Note:
This is a translation of the RSK statement entitled “Blitze mit Parametern oberhalb der genormten Blitzstromparameter”. In case of discrepancies between the English translation and the German original, the original shall prevail.

RSK Statement
(488th Meeting of the Reactor Safety Commission (RSK) on 03.11.2016)

Lightning with parameters above the standard lightning current parameters

1 Background

In accordance with the RSK Statement "Assessment of the coverage of extreme weather conditions by the existing design" [1] and following international developments (ENSREG, RHWG/WENRA), proof is to be furnished that weather conditions with a recurrence frequency of 10^{-4}/a are controlled as per design. If the influence of weather conditions in this frequency range cannot be ascertained with sufficient reliability, engineering evaluations are be used to show deterministically that the effects of these weather conditions are safely controlled. Considering robustness, it was suggested in addition to take into account events with further-reaching impacts by applying engineering judgement to determine safety margins.

The RSK asked the Committee on ELECTRIC INSTALLATIONS (EE) for corresponding consultations on the topic of lightning.

2 Consultations

In order to clarify the above questions, TÜV SÜD IS was asked to provide information. This reporting took place at the 231st meeting of the EE on 18.09.2013 [2]. By a letter dated 20.11.2013 [3], VGB was asked for further information (see also 233rd meeting on 20.11.2013). At the 239th meeting on 27.08.2014, the Committee had information provided by VGB on the current status of the lightning protection and grounding concepts as well as on the interference voltage strength of the instrumentation and control (I&C) systems used [4]. In a letter of 01.09.2014 [5], the Committee specified its questions to VGB. At the 240th meeting on 23.09.2014, the expert Prof. Kern, who was consulted by VGB, presented the initial situation and the possible effects of lightning with parameters above the standard lightning current parameters [6].

The Committee then asked that the qualitative assessment presented in the expert's lecture be used to furnish quantitative proof that the design according to KTA 2206 [7] also includes the control of lightning effects with a recurrence frequency of 10^{-4}/a [8]. This proof could be furnished as an example for the nuclear power plant site with the highest lightning density and should focus on the two relevant lightning current parameters (peak current and current gradient). The results were presented to the Committee at the 249th meeting on 11.02.2016 [9]. At the 253rd meeting on 07.09.2016, the Committee summarised the results in a draft statement and submitted this to the RSK for approval at the 488th meeting on 03.11.2016.

3 Basics

3.1 Physical background

3.1.1 Lightning discharges

Thunderstorms occur when warm air masses with high humidity are transported at high altitude. A distinction is made between heat thunderstorms (heated ground), multicell cluster storms (cold fronts) and orographic thunderstorms (rising terrain). Due to the high vertical velocities within the thunderstorm clouds, charge separation occurs (positive charge in the upper region, negative charge in the lower region of the thunderstorm cloud). A lightning flash is a potential equalisation within the cloud (intra-cloud lightning) or between the ground and the cloud (cloud-to-ground lightning). This potential equalisation takes place via a channel of ionized air (a so-called leader) generated by the lightning. As regards the question presented to the EE Committee, the relevant lightning flashes were cloud-to-ground lightning flashes, with negative cloud-to-ground lightning flashes making up approx. 90% and positive cloud-to-ground lightning flashes approx. 10% of the number of cloud-to-ground lightning flashes [2]. Since the positive cloud-to ground flashes originate in higher cloud layers and thus require longer leaders, they also tend to have higher peak currents [12]. Several subsequent current impulses of different intensities may flow through the leader that has been produced by an initial strike, in particular in the case of negative lightning strikes (subsequent strikes). Since here the leader is already present, these flashes reach the steepest current gradients.

3.1.2 Lightning protection standards

The lightning protection standards define a total of four lightning protection levels with the corresponding parameters to cover natural lightning events. For example, the highest lightning protection level covers 98% of all natural lightning events; 1% are lightning flashes with lower and 1% with higher parameters. The lower 1% are irrelevant from a safety-related point of view.

KTA Safety Standard 2206 [7] lists the lightning current parameters that correspond to the parameters of the highest lightning protection level of DIN EN 62305-1 Ed.2: 2011-02 [10]. For the definition of the lightning strike locations and lightning-strike-protected areas, KTA 2206 stipulates that the rolling-sphere method with a radius of 20 m be applied for the design of capture devices (exterior lightning protection). Irrespective of that, lightning strike with a maximum peak current of 200 kA (positive initial lightning strike) and a maximum average current gradient of 200 kA/µs (negative subsequent lightning strike) is assumed for each building for the design of equipment (interior lightning protection).

3.1.3 Standard lightning values and "natural upper limit"

Of the four effect parameters of a lighting current, it is the lightning peak current (also referred to as the maximum current value) and the average current gradient that are relevant for the impact on electrical systems in nuclear power plants. The other two parameters, impulse charge and specific energy, are essential for the design of the exterior lightning protection systems [2], [6].

The peak current results from ground potential rise. Lacking potential equalisation will lead to a flashover (lightning strike). The average current gradient describes the temporal change of the current between 10 % and 90 % of the current's rise. Both parameters determine the height of the electromagnetically induced voltages in open conductor loops and, for electromagnetically induced currents, in closed conductor loops. This applies to overvoltages in the conduit systems in interior as well as in exterior areas of the installation, depending i.e. on the quality of the shielding of the structural components (buildings, cable ducts) and the cables.

The lighting protection standards define an average current gradient, with the value of the current gradient averaged over a relatively long period of time (several 100 ns). The maximum value of the current gradient may be higher for a short time. Steep current gradients with values in the area of > 100 kA/µs generally only occur in the case of (negative) subsequent lightning strikes. The maximum value specified in KTA 2206 for the average current gradient of 200 kA/µs is derived for negative subsequent lightning strikes from a current rise to 50 kA over a period of 250 ns.

Studies of lightning strikes with high peak currents are still the subject of research. In addition, the data base of current lightning research is unsatisfactory. In the following section, statements from different sources are presented.

The standard values for lightning peak currents for Central Europe are based on the CIGRE statistics [1] .

According to the CIGRE report, no peak currents > 300 kA for direct lightning strikes have been verifiably documented in direct lightning measurements worldwide. What is internationally acknowledged is the fact that ≤ 10 % of all lightning flashes of the positive initial lightning strike have a standard peak current of > 200 kA. According to one source, values > 200 kA only occur during winter thunderstorms in Japan [9].

In the case of negative lightning strikes, the maximum value lies at < 200 kA. Approx. 90 % of the lightning strikes are negative and approx. 10 % positive; hence, for all lightning flashes there is an occurrence probability of < 1 % for peak currents of > 200 kA. Owing to the very small number of direct lightning measurements and the associated large statistical uncertainty, an extrapolation of this parameter to the range of values verified by measurements is scientifically unsustainable.

Now that lightning detection systems (e.g. BLIDS by Siemens AG[2]) are installed all over the world, results showing peak values of > 500 kA have from time to time been reported from these systems in recent years. However, in some publications (e.g. [12]-[15]), these values have been strongly questioned. Several authors have therefore attempted to determine natural upper limits for lightning peak currents with mathematical-physical models. A maximum peak current of 450-500 kA for tropical areas and 300 kA for temperate zones was derived, based on measurements carried out by Berger [16] and the determination of a maximum electric field above ground (150 kV/m) [15]. According to [9], these limits apply to positive as well as negative initial lightning strikes. Owing to the model assumptions, these values only apply above large surfaces of water (oceans). In vegetated and/or built-up areas, the maximum electrical field is reduced (corona effect), which causes the maximum peak current to decrease.

A corresponding derivative for a natural upper limit for the current gradient is not known from the literature.

3.1.4 Rolling-sphere method and dynamic electro-geometric model (DEGM)

The calculations listed in the standards are based on the electro-geometric model (rolling-sphere method). The model is based on the assumption that the leader head approaches the objects on earth up to breakdown distance. What happens then is that a connecting upward "leader", similar to the downward leader, grows towards the leader's head. The higher the charge in the downward leader, the earlier will the upward leader connect, and the longer is the striking distance. The latter corresponds to the radius of the rolling sphere, whose centre represents the leader's head. The higher the charge of the downward leader and thus the higher

[1] CIGRE-Report: „Lightning parameters for engineering applications" Report No. 549, August 2013. IISBN 978-2-85873-244-9
[2] http://www.industry.siemens.com/services/global/de/blids/seiten/default.aspx

the lightning peak current, the more likely will lightning strikes into exposed locations of a structural component have to be expected. These exposed locations are usually protected by means of lightning rods that have high lightning capture effectiveness. However, in line with the most stringent requirements of the conventional DIN EN 62305 regulations, KTA 2206 demands that the strike locations should be determined according to the rolling-sphere method with a sphere radius of 20 m.

In supplement to the classic rolling-sphere method, the dynamic electro-geometric model (DEGM) uses varied radii of the rolling sphere (Collection Surface Method) [9] instead of rolling spheres with constant radii. This method uses results that have been acknowledged in international standards, physical basics and studies related to lightning (e. g. lightning statistics from the CIGRE report), and a numerical method is developed on this basis. The empirical formula derived from the rolling-sphere model is applied to the discretised total volume above the built-up areas for various volume points [9]. This way, the probability of a lightning strike in a specific location of a structural component as well as the maximum possible peak current values in this location there can be derived from the DEGM.

3.2 Voltage calculation

3.2.1 Dielectric strength of the I&C systems

When the German nuclear power plants were built, the dielectric strength of the installed I&C systems was not explicitly specified. For the I&C equipment, there were requirements for protection against galvanic, capacitive or inductive coupling. At a later stage, the EMC requirements specification of VGB "Nachweisführung Elektromagnetische Verträglichkeit für Altsysteme der Leittechnik" (VGB requirements specification) was initiated, which represents an EMC analysis with plausibility and EMC tests with regard to dielectric strength for the "legacy I&C systems" in operation in the plants (I&C systems used in the construction of the German nuclear power plants). Requirements for furnishing such proof are described in KTA 2206 and in DIN EN 62305-2:2013 [11]. It is postulated that the legacy I&C systems will be able to cope with a coupled longitudinal voltage of up to 500 V. Proof of a dielectric strength of 500 V[3] has been furnished by testing for a representative I&C equipment module of the legacy systems [4].

For more recent I&C systems (from TXS/TXP and others), the proof of EMC (incl. dielectric strength > 500 V) had already been part of type-testing.

3.2.2 Basics of voltage calculation

Lightning strikes lead to voltage loads on electrical and electronic devices. Regarding the I&C equipment in nuclear power plants, the following four cases have to be distinguished:

- voltages inside buildings that are struck directly by the lightning,
- voltages inside buildings caused by lightning strikes close by,

[3] corresponds to testing accuracy level 1 according to DIN EN 61000-4-5 *„Elektromagnetische Verträglichkeit (EMV) - Teil 4-5: Prüf- und Messverfahren - Prüfung der Störfestigkeit gegen Stoßspannungen"* (Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test.

- voltages on cable sections in cable ducts,
- voltages in shielded ground-routed cable trays.

Inside buildings, the voltages induced magnetically in cable loops must be considered. To do so, the current gradient is to be used as a determining lightning current parameter. Both in the case of direct lightning strikes and in the case of flashes of lightning close by, a lightning striking into a building structure has to be assumed. Due to the structural resonance of the buildings, the steep current gradients are attenuated. According to KTA 2206, an inadmissibly high lightning-induced voltage coupling in the cable sections within the buildings need not be assumed if the shielding of the buildings and the routing and shielding of the cables are implemented in accordance with KTA 2206.

In cable ducts, the cables are located in a shielded environment due to the steel-reinforced concrete structure. In this case, the cable ducts are routed with direct contact to the ground, i.e. when a lightning strikes, the lightning current is dissipated through the ground. Cable trays, especially if covered, act as a further shielding and thus increase protection. KTA 2206 contains calculation instructions for possible voltage inputs into I&C cables in cable ducts. High-frequency lightning impacts of negative initial lightning strikes and/or negative subsequent lightning strikes represent the highest relevant loads. Based on the postulated maximum average voltage gradient according to KTA 2206 (200 kA/µs for negative subsequent lightning strikes or 100 kA/µs for negative initial lightning strikes), voltages in the range from a few 10 V to a few 100 V are usually determined in such cable routes.

An ground-routed cable tray, on the other hand, is usually a PVC/PE pipe in which the cable(s) with cable shield are located. The cable shield is connected at both ends with low impedance to the building reinforcement. Along the cable, no significant current can flow to the ground due to the PVC/PE pipe insulation. Hence high-frequency lightning currents do not play a role since cable trays act like a low-pass filter due to the high inductance. Regarding cable trays, the maximum lightning peak current is therefore to be considered as potential impact. In KTA 2206, only the positive initial lightning strike is used for the calculation as this causes the highest voltage inductions in the cable due to the highest peak current. Here, the induced voltage is directly proportional to the peak current.

4 Justification of the underlying limit values

Due to the insufficient data base, it is not possible to empirically determine the relevant lightning parameters for lightning strikes with an occurrence frequency of 10^{-4}/a (see section 3.1.3). According to WENRA, it is alternatively suggested that if effects in this frequency range cannot be ascertained with sufficient reliability, the reliable control of such events as well as a high degree of robustness should be demonstrated by means of engineering judgement.

According to the RSK, a natural upper limit of a lightning peak current of 300 kA may be assumed in temperate zones on the basis of the available measurements, observations in temperate zones, and theoretical studies. This corresponds to 1.5 times the value of the maximum peak current defined in KTA 2206. Such a natural upper limit is not known for the average current gradient. For the further consideration, in analogy to the peak current, the maximum average current gradient was increased by 50% compared to the value of the KTA standard, i.e. to a value of 300 kA/µs.

5 Concrete considerations using a reference plant

The methods described were applied to a concrete NPP. As reference plant, the plant which due to its geographical location has the highest lightning density (about 3.6/(km²*a)) of all German NPP sites was chosen. With the area of the nuclear power plant being approx. 0.44 km², 1.6 lightning strikes per year are expected. In a conservative approach, the calculations did not consider the possible protective effect of buildings not belonging to the plant under consideration.

For the following consideration, it is assumed that the reference plant is equipped with shielding in accordance with KTA 2206. Therefore the induced voltages in the interior of the buildings caused by direct or nearby lightning strike were not considered.

The I&C cables to be examined were chosen under conservative aspects (with regard to cable lengths and installation method). For these cables, the maximum lightning-induced longitudinal voltages for the standard lightning current values (200 kA; 200 kA/µs) and also for the increased lightning current values (300 kA; 300 kA/µs) derived above were calculated.

For the considerations regarding EMC verification, the I&C equipment cable routes that were studied were those in cable ducts and in ground-routed cable trays in the area of the unit buildings or within the protected area and also leading to peripheral buildings outside the protected area. The object of the study was to look at to what extent there is still a margin to the demonstrated dielectric strength of 500 V of the I&C equipment in case of a lightning strike due to the induced longitudinal voltages at the outgoing cable sections (cable ducts and ground-routed cable trays).

The individual buildings were modelled and the lightning strike probabilities and intensities were calculated according to DEGM [9]. This model was used to determine both the probability of a lightning strike into a particular building and the maximum possible peak current per building. For the peripheral buildings (service water intake structures 1UPD and 2UPD as well as essential water pump building 2UQB), the lightning probability was determined according to DIN EN 62305-2: 2013 [11], and the maximum lightning peak current was assumed to be 300 kA as there are no protective buildings around.

The tabular compilation in [9] shows the stack (UKH), the cooling tower (URA) and the turbine building (UMA) as well as the peripheral auxiliary service water buildings (1UPD, 2UPD and 2UQB) to be the structures that will most likely be struck, with a lightning peak current of > 200 kA. All other buildings (storage buildings, other supply buildings) for which lightning peak currents of > 200 kA have been determined have no safety significance. As expected, the stack (N_D[4] = 0.4/a) and the cooling tower (N_D = 0.8/a) can most often be struck by lightning.

Furthermore, voltage calculations were carried out on I&C cables in cable ducts and in ground-routed cable trays.

Regarding lightning-induced voltages in I&C cables in cable ducts, the calculation is carried out according to KTA 2206 (methodology and maximum values). Within the scope of the implementation of KTA 2206 in the reference plant, voltage values <100 V, i.e. far below the dielectric strength resistance of the I&C systems, were determined for all cables in the cable ducts [17]. Even when values for the lightning peak current and the current gradient are increased by 50%, there are no intolerably high voltages in the I&C equipment.

Regarding the shielded cables in ground-routed cable trays, at least one ground-routed cable tray was selected under conservative aspects for the analysis of each building with safety-relevant equipment. Particularly important are long cable routes with ground-routed cables. For this purpose, a table was drawn up which shows the length of the cable routes between the individual buildings. Using these cable lengths and the maximum current value of 200 kA, the longitudinal voltages were determined according to KTA 2206 for the cable routes between buildings containing safety-relevant equipment. Longitudinal voltages of > 500 V were determined for six cable routes (eight cable routes with assumed peak current values of 300 kA).

Subsequently, the longitudinal voltages were determined, using the maximum peak current (up to 300 kA) of the buildings determined according to DEGM. With this approach, it was found that the coupled longitudinal voltages exceed the value of 500 V in only four cable routes.

VGB pointed out that the need for the retrofitting of surge protection devices had already been recognised before. This need has been confirmed by the analysis. In this case, two of the four cable routes contain safety-relevant I&C cables of the accident monitoring system that are relevant i.e. for the measuring of the total activity output and the monitoring of the temperature in the pump chambers of the service water system. For the measurement of the total activity output, the operating manual specifies substitute measures in case of a failure. In all, the affected cables are important in terms of safety, but are not relevant with regard to maintaining vital functions.

It has to be pointed out that the excess voltages in these cables already resulted when applying the standard lightning parameters according to KTA 2206.

6 Assessment

6.1 Reference plant

The choice of the reference plant is comprehensible from the point of view of the RSK due to the geographical location (high lightning density) and the area of the plant. The method of furnishing proof, based on the deterministic design according to KTA 2206 with the specified standard parameters, supplemented by the use of variable rolling-sphere radii (as also used in DEGM) with lightning parameters up to the set upper limits, is comprehensible from the point of view of the RSK and corresponds to the state of the art in science and technology.

In the case of voltages in I&C cables in cable ducts, the calculation was carried out according to KTA 2206. For the reference plant, this resulted in longitudinal voltages of <100 V for all kinds of lightning. It is thus possible to assume that only tolerable voltages (< 150 V) will occur in the I&C equipment, even if higher lightning peak currents are used for the positive initial lightning strikes and steeper current gradients are applied to the negative subsequent lightning strikes.

In the case of the ground-routed cable trays, the permissible values of the coupled longitudinal voltages were exceeded in four cable routes. These excess values had already been obtained when using the maximum peak currents according to KTA 2206 (200 kA).

As for the reference plant, it was shown that by fulfilling KTA 2206, it was also possible to demonstrate the control of lightning strikes with parameters with the underlying upper limits while simultaneously applying variable rolling-sphere radii.

The value of the average current gradient is irrelevant under the conditions of the reference plant. In the considerations, the "natural upper limit" according to [9] was used as the maximum peak current. Provided that the surge protection devices are retrofitted in the identified cable routes, compliance with the limit value of dielectric strength can be shown for all safety-relevant I&C cables. On this understanding, the safe control of events from a deterministic point of view as well as a high degree of robustness can be attested to the reference plant.

6.2 Recommendation

A general application of the results of the analysis of the reference plant to other plants is not possible from the point of view of the RSK. The question of whether higher voltages than in the reference plant would be induced in case of any postulated lightning strikes into plants that e. g. do not have a cooling tower requires a system-specific analysis in the opinion of the RSK. In the analyses, magnetically-induced voltages inside the buildings have to be taken into account unless buildings are equipped with shielding according to KTA 2206. It also showed that the layout, number and length of cable ducts or ground-routed cable trays are also of decisive relevance for the verification.

Since the effects of lightning strikes within the frequency range up to 10^{-4}/a cannot be ascertained with sufficient reliability, the reliable and robust control of such impacts is to be shown deterministically by engineering assessments. The RSK recommends in addition to the requirements of KTA Safety Standard 2206 to furnish proof that lightning strikes with lightning parameters of the set upper limits (300 kA; 300 kA/µs) are controlled. This can be done either on the basis of the calculation specifications of KTA 2206 or alternatively by means of variable rolling-sphere radii.

7 References

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