by (10), e.g. at the discrete time sample \( t_k = k T_0 = k / (N f_0) \)

\[
u(k) = \frac{1}{N} \sum_{l=0}^{N-1} V(l) e^{j2\pi k l / N} \forall k
\] (10)

with the sampling period \( T_0 = 1 / (N f_0) \) and \( N \) is the number of samples. A system must be known in time-domain or in frequency domain with its impulse-response (shape, duration) or its filter characteristic (bandwidth and its resonance), respectively. A signal shall be known in time-domain or in frequency domain with its shape or with its spectrum, respectively. If the impulse response of a system has a finite duration \( T_{sys} \), a pulse signal with a pulse period larger than \( T_{sys} \) can be considered. The system response can be described by the response of a single impulse or vice versa. FEKO uses this characteristic to solve time-domain problems using impulses by extending this to a pulse signal and by a discrete sampling (related to the pulse period) of both spectrum and signal. For the time-domain analysis using impulse or pulse signals, mainly three different cases can be specified:

a. All-pass – behavior: The spectrum of the signal is very narrow compared to the bandwidth of the so-called ‘filter’ or system. This leads to a simple delay and attenuation of the impulse or pulse.

b. Filter-behavior: Both the signal spectrum and the system bandwidth are in the same range. This leads to the necessity to combine the spectrum with the filter characteristic of the system and to apply an inverse Fourier transform to get the impulse or pulse response.

c. Dirac-impuls behavior: The signal spectrum is very wideband and particularly constant in the pass band of the system. The impulse’s shape is simply the impulse response of the system scaled with the signal energy of the single impulse.

The Nyquist criterion has to be applied to sample the spectrum up to a maximum frequency \( N f_0 > 2 f_{max} \) of twice the signal bandwidth \( f_{max} \). It is also applied sample the spectrum with a pulse period frequency \( f_0 \) corresponding to the duration \( T_{sys} < N T_0 \) of the system impulse response:

\[
\phi(t) = \begin{cases} \frac{0}{t^0} & \text{for } t \leq t_0 \\ u_0 e^{-\frac{t - t_0}{\tau_1}} - e^{-\frac{t - t_0}{\tau_2}} & \text{for } t > t_0 \end{cases}
\]

(11)
To approximate the shape of a lightning stroke (on bottom of Fig. 4) a number of predefined pulse shapes can be chosen as excitation in FEKO, e.g. a ramp function or a double logarithmic shape (as given in equation (11) and the lower part of Fig. 4).

For a rise time of $T_1 = 10\,\mu s$ and a fall time of $T_2 = 350\,\mu s$ the time constants can be set to $\tau_1 = 462.5\,\mu s$ and $\tau_2 = 5.45\,\mu s$.

In FEKO the impulse shape and its spectrum can be combined with the filter characteristic of the system sampled by FEKO in frequency domain. The program code FEKO has a built-in inverse Fourier transformation allowing the calculation of the resulting impulse (or pulse) response of the quantity being specified. This approach is needed for the cases b. and c. where the entire frequency response of the system must be calculated. In the case being considered the geometry is very small relative to the wavelength of the highest frequency in the signal spectrum. Hence case a. is valid. It is sufficient to run only one calculation at one specific frequency e.g. at the center of the bandwidth of the all-pass to determine the attenuation and delay.

### 3.4 Parameter Optimization

Another advantage of the software package FEKO is the possibility to define nearly all-geometrical and electro-magnetic parameters as a variable. The value of such a variable usually has to be fixed for one calculation. The values of distinct variables and the settings of subsequent calculations can be embedded into an optimization procedure, such that the value (or a set of values) of one ore more quantities from the output-file from FEKO can be extracted to calculate an aim-function. This can be used in conjunction with a standard optimizer (e.g. conjugate gradient or simplex algorithm) to determine a next value for the distinct variables. FEKO has a built-in-module for such optimizations for a number of predefined aim-functions among which are gain, pattern, impedance matching or field-strength shaping. FEKO also allows the user to embed it into a user-defined optimization algorithm (e.g. written in MATLAB/Simulink) to perform specific model optimizations.

### 3.5 Limitations

FEKO is a frequency domain solver and cannot take into account a hysteretic behavior of the ferrite body. This problem can be addressed by some worst-case studies in the frequency domain, however, a good knowledge of the materials and their influence on the current distribution is required. The frequency domain approach will also not allow an analysis of the influence of specific circumstances such as a shorting of the lighting strike by a burned insulation on the shape of the impulse response. However, it is possible to determine the maximum field strength at arbitrary positions enabling a determination of the probability and the position of such an event.

### 3.6 Time Domain Analysis

The transition from a harmonic CW-signal to a pulse or impulse signal can be performed in both the frequency domain (using a spectrum or spectral density) and the time domain (using the signal shape). The main requirement for such an approach is the linearity of the system. The Fourier transformation is commonly used to switch between these two domains.

### 4 Electromagnetic Simulation Results

The model in this study was directly transferred from a CAD-file. In a first step the model has been reduced to the relevant parts (e.g. without details as are screws or additional holders). In a second step the reduced model was meshed into triangular surfaces and wire segments. The cables and their end loads were entered in FEKO to set some material parameters. The detailed waveforms of the lightning currents and the corresponding magnetic fields are of interest.

With efficient measurement methods like the time-domain measurement principle [9] a deeper understanding of the lightning current influence on the electrical energy systems is possible.
4.1 Lightning Strike Current Density
In Fig. 6 the current distribution for a harmonic stimulus (f = 500 kHz) is shown.

4.2 Magnetic Field
The result of the numeric electro-magnetic field simulation is shown in Fig. 7.

5 Conclusion
The effects of lightning strikes on large wind turbine generators are discussed. Special attention is given to the transient electro-magnetic field distribution in areas close to the lightning current path. The method of moments is presented as one approach to solve transient electro-magnetic field problems. Basic requirements are geometrical, material data and excitation source waveform.

A commercially available simulation tool was evaluated. The tool was used to specifically analyze the electro-magnetic field distribution in the hub of a large wind turbine during a typical lightning strike. Initial results using this approach are encouraging; the validation of the simulation results using measurements will be discussed in a future publication.

A statistical risk evaluation method of damages to large wind turbine generators is also presented. A detailed electro-magnetic field analysis conducted for critical areas in the wind turbine in conjunction with a statistical evaluation of the lightning strike risks serve as a foundation to minimize hardware damage in wind turbine installations.

References: