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Fiber Optic Sensor Network for Lightning Impact Localization and Classification in Wind Turbines

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***Abstract*— As wind turbines are increasing both in number and in height, they are exposed to a major threat in form of lightning strikes. The protection of these structures from the effects of lightning is an important issue in today's wind turbine development. However, as lightning is random in nature, a complete protection against its damages is not achievable. The presented method for lightning impact localization and classification using a fiber optic current sensor network helps to detect damages caused by lightning and to monitor the blades. The system is connected to the wind turbine control and monitoring system.**

I. Introduction

The damages caused by lightning to a wind turbine (WT) are based on diverse effects. The lightning current, which can reach levels up to several hundred kA, and the related carried total charge heats up the materials and can so lead to structural damages, particularly in insulating components within the blades. Blade damages involve long down times and high costs. The current steepness is an important parameter with regards to the electromagnetic interference (EMI), which poses a major threat to sensitive electronic systems, e.g. the control unit.

Hence, the protection of WTs from the effects of lightning is an important issue in today's WT development. To prevent damage, they are equipped with a lightning protection system, as most modern buildings. The lightning's path is so predefined from the impact point in the arrester system to the grounding [1]. By using different kinds of receptors, the risk of lightning strikes in insulating materials should be reduced. But as the blade is an aerodynamic structure, the receptor configuration is limited by the blade specification.

To detect damages which cannot be totally avoided by the protection setup as soon as possible, lightning detection systems have been developed. For the forthcoming offshore wind parks, these lightning surveillance and control systems become of much higher importance as compared to WTs on land [2] as the dimension of the WTs increases in height, and maintenance takes more time and money because of the difficult access to the offshore facilities. The presented state of the art systems do not meet all the specifications for a remote monitoring of lightning events which not only register an impact but also measure the current lightning parameters and the local impact point on the blade. The used sensors represent local single-sensor applications.

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Therefore, a distributed sensor network has been developed, enabling online lightning impact localization and classification. One big problem using distributed sensors for lightning measurement is the EMI, which could destroy sensor elements or disturb the data communication. One solution was to use fiber optic sensors, which are EMI stable and allow an almost undisturbed communication over long distances. Further challenges in lightning measurements that have to be considered are the random parameters of lightning and the short unpredictable appearance.

The connection of the presented sensor system to other sensor networks, and the intelligent data fusion can lead to an increased performance. By connecting the lightning detection system to the central WT monitoring system, the causes of some electrical effects induced by lightning can more easily be related to the impact. Furthermore, by comparing online the measured results with the data from national lightning detection networks, like the European Cooperation for Lightning Detection (EUCLID) in Europe, the lightning parameters of interest could be verified.

II. Lightning Parameters

Lightning is random in nature. All known parameters are expressed in terms of degrees of probability from data measured in field. These may vary depending on the geographical conditions and the nature of lightning (negative or positive ground-to-cloud or cloud-to-ground stroke). Important lightning parameters are the peak current, the specific energy, the total charge, the average current steepness, and the number of current impulses of a lightning event. For lightning measurements, especially the average current steepness has influenced the used measurement equipment, because this parameter is responsible for the dimension of the magnetic induction in metallic wires and circuits [3]. Some guiding values can be found in [4] or [5], where its median value is given with $24.3\ \mathrm{kA}/\mu\mathrm{s}$, but it also may reach the value of $162\ \mathrm{kA}/\mu\mathrm{s}$ with a probability level of 5%.

Together with the peak current value, whose median value is $31.1\ \mathrm{kA}$ [5], the induced current and voltage drops across cable shield would make it impossible to use wired sensors in a WT blade. For the peak current, an empirical formula is proposed in [6] which relates the mean value of the absolute current peak I_m to the structure height h in meters. The formula is based on statistical analysis of lightning data obtained from 161 lightning protection installations on structures in Hong Kong, and is given by:

$$I_\mathrm{m} = 138\,(h/\mathrm{m})^{-0{,}46}\ \mathrm{kA}\,. \qquad (1)$$

TABLE I
PROTECTION LEVELS AND MAXIMUM VALUES OF LIGHTNING PARAMETERS [4].

Protection level	Peak current (kA)	Specific energy (kA)	Average rate of current rise (kA/μs)	Total charge transfer (C)
I	200	10000	200	300
II	150	5600	150	225
III	100	2500	100	150
IV	100	2500	100	150

Geographical conditions are not taken into account. This formula can only be used to get the approximate dimension of the mean value, knowing that the height of a modern WT is over 100 m, and does not give any information about the maximal value possible.

The protection levels define the electrical parameters which a lightning protection system has to divert without being damaged. These parameters are listed in Table I.

If parameters within a certain protection level are to be measured, a wide measurement range is necessary. The lightning with some kA should be captured as well as a maximum peak of 200 kA for the protection level I.

Other important parameters to design the lightning detection and measurement system are the front time, the time interval between the 2 kA point on the front and the first peak, and the stroke duration—the time interval between the 2 kA point on front and the 50% of peak current on tail. The front time can be estimated from the peak current and the average current steepness. In this time range, the local detection of the impact point should be executed. To ensure this, a sample rate of over 1 MHz is required, considering front times under 1 μs.

For the simulations and feasibility studies for the presented lightning detection method, two more lightning specifications are important: the current curve of a typical return stroke and the amplitude spectrum of this current pulse.

Several empirical equations have been proposed for the curve progression of the negative first stroke current, of which the following has been widely used [5]:

$$i(t) = \frac{I_{\text{peak}}}{\eta} \frac{k_{\text{s}}^n}{1 + k_{\text{s}}^n} \mathrm{e}^{-\frac{t}{\tau_2}} , \quad (2)$$

where I_{peak} denotes the peak current, η is a correction factor for the peak current, k_{s} is t/τ_1, n is the current steepness factor, and τ_1, τ_2 are time constants determining the current rise and decay times, respectively. The double-exponential function (3) has also been used to give an approximation of the transient current wave shape:

$$i(t) = \begin{cases} 0 & \text{for } t \leq t_0 \\ I_{\text{peak}} \left(\mathrm{e}^{-\frac{t-t_0}{\tau_1}} - \mathrm{e}^{-\frac{t-t_0}{\tau_2}} \right) & \text{for } t > t_0 \end{cases} . \quad (3)$$

This function can be found in FEM or MoM (Method of Moments) simulation programs as an already defined transient current stimulation [7], but as mentioned in [5], this function has a discontinuity of its first derivative at $t = 0$. Therefore, it is not convenient for the lightning electromagnetic impulse (LEMP) calculations. To use this function in simulations and to get more realistic current curves, as can be expected in a WT, an equivalent circuit diagram has been developed. The inductances and capacitances of the whole structure are simulated in this diagram to get the reflections from the structural discontinuities, especially ground reflections, and resonant effects.

The transient current impulses could not be realized by the MoM simulation so far. However, to get possible resonant effects in the structure and to get the near field in the blade, sinusoidal waves of different frequencies were used. To get the maximum frequency in the current of a blade, the amplitude spectrum of a lightning current pulse described in [8] (Fig. 1) was taken as reference, which shows a maximum frequency under 5 MHz.

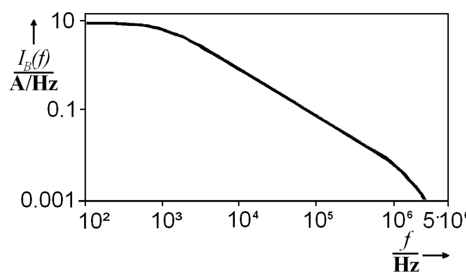

Fig. 1. Amplitude spectrum of a lightning current pulse.

III. STATE OF THE ART

Different Lightning Detection (LD) techniques exist depending on the application, which can be a global localization of lightning impacts or local lightning measurements to gain data to analyze lightning hazards.

Worldwide lightning detection systems allow to detect not only the impact point with a resolution of some 100 meters, but also yield an estimate of the peak value of the lightning current by analyzing the electromagnetic field [9]. These data are detected by electromagnetic antennas which send raw data to a central analyzer. Smaller and single-sensor applications are radio frequency detectors measuring the energy discharge from lightning by radiation.

On tall structures, like radio towers, different measurement concepts have been proposed to measure important lightning parameters, such as the current peak value, the current rise time, the maximal current steepness, and the total charge [10]. The return stroke current has traditionally been measured by installing transducers—e.g. differential or integrating Rogowski coils, shunt resistors, or current transformers—on the top or on the bottom of the towers [5], [11]. In all cases, the output signals are fed into a recording device to analyze the current curve.

Even if the sample rate and the dynamics of these systems are very high, a second method is often used to get the return-stroke peak value current. It consists of magnetic links, small bundles of high retentivity steel laminations, magnetized by the peak current flow close to these probes [5].

For LD in WTs, two commercial state-of-the-art systems can currently be found on the market. One of them works like the magnetic links. It consists of magnetic cards positioned in the blade or on other parts of the structure through which the lightning current passes. After a lightning impact, the cards can be read out manually by a card reader unit to get the current peak value. Originally developed by a German company for lightning monitoring in buildings, this system is not able to detect the number of lightning sequences striking the building between two card reading periods. An integration of this detection application into a condition monitoring system, existing in most WTs, is also not possible because of the manual card reading process.

Another LD sensor system, developed especially for WTs in a project headed by DEFU (The Association of Danish Energy Companies), is now supplied by a Danish company and used or tested in several WTs over the world [2]. This system will detect the lightning strikes using small antennas fixed on the body of the WT tower, where the lightning current passes and induces a field. The signals from antennas are transformed from an electrical signal to an optical signal, which is transferred via an optical fiber to a control box. The output of the control box indicates a lightning impact immediately. However, before another strike can be detected, the system has to be reset by an acknowledge signal.

IV. Fiber Optic Sensor Network

A. Fiber Optic Current Sensors (FOCS)

Two different technologies for FOCS, based on different physical effects, are known. One solution exploits magnetostriction, but has never been used commercially [12]. The second one is based on the Faraday effect, where the external magnetic field of a current induces a rotation in the plane of polarization of linearly polarized light propagating in the fiber. The rotation is detected by using polarizers and analyzers at the input and output of the material, respectively. By monitoring the rotation of the incident polarization state, a direct measurement of the magnetic field intensity can be inferred. The relationship governing this phenomenon is best stated as:

$$\Theta(\lambda, T) = V(\lambda, T) \int H \, \mathrm{d}l \,, \tag{4}$$

where Θ denotes the measured angle of rotation of the field, λ the free space wavelength of light, T the ambient temperature, V Verdet's constant of the magneto-optic material and H the magnetic field intensity along the propagation path l. The Faraday effect is illustrated in Fig. 2. All crystalline materials exhibit the Faraday effect, but its magnitude varies greatly and may be enhanced by choosing a sensing element with a large Verdet constant. Currently, fibers with a quite large Verdet constant exist, but a long propagation path l is necessary to obtain measurable effects.

Depending on the applied optical materials, two different configurations based on the Faraday effect are commercially available. One solution works with an optical fiber wounded around the conductor [13]. The angle Θ, through which the polarization plane of light rotates in the fiber in the presence of a magnetic field induced by the current I in the wire, is given by [14]:

$$\Theta = VNI \,. \tag{5}$$

To achieve a high signal-to-noise ratio in the output signal, several turns N of the sensing fiber around the current carrying wire are needed, and different optical paths and light rotation detection methods have been developed to eliminate external effects.

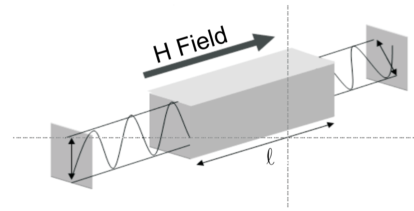

Fig. 2. Principle of Faraday rotation.

Another configuration works with optically transparent ferromagnetic crystalline materials featuring a large Verdet constant and hence a bigger sensitivity due to an increased rotation angle per length l. An advantage of this system is that the sensor head is very small and can easily be added to any existing structure, but it will measure the resulting magnetic field parallel to the light propagating in the crystal.

B. System Configuration

Today, WT blades can reach up to 60 meters and are mainly made of glass-fiber reinforced plastics. The generic problem of lightning protection is to conduct the lightning current safely from the attachment point to the hub such that the formation of a lightning arc inside the blade is avoided. This can be achieved by diverting the lightning current from the attachment point on the surface to the blade root, using metallic conductors either fixed to the blade surface or inside the blade. Different solutions for lightning protection of WT blades are presented in Fig. 3.

For lightning protection systems which are using only one down conductor, a magnetic field induced by lightning current will surround this arrester. For low frequencies, the near field can be calculated by Biot-Savart's law:

$$\mathrm{d}\vec{H} = \frac{I \, \mathrm{d}\vec{l} \times \vec{r}}{4\pi r^3} \,, \tag{6}$$

where $\vec{H}$ denotes the magnetic field, I the current in the wire segment, $\mathrm{d}\vec{l}$ the length element of the wire, and $\vec{r}$ the displacement vector from the element to the field point.

Fiber optic current sensors surrounding the conductor or placed near it can detect this magnetic field. Depending on the chosen FOCS, the field at a certain point or the circular field along a fiber can be measured. Sensors using winded optical fibers as a measurement unit will only detect the current in the arrester passing through the fiber coil without disturbances from other current sources. Since most

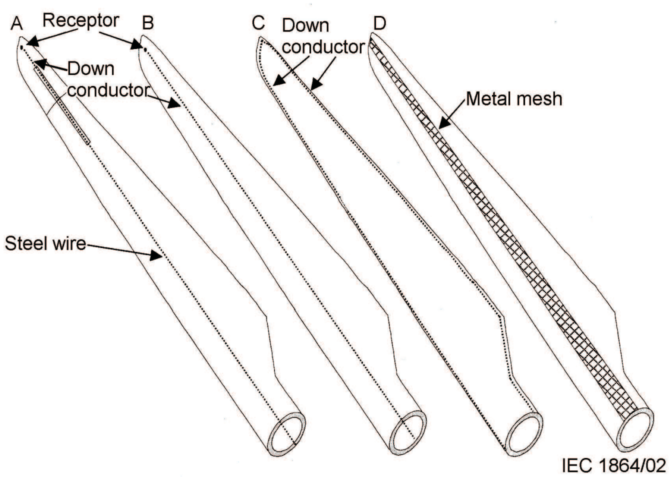

Fig. 3. Lightning protection for large modern wind turbine blades [14].

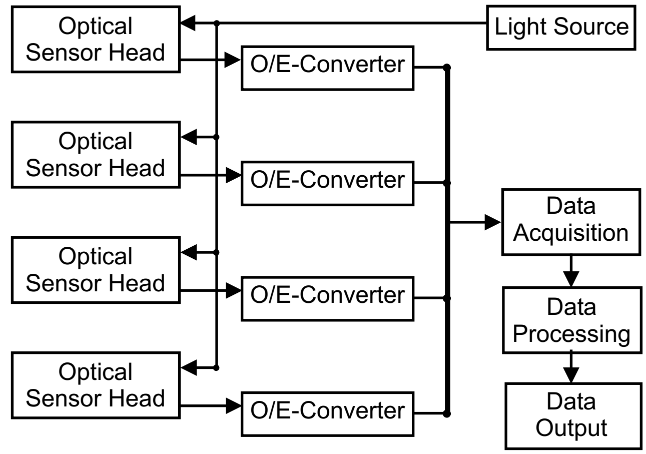

Fig. 4. Lightning detection sensor network configuration.

arresters are fixed on cross members, an installation of these sensors into an existing structure would imply an additional complexity.

A better solution is to use Faraday rotating sensors working with ferromagnetic crystals. Furthermore, such sensors can also be applied to newly developed blades without central arresters, as they measure the resulting magnetic field at the installed point. Even if the sensor system is designed for a certain maximum current, the induced magnetic field of the over-current will not destroy the fiber-optic sensor but lead to incorrect outputs. Regarding the requirements for WTs, lightning measurements and the commercial availability of FOCS, those using crystals were chosen for this application [15]. They can measure magnetic fields up to 150 mT.

To extract the lightning parameters, one sensor at the bottom of the blade would suffice. However, to achieve a higher reliability and a localization of the impact, a sensor network is needed. For this reason, a network of sensors with a sampling rate of 2 MHz was prepared. To get the lightning parameters, the digitized lightning impulses can accurately be represented by mathematical functions, and the variables of interest can then be derived mathematically [10].

The lightning impact point is detected by the sensor network installed in each of the blades (Fig. 4). To determine the optimal distance between adjacent sensors and to get the different parameters on which the resolution of the localization depends, the following worst case has to be considered. A lightning stroke hits near a sensor in the middle of a blade. The next sensor positioned in the direction to the top of the blade should just get no measurable field. The maximal distance between these sensors is given as:

$$d = \mu \frac{I_{\min}}{2\pi B_{\min}}\,, \tag{7}$$

where μ denotes the permeability, $I_{\min}$ the minimal lightning current to be detected for localization, and $B_{\min}$ the minimal magnetic induction measurable by the current sensor.

The number of sensors needed strongly depends on the minimal lightning current $I_{\min}$ that is to be detected by the next sensor located in the top side of the blade. As damages on WTs are caused above all by the first impulse current and the long-duration current [16], the critical intensity must be known. A detection of low-intensity lightings would otherwise only lead to a huge and unadjusted sensor network. An important feature of this network is that all sensors within a blade are triggered and sampled simultaneously. Due to possible current reflections in WTs [17], the localization has to take place during the current rise time. According to simulations, sample rates of at least 2 MHz are necessary to extract the parameters of interest.

The light source and the data processing unit for the presented sensor system in WTs is to be located in an electromagnetically isolated place in the hub. A suitable place is the pitch control box, in which additionally an emergency power supply is available. Only if a lightning stroke is captured, the corresponding data are stored and are then sent to the WT's controller system.

C. Data Processing and Fusion

The fiber optic sensor network in the WT blades can be divided into subnetworks, each one consisting of several fiber optic sensor heads and a data acquisition unit that samples all sensors simultaneously; see Fig. 4. The signal processing, the data handling, and the data fusion are the same for each subnetwork and are accomplished by a single central system. The aim of the data fusion is not only to determine the impact point of lightning strikes but also the parameters describing the lightning current, such as the peak current, the current steepness, and the total charge transferred. Additionally, a classification of the detected lightning impacts is to be performed to determine whether a defect has likely occurred as well as its severeness.

Each sensor has its own data acquisition channel. The data recording unit consists of an optical to electrical transducer and a sampling unit with an analog to digital converter. The sampling frequency is 2 MHz.

To perform an optimal fusion in a Bayesian sense, the measurement error has been modeled [18]. Its distribution

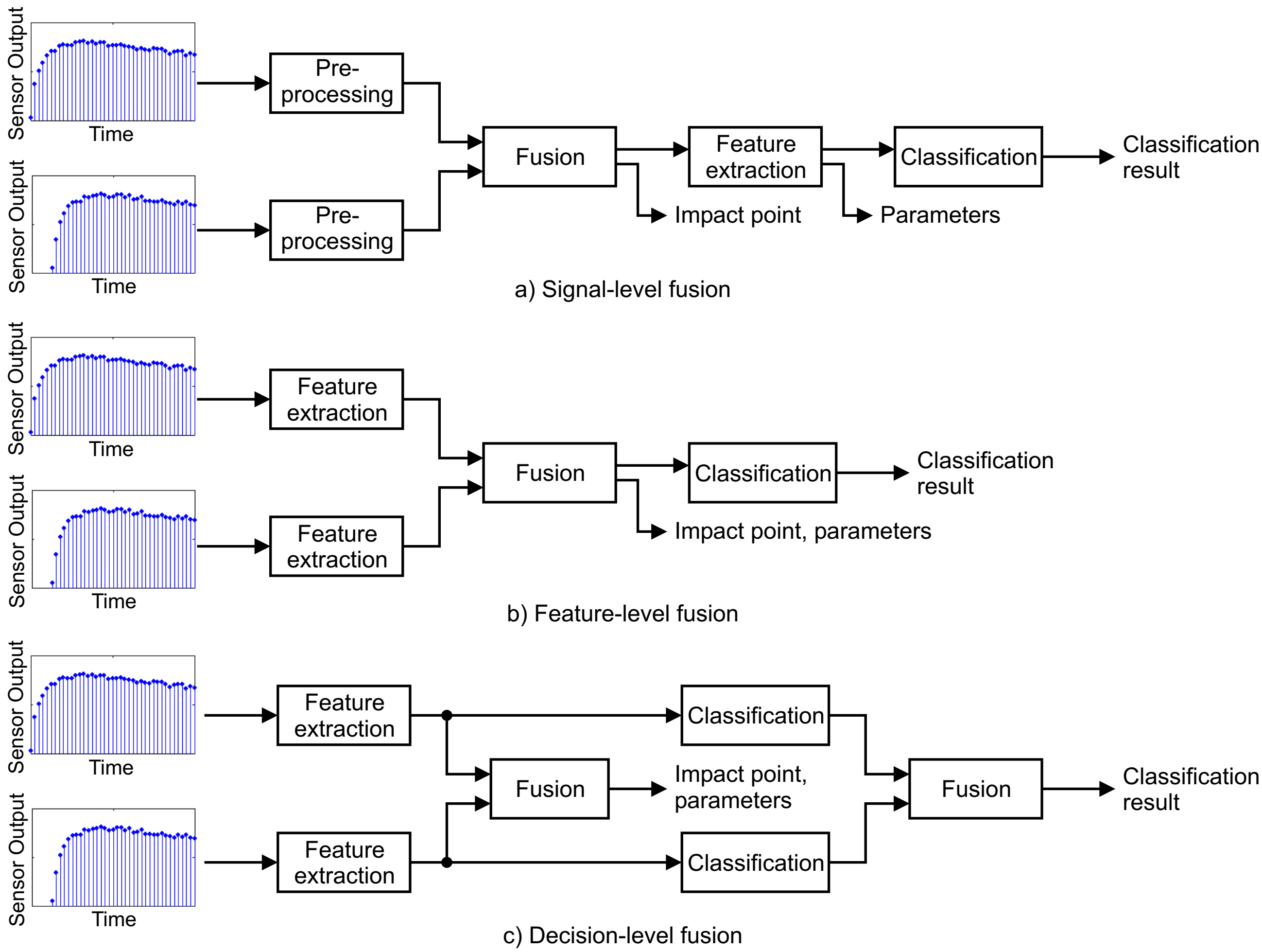

Fig. 5. Fusion of the sensor data at different levels of abstraction.

is a function of the lightning current itself. Depending on the abstraction level at which the data are combined, three different fusion architectures have been investigated; see Fig. 5.

- At the lowest level of abstraction, the simultaneously measured signals are combined by means of a weighted superposition for each point in time; see Fig. 5(a). To avoid destructive interferences of the signals due to different signal propagation paths, an alignment of the signals is to be performed before in a preprocessing step.[1] The fusion delivers information on the impact point as well as an enhanced signal describing the lightning current in the respective blade. Thereafter, the parameters of interest are extracted from this signal by the data processing unit, and a classification is accomplished.
- The second architecture performs a feature-level fusion; see Fig. 5(b). In this case, the signal descriptors are directly extracted from the different signals measured and are then combined at a feature level. Following, the same classification takes place as in Fig. 5(a) based on the extracted features. Since the fusion takes place at a feature level, an alignment is not necessary in this case.
- Figure 5(c) presents a strategy to perform the fusion at the highest level of abstraction. Here, the output of each sensor is separately subject to a feature extraction and a classification. The fusion is performed at a decision level and yields the wanted information on potential defects. To determine the impact point and the lightning parameters, an additional feature fusion is performed similar to Fig. 5(b). This results in a multi-level fusion approach.

Independently of the architecture used, the lightning detection and classification parameters are computed and stored in the data processing unit. Only when a lightning strike is detected or the system experiences an error, the controller of the turbine is notified. The controller downloads then the stored data.

[1]The lightning impulse moves approximately with the speed of light from the impact point to the grounding system [19]. Thus, the current measured at different points of the down conductor can vary significantly, if an time alignment is not performed. E.g., for two sensors at a distance of 30 meters, the traveling time of the impulse is about 0.1 μs.

To enhance the lightning detection system, new sensors can be connected to the existing sensor network. Lightning warning field mills could measure the electrical field caused by thunderclouds and activate the lightning detection system only if an increased risk of lightning exists. In addition, collaborations with the national lightning detection networks could be used to synchronize the lightning parameters as the peak current.

V. Simulation and Results

The three presented data fusion models were tested with simulated sensor data. Different lightning current pulse shapes as well as different blade impact points with variable blade angle positions have been used to get a wide range of possible data. Four fix sensor positions in the blade have been chosen to simulate the sensor output with a superposed Gaussian noise.

In the feature-level and the decision-level fusion, the feature extraction and the parameter estimation are the same. However, for all models the relative error of all calculated parameters and of the impact point localization show a dependency on the impact point. In Fig. 6 the relative error of the calculated peak current of a lightning stroke has been simulated for different impact points. Since for the data fusion at least two sensors have to register the whole lightning current, the parameter calculation is only possible between the tip and the second sensor from the bottom of the blade.

Fig. 6 also shows that the signal-level and the feature-level fusion model work in the same accuracy range. One difference between the two models is the data processing time: currently, the signal-level fusion is 50% faster than the two other models.

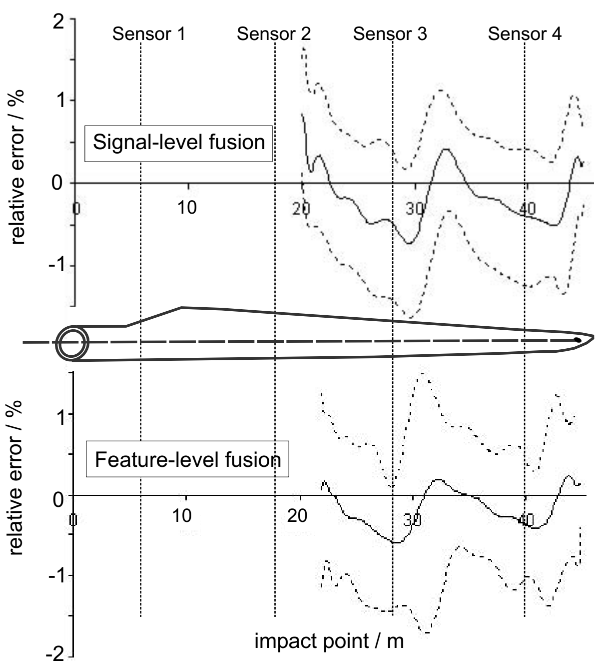

Fig. 6. Accuracy of the current peak measurements depending on the lightning impact point.

VI. Conclusion

The presented fiber optic lightning detection network shows that, by using a sensor network, it is possible not only to precisely determine the parameters of lightning strikes, but also to localize the impact point. The selection of adapted data fusion algorithms and a compatible hardware are fundamental to improve both the performance and resolution of existing lightning detection systems. Furthermore, the connection of additional sensors to the presented network will lead to a more reliable and accurate monitoring system.

VII. Acknowledgments

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