Key Issues in Lightning Protection of Wind Turbines

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Abstract: - Lightning damage to wind turbines has been one of the main causes of wind power outages. Wind turbines are steadily growing in both height and numbers explaining why an increased frequency of lightning damage is observed. This coupled with the costs of repairing such large wind turbines increased the need for a form of lightning protection system standardisation within the wind power industry. This paper presents an overview of selected parts of the latest IEC 61400 standard dealing with lightning protection of wind turbines. Particular emphasis is given to wind farm grounding systems.

Key-Words: - Lightning protection, wind turbines, risk assessment, safety, grounding.

1 Introduction

Modern, large wind turbines have a rated power in the order of 1 MW to 3 MW, typical hub height in the range of 50 m to 100 m and blade length greater than 30 m. The large size and the placement of wind turbines in often isolated, mountainous conditions results in an increased number of lightning strikes. Furthermore, lightning damage to a wind turbine results in wind power outage and probably expensive repairs.

A typical wind turbine is shown in Fig. 1. Its lightning protection has to deal with problems not normally seen with other structures. These result from the following:

- Wind turbines are tall structures of up to more than 150m in height. They are also frequently placed at locations very exposed to lightning strokes.
- Their most exposed components such as blades and nacelle cover are often made of composite materials incapable of sustaining direct lightning strike or of conducting lightning current.
- The blades and nacelle are rotating
- The lightning current has to be conducted through the wind turbine structure to the ground, whereby significant parts of the lightning current will pass through or near to practically all wind turbine components.
- Wind turbines in wind farms are electrically interconnected and often placed at locations with poor grounding conditions.

Protection of the wind turbine that uses insulating material for the blades and sensitive electronic systems for control purposes is necessary for reliable operation. Other considerations include risk assessment, bearing/gearbox and electrical/control system protection. This paper presents an overview of these issues, as detailed in the last IEC 61400 standard [1] dealing with lightning protection of wind turbines and the research conducted within the EU R&D project JORJ-CT95-0052, JORJ-CT98-0241 [8]. A key issue in lightning protection is the effective design of windfarms grounding systems. This is particularly discussed at the end of the paper.

2 Damage Statistics

Several countries, like Germany, Denmark and Sweden, U.S.A. operate database reporting systems where lightning incidents can be collected [2][3] and [4].

Table 1 gives an overview of the data relating to lightning damage frequency collected in these databases. It summarises the lightning faults per 100 turbine years for a minimum six year period. It is clear that the greatest number of faults per hundred turbine years occurs in Germany. This is in agreement with the increased average ground flash density in Germany.

Not shown in the table is the percentage of lightning faults that are caused by direct or indirect strokes. The German database suggests that 70% of all lightning faults are caused by indirect lightning strokes. Indirect lightning damage is likely to affect the wind turbine electronics that control the wind turbine operation and the SCADA (supervisory control and data acquisition) system used for remote data-logging and limited operation.

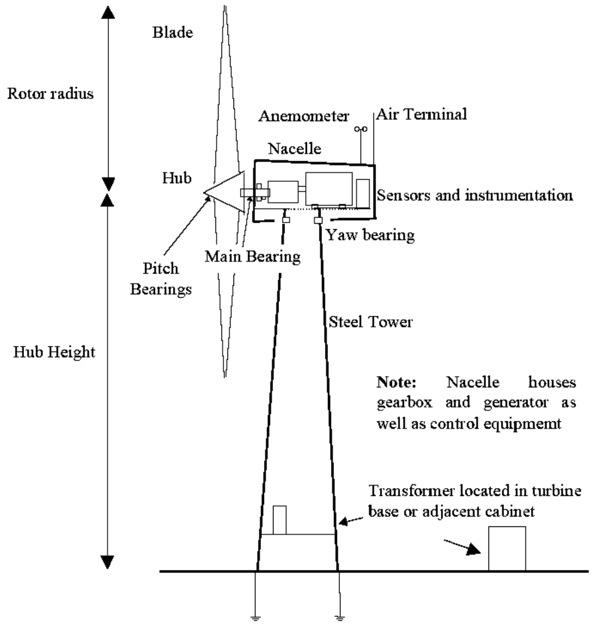

Fig. 1. Typical wind turbine structure

In all databases, the various electronic systems in the wind turbine account for the greatest number of faults. An example can be given in the Danish database component damage distribution shown in figure 2. A similar pattern of damage distribution was observed in the German database.

Table 1: Wind Turbine Lightning Damage Frequency

Country	Period	Turbine Years	Lightning Faults	Faults per 100 turbine years
Germany	'91 to '98	9204	738	8.0
Denmark	'91 to '98	22000	851	3.9
Sweden	'92 to '98	1487	86	5.8

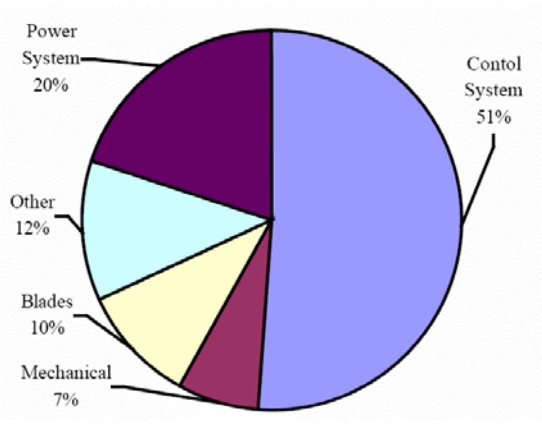

Fig. 2. Component damage distribution (Denmark)

For the sake of comparison, turbines above 450 kW were considered to be of recent construction. These turbines should reflect some implementation of lightning protection. Figure 3 shows the distribution of component damage for new and old construction using this 450 kW delimiter and the data from the German database.

It is interesting to note that damage to newer turbines appears to be less frequent. This cannot be explained by just better protection because there are fewer of these turbines than old units. While wind turbine manufacturers may regard this as evidence that the incidence of lightning damage is falling on modern units, they should also consider that the relative cost of repair increases.

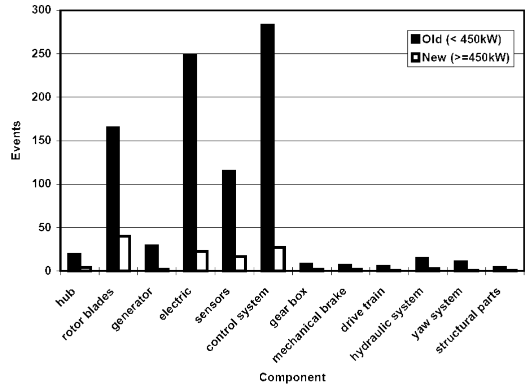

Fig. 3. Damage distribution according to wind turbine component and grouped according to wind turbine size

The German database reports the cost of repairing each component type. The repair costs include the labour, the component and the use of other services such as cranes. By separating this data according to turbine size, it is possible to see the change in repair costs as turbines grow in size. The results of the analysis for eight wind turbine components are shown in figure 4.

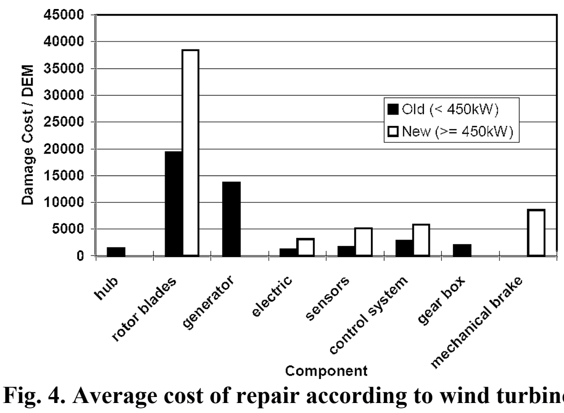

Fig. 4. Average cost of repair according to wind turbine component and grouped according to windturbine size

The cost of repair is seen to increase as the turbine size increases. When turbines are placed offshore, the cost of repair may dramatically increase in comparison to the repair cost for the same size turbine based on land.

The information related to damage statistics clearly demonstrates the need for wind turbine lightning protection. The need for detailed reporting lightning damage into a database continues to be necessary.

3 Risk Assessment

Methods for assessing the lightning flash frequency to a structure are given in the IEC standard IEC 61024-1-1 [12]. Furthermore, the technical report IEC 61662 [11] includes some information relating to the evaluation of the lightning risk to a structure.

The main consideration with wind turbine lightning strike frequency estimation is how to account for the rotating blades. Concerning the rotation of the blades, it can be shown that the average height of the wind turbine will be the hub height plus 86% of one rotor blade length. To be on the safe side when calculating the ground flash density, the hub height plus one rotor blade length is considered in any IEC calculations.

Experience with blades containing no metallic parts has shown that they are also struck by lightning. It is therefore recommended that all blades are included when a calculation of the lightning flash frequency is made.

4 Blade Lightning Protection

Modern wind turbine blades are large hollow structures manufactured of composite materials, such as glass reinforced plastic (GRP), wood, wood laminate and carbon reinforced plastic (CRP). CRP is typically used for reinforcement of the blade structure or for special components such as the tip shaft for blades with tip brakes (tip-stall braking mechanism). Some parts and discrete components are made of metal.

Typical types of damage when lightning attaches to blades are delamination and incineration of the surface composite material, and heating or melting of metallic components. The most severe damage to wind turbine blades is caused, however, when lightning forms arcs inside the blade. All grades of damage are seen ranging from surface cracking to complete disintegration of the blade.

To avoid damage, the lightning current must be conducted safely from the attachment point to the hub, in such a way 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 along the surface to the blade root, using metallic conductors either fixed to the blade surface or inside the blade. Another method is to add conducting material to the blade surface material itself, thus making the blade sufficiently conducting to carry the lightning current safely to the blade root. Variations of these methods are used with wind turbine blades.

External lightning protection using conductors on the blade surface has been tried by a number of manufacturers, but problems with erosion of the lightning protection system material or corrosion has occurred in a number of instances. The method widely used throughout the industry at the present time uses receptors at the blade tip and an internal down-conductor leading the lightning current to the blade root. For blades with tip brakes, the steel wire controlling the tip is used as a down conductor. If the blade is without a tip brake, then a copper wire placed along the internal spar is used as a down conductor. Within the last few years several thousands of blades with this lightning protection system have been produced. Early experiences with this lightning protection system for blades as long as 20m are very promising [6]. However, experience with longer blades is insufficient at the time of publication. The main concern about longer blades using internal down conductors relates to the interception efficiency. Solid conductors and segmented diverters on the surface and discrete receptors penetrating the surface must be placed in such a way that the likelihood of lightning attaching to the unprotected part of the surface is reduced to an acceptable level.

The spacing of discrete receptors giving an interception efficiency equal to that of solid conductors would in theory is the spacing where the flashover voltage along the blade surface is smaller than the breakdown voltage of the blade skin. In practice these voltages are difficult to establish. Furthermore, the interception efficiency of segmented diverters and of discrete receptors will be influenced by the presence of conducting materials inside the blade [5].

5. Bearing and Gearbox Protection

Once lightning has attached to and been safely conducted through a blade, it must then pass through the rest of the wind turbine to reach the earth. In fact all or part of lightning current will pass through a number of bearings before reaching the earth. These include the pitch bearings, the main shaft bearing, gearbox/generator bearings and the yaw bearing. Research concerning the distribution of the lightning current in a wind turbine nacelle has shown that 80% of the lightning current would generally flow onto the nacelle bed-plate via the main bearing closest to the rotor. While other bearings, notably the yaw bearing and pitch bearings, may take 100% of the lightning current these are large bearings and can be considered stationary during a lightning strike.

It is known that DC and AC currents can cause damage to bearings. While lightning current has a much shorter duration, the current density is extremely high. The possibility of lightning current damaging wind turbine bearings, and possibly the entire gearbox, therefore, has to be addressed.

The potential impact of bearing damage is high since the failure of the main bearing would generally require the removal of the entire wind turbine rotor for repair.

Practical experience with lightning damage to wind turbine bearings is scarce since wind turbine bearings are not normally checked after lightning strikes. Also, it is difficult to establish the chain of evidence as it may take years before the ensuing damage has developed.

In order to reduce the lightning current through bearings, the lightning current must be diverted via a low impedance path, and the impedance of the bearing structure must be increased by incorporating a resistive or insulating layer somewhere in the current path through the bearing [9][10]. An alternative current path is possible to be established at the front end of the low speed shaft, while at the same time introducing insulating layers in all the current paths through the bearings, the gearbox and the high speed shaft to the nacelle bedplate (local ground plane). Many manufacturers make use of a flexible coupling inserted in the high speed shaft, which may also provide the needed insulation and thereby protect the generator from lightning currents entering into the generator shaft [11]. Consideration must be given in this case to the large voltages that may develop between the driveshaft components and the nacelle bedplate.

6. Electrical and Control System Protection

A mix of electrical and electronic equipment can be found in a wind turbine. The unavoidable introduction of lightning current into a wind turbine nacelle means that a large number of control system components will be subject to high levels of electromagnetic field and induced voltages. *The high level (70%) of indirect lightning damage to wind turbine control systems reported in the German database emphasises the vulnerability of these components.*

The methodology for protection proposed in the technical report [8]was based on IEC 61312 [13].

- LPZ 0A (Lightning Protection Zone) 0A includes most of the surface of the wind turbine where lightning flashes may attach.
- LPZ 0B may include air terminations (e.g. lightning rods) placed at the rear edge of the nacelle cover, and a zone at the top of the nacelle whereby meteorological instruments can be protected against direct lightning attachment.

The boundary between LPZ 0A and LPZ 0B is determined by means of the rolling method. The boundary between LPZ 0A or LPZ 0B and LPZ 1 can be made at the tower or at the top cover of the nacelle if there is a metal cover (or sufficient metal content) to protect components beneath with a Faraday cage. In the case of GRP nacelle covers, it is recommended that a metal frame or strapping be integrated into the nacelle cover to, as a minimum, define the area within as Zone 0B to protect nacelle components from direct strokes. This should, of course, be bonded thoroughly to the bedplate.

At each zone boundary, it must be ensured that cables and wires crossing the boundary do not conduct large parts of the lightning current or voltage transients into the protection zone with the higher number. This is accomplished by means of proper bonding and shielding practices and overvoltage protection of cables and wires at the zone boundary. The goal is to reduce current and voltage to a level tolerable for the equipment placed in the protection zone with the higher number. The amount of components for protection against overvoltages can and should be reduced by means of appropriate division into zones, appropriate positioning of cables, use of shielded cables and use of optical fibres for transmission of signals and data. The use of surge protective devices should be limited to locations where the above precautions are not adequate.

7. Grounding

To disperse lightning currents flowing from a wind turbine into the earth it is necessary to provide a suitable earth termination system to limit overvoltages that can be dangerous to both humans and equipment. This is achieved by the provision of a low impedance earth termination system. Each wind turbine must be equipped with its own earth termination system, even if it is connected to a larger wind farm grounding system. The lightning protection system earth termination should be designed in accordance with a relevant lightning protection standard such as IEC 61024-1 [12] .

Ground electrodes should be designed to a ring or multiple horizontal and in some cases vertical electrodes. The foundation reinforcement steel should be connected to turbine ground electrodes. The effectiveness of linking wind turbine ground electrodes with bare conductor between turbines when designing the grounding system for lightning protection purposes is discussed next.

7.1 Effective length

Individual wind turbine grounds are usually connected by the metallic screen or armour of the main power cable running between Wind Turbines. This has the effect of reducing the overall site ground impedance to a low value, often 1-2ohms. However where the Wind Farm is sited in an area of high soil resistivity, each turbine ground may be connected by a strip electrode in addition to the connection provided by the power cable screen/armour. Undoubtedly, these grounding interconnections contribute significantly to the reduction of the Ground Potential Rise (GPR) and the related step and touch voltages. In the case of lightning strikes however, there is an upper limit in the length of the electrode that seriously affects the max GPR value. This limit is called "effective length" in [14][15] and implicitly in IEC 61400[1] does not exceed 60m.

More analytically, the maximum GPR produced at the injection point of a horizontal grounding electrode by an impulse current and by a sinusoidal current, for will vary when the length exceeds a value of greater than 60m. In the case of the sinusoidal current the maximum GPR decreases constantly with the electrode's length, although at a reduced rate above approximately 60 meters. On the other hand, in the case of the lightning strike the max GPR remains fairly constant for an electrode longer than the above value. This raises the issue of examining the benefits obtained by interconnecting individual WTs by horizontal electrodes longer than their effective lengths characteristic to the ground resistivity. The effectiveness of utilizing the same or reduced amount of grounding conductors in local WT grounding structures against lightning strikes and other fault situations has to be carefully analysed.

7.2 Calculation of transient response of Wind Farm Grounding Systems

The calculation of the transient response of interconnected grounding arrangements, such as windfarms, requires specialized software and long computational times. Many attempts have been made in the past for the calculation of this transient behaviour. They can be divided in two main categories as follows:

- Methods based on frequency domain calculations with subsequent transformation of the solution in time domain using Inverse Fast Fourier Transformation (IFFT) [16],[17], and
- Methods based in calculation of the solution directly in time domain [18]-[20], using ATP or not.

In [15] an efficient calculation method based on "effective length" consideration is proposed.

It should be noted that consideration of the grounding system resistance only to estimate the GPR at a point following a lightning strike leads to inaccurate results due to the high frequencies contained in the lightning current. This is clearly shown in the case of two windturbines situated a distance of 100m apart connected with strip electrode in 1000Ωm resistivity soil. The computed resistance of the network is 18.59Ω and the maximum voltage rise for an injection of 1A at 50Hz is 18.59V.

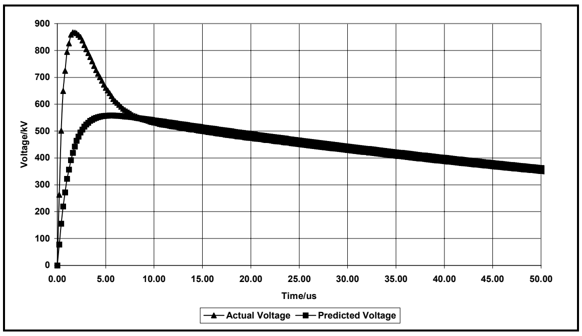

Fig. 8- Voltage waveform following lightning current injection into resistance only (lower plot) compared with impedance (upper plot)

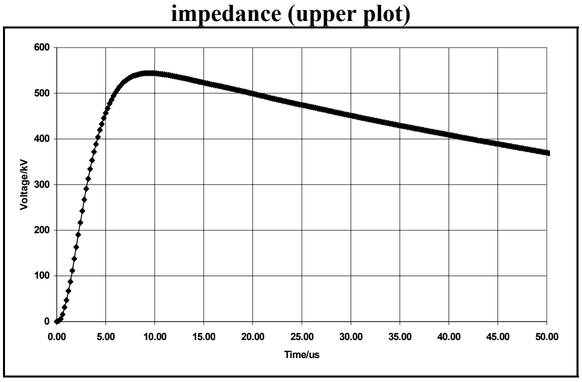

Fig. 9: Voltage at the turbine remote from the injection point.

An injection of a lightning current with peak current of 30kA results in a maximum voltage of 868kV at the injection point. This can be compared to a voltage of 558kV that would be expected if the same current has been injected into the 18.59Ω resistance. The voltage waveform produced at the base of the first wind turbine is shown in figure 9 long with the waveform expected had the same current being injected into a pure resistance. Note that the inductance increases the peak voltage and changes the time of its appearance.

7.3 Raised Potentials in a Windfarm

Individual WTs are usually connected by the metallic screen or armour of the main power cable. In order to investigate the effect of power cables and of the interconnection power ground electrodes on the maximum GPR and on the transferred potentials, an example of five WTs in series in a typical WF consisting of them and a substation connected to one end, is considered. Three distinct cases are examined:

- Individual WT grounding structures are interconnected only by the amour of the power distribution cable
- Horizontal ground 25m electrodes are connected to either side of each WT in parallel with the power cables
- Horizontal ground electrodes are connected in parallel to the whole length of the power distribution cable.

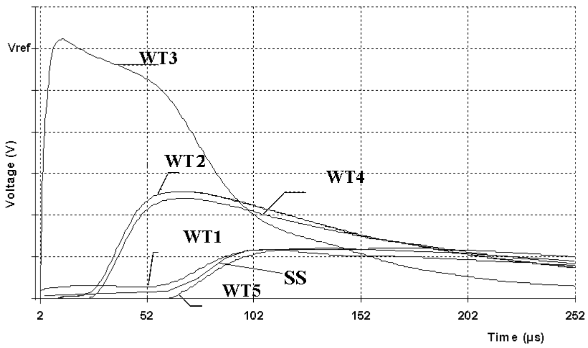

Fig. 10: Case (i): Potential vs. time at windturbine grounding systems

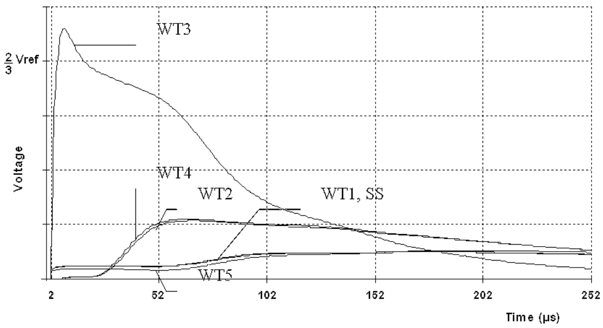

Fig. 11: Case (ii): Potential vs. time at windturbine grounding systems

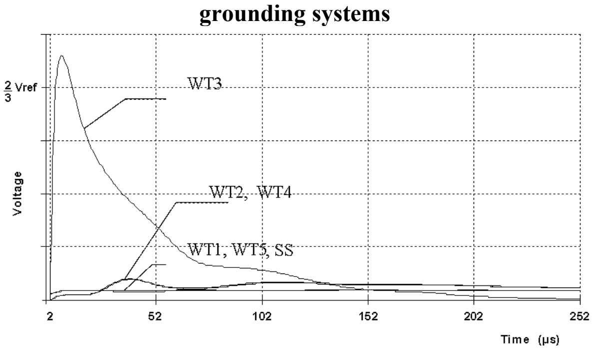

Fig. 12: Case (iii): Potential vs. time at windturbine grounding systems

A lightning current with 5.5us and 75us peak and half value time is injected to the third wind turbine. From the above results it can be concluded that:

- Maximum GPR is always obtained at the point where lightning strikes. This rise is lowered when long horizontal electrodes connecting wind turbine grounding systems are used.
- The contribution of the interconnecting horizontal electrodes to the reduction of the maximum GPR caused by lightning is limited by their effective lengths. In fact, the maximum GPR is not noticeably reduced if grounding electrodes longer than their effective lengths are used.
- The level of transferred overvoltages has to be carefully studied in order to decide the extent of WTs grounding systems interconnections.

8 Conclusion

The technical report of International Electrotechnical Committee IEC 61400-24-CD, addresses the major issues relating to 'Lightning protection for wind turbines'. These include those unique to wind turbines such as previous statistics, blade protection, risk assessment, electronics protection, bearing protection, grounding and safety.

Certain issues considering long blades and bearings deserve of further investigation. Particular emphasis is given to wind farm grounding systems

References:

[1] IEC 61400-24-CD, *Lightning Protection For Wind Turbines,* Committee Draft

[2] WMEP, ISET, Konigstor 59, D-34119 Kassel, Germany

[3] Energi og Miljoedata, Niels Jernes Vej 10, DK 9220 Aalborg, Denmark

[4] SwedPower AB, Vindstatistik, PO Box 527, S-162 16 Stockholm, Sweden

[5] F A Fisher, J A Plumer, *Lightning Protection Of Aircraft,* Lightning Technologies Inc, Pittsfield, MA, USA, 1980

[6] T Soerenson, M Brask, K Olsen, M L Olsen, P.Grabau, Lightning Damage To Power Generating Wind Turbines, 24th ICLP, pp938-943, Birmingham, UK, 1998

[7] O Celi, A Pigini, *Evaluation of damage caused by lightning current flowing through bearings.* IEA: Lightning protection of wind turbine generator systems and EMC problems in the associated control systems. IEA Annex XI, 26th meeting of experts, Italy, 1994

[8] I Cotton, N Jenkins, N Hatziargyriou, M Lorentzou, S Haigh, M Hancock, *Lightning protection of wind turbines – a designers guide to best practice,* UMIST, 1999

[9] DEFU TR394, *Lightning protection for wind turbines* DEFU Technical Report TR394 (In Danish)

[10] IEA: *Recommended practices for wind turbine testing and evaluation – 9. Lightning protection for wind turbine installations,* IEA 1997

[11] IEC 61662: 2001Assessment of the risk of damage due to lightning
[12] IEC 61024-1 Ed. 1.0 b:1990 Protection of structures against lightning - Part 1: General principles
[13] IEC 61312-1, 1995: Protection against lightning electromagnetic impulse (LEMP)
[14] M.Lorentzou, N.Hatziargyriou, B.C.Papadias: “Time domain analysis of grounding electrodes impulse response” IEEE Trans on PWRD, Vol.18, Issue 2, April 2003, pp 517 - 524.
[15] M.Lorentzou, N.Hatziargyriou: “Proposed Methodology for Calculation of the Transient Response of Grounding Systems” Proc, of the 4th Med Power Conference, Athens, 11-14 November 2002.
[16] Grcev: “Improved Earthing System Design Practices for Reduction of Transient Voltages” paper 36-302 CIGRE Session 1998.
[17] L.Grcev F.Dawalibi: “An electromagnetic model for transients in grounding systems”, IEEE Trans., on Power Delivery, vol.5, 1990, pp.1773-1781
[18] F.Menter, L.Grcev: “EMTP Based Model for Grounding System Analysis”, IEEE Trans on PWRD, Vol.9, no.4, October 1994.
[19] A.P.Meliopoulos, M.G.Moharam: “Transient Analysis of Grounding Systems”, IEEE Trans.on Power Apparatus and Systems, Vol PAS-102, No.2, Feb. 1983
[20] N.D. Hatziargyriou, M.Lorentzou: “Grounding Systems Design Using EMTP”, 23rd European EMTP Users Group Meeting, Barcelona, 9-11 November 1997.