Protection of wind turbine against the lightning damage

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Abstract- **Damages of wind turbines by lightning is currently one of the main sources of wind turbine insurance claims and downtime. Understanding the effects of lightning strikes has become increasingly important as the size and rated power of wind turbines increase and they are placed in locations where repair is difficult and costly. The wind turbines are important structures, since they can easily attract the wrath of storms hits heights close, they can also capture the most distant. The rotation of the blades may also trigger lightning and result in considerable increase in the number of strikes to a wind turbine unit. Since wind turbines are tall structures, the lightning currents that are injected by return strokes into the turbines will be affected by reflections at the top, at the bottom, and at the junction of the blades with the static base of the turbine. We present our contribution in this paper to study lightning strokes and their effects on the wind turbines with the aim to enrich the work and to suggest more effective means of protection against lightning.**

Keywords: ***wind turbine, lightning, protection, blade, current return stroke, carbon reinforced plastics***

I. INTRODUCTION

Lightning damage has mainly been to home appliances and telephones, towers and power transmission and generation equipment mal functions and damage due to strikes on power lines. With the adoption of wind power generation equipment, however, lightning damage is also increasing in this area. Through his dimensional characteristics, the wind power system is more exposed in the nature compared to all others systems. Lightning damage is the single largest cause of unplanned downtime in wind turbines, and that downtime is responsible for the loss of countless megawatts of power generation.

Wind turbine technology is constantly evolving in all areas in recent times but lightning remains the first danger to this technology growth. Being higher than 100 meters and being located in remote areas, wind turbines are exposed to lightning strokes much as 10 times per year, implying an alarming frequency of lightning strokes, implying an alarming frequency of lightning strikes. In the 1990s that quite often caused heavy damages.

In 1995 approx 80% of the damages registered by insurances were caused by lightning however, modern wind power generation units are characterized by ever taller turbines and wind turbine blades are now being produced with lengths of 60 m and beyond. Since insurance companies demand for proper lightning defense, lightning has nowadays lost its terrifying effect for the users. Even retrofitted turbines withstand lightning strokes without serious problems.

Wind turbines are tall, isolated towers composed of sensitive electronics, all of which are factors that make lightning a persistent and real threat. A properly installed lightning protection system, however, will intercept the lightning and effectively and safely conduct it to the earth without risking physical destruction to the wind turbine. According to a German study, lightning strikes accounted for 80% of wind turbine insurance claims.

- During its first full year of operation, 85% of the down time experienced by one southwestern commercial wind farm was lightning-related. Total lightning related damage exceeded $250,000.
- The German electric power company Energieer-zeugungswerke Helgoland GmbH shut down and dismantled their Helgoland Island wind power plant after being denied insurance against further lightning losses. They had been in operation three years and

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suffered more than $540,000 (USD) in lightning-related damage.

II. Lightning Damage to Wind-Turbine

The statistics presented in this paper are quoted in IEC/TR 61400-24, highly informative and which present data on the European countries that have known of Events of the turbines damage by lightning strokes (Germany, Sweden, and Denmark) where lightning is comparatively infrequent, 4%–8% of all wind turbines will suffer lightning-caused damage every year. However, in areas of greater lightning density, this figure is reported to be considerably higher.

In some countries, damaged number by lightning increased doubled than before. In this way, the increasing installation of wind power generation equipment is causing problems not found in other countries because of the weather conditions.

A. Wind Turbine Component Damage

The following systems, arranged in order from most to least vulnerable, may be damaged by lightning strikes:

- damage to the control system. These include sensors, actuators, and the motors for steering the equipment into the wind. According to the updated National Fire Protection Association handbook: "While physical blade damage is the most expensive and disruptive damage caused by lightning, by far the most common is damage to the control system";
- damage to electronics. Wind turbines are deceptively complex, housing a transformer station, frequency converter, switchgear elements, and other expensive, sensitive equipment in a relatively small space;
- blade damage. A lightning strike to an unprotected blade will raise its temperature tremendously, perhaps as high as 54,000° F (30,000° C), and result in an explosive (Fig.2) expansion of the air within the blade. This expansion can cause damage to the blade surface, melted glue, and cracking on the leading and trailing edges. Much of the damage may go undetected while significantly shortening the blade's service life. One study found that wood epoxy blades are more lightning-resistant than GRP/glass epoxy blades;
- damage to générateurs
- batteries can be destroyed, or even detonated, by a lightning strike.

Note that lightning dangers increase with turbine height

Fig 1. Wind turbines exposed to lightning strokes

In recent years, windmills have become markedly larger. The height of the blade tips on many of these large windmills is over 100 meters, which increases the frequency of damage from lightning strikes. Damage to the blades of large windmills have higher repair costs and require more time for replacement (including transport and installation). The increase in windmill downtime has brought about a decrease in the operation rate and utilized capacity of windmill equipment [9].
Almost all modern turbine blades are constructed with built-in lightning protection in the form of conducting elements. This improved blade design has significantly reduced the amount of blade damage [2].

B. Principal Lightning risk Factors

The above statistics give credence to the main conclusion of a study commissioned by the European Union and conducted by the University of Manchester: "the protection of wind turbine electronic systems from indirect effects is of equal importance to, if not greater than, the protection against direct effects" [10].
The three risk factors to be mitigated then are as follows:

- *Damage to blades caused by direct strikes:* This damage can be caused by strikes to the tips of the blades and also to strikes along the length of the blades. Almost all direct strikes to a wind turbine will hit the rotor blades.
- *Damage caused by surge currents:* This damage can be caused by surge currents originating from either direct strikes to the blades or coming from (indirect) strikes to connected power and data lines. This would include the ac power lines as well as the telephone or supervisory control and data acquisition lines used to remotely control the turbines.
- *Damage caused by voltages:* This damage can be caused by voltages induced in circuits (power as well as control) adjacent to the necessary down-conductors that carry the lightning current to "earth."

III. Evaluation of Lightning Incidence to Wind Turbines

The design of an lightning protection system LPS should be based on the risk of lightning striking the structure in question. This risk is a function of the structure height, the local topography and the local level of lightning activity.

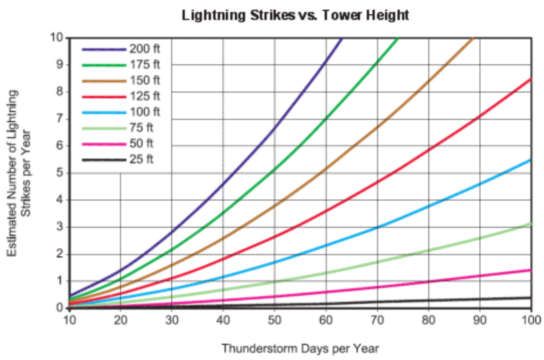

Fig 2. Variation of lightning strikes with Tower Height

Elevated objects such as wind turbines experience both downward and upward flashes, the proportion being a function of object height [11]. The total annual lightning incidence N (in year-1) is given by

$$N = N_u + N_d \qquad (1)$$

Where N_u and N_d are the annual number of upward flashes and downward flashes, respectively.
Based on observations of the lightning incidence to structures with heights ranging from 20 to 540 m situated on a flat surface in different regions of the world, Eriksson [6] derived the following equation:

$$N = N_g .24. h_s^{2.05}. 10^{-6} \qquad (2)$$

where h_s is the height of the structure in meters and N_g is the ground flash density in km^{-2} $year^{-1}$.

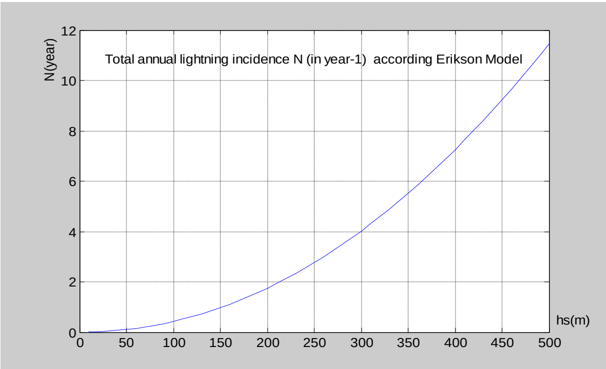

Fig 3. Total annual lightning incidence N (in year-1) according Erikson Model

IEC [6] recommends that wind turbines on a flat terrain be modeled as a tall mast with a height equal to the hub height plus one rotor radius, the equivalent attractive or collection area being defined as a circle with a radius of three times the turbine height

$$R_a = 3. h_s \qquad (3)$$

In IEC [6], the overall number of lightning flashes to the wind turbine is calculated using the expression

$$N = N_g .\pi. (3h_s)^2. 10^{-6} \qquad (4)$$

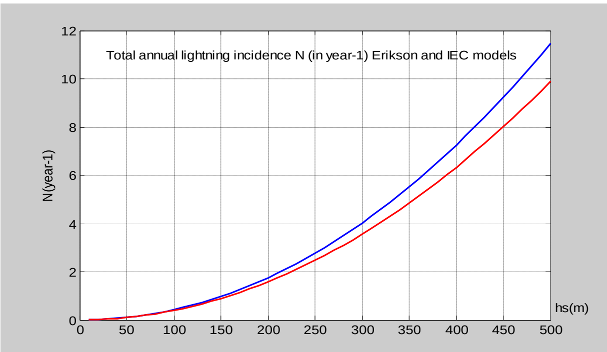

Fig.4. Total annual lightning incidence N (in year-1) according Erikson (Red) and IEC model (blue)

Wind turbine failures due to lightning depend strongly on the terrain where the wind parks are installed. As reported in [2], wind turbines installed in the low mountain areas in Germany have a higher risk of lightning damage (14 faults per 100 unit years) compared to wind turbines installed in the coastal areas (5.6 faults per 100 unit years). The evaluation of lightning incidence to wind turbines situated in mountainous regions is much more difficult than on flat ground due to the fact that topological factors will play a major role in the enhancement of the electric field at the top of the wind turbine.

IV. Lightning Transient Current Behavior inside the Turbine

When lightning strikes an elevated tower or wind turbine, the transient phenomena in the strike object introduce changes in the original lightning current waveform. The influence of the strike object on the current waveform fig (2), has been recently investigated by a number of research groups around the world and several of the so-called engineering return-stroke models have been extended to take into account the presence of the elevated strike object. In some of these studies, the strike object was modeled as an ideal, uniform transmission line.
In the return stroke models that take into account the strike structure, it is often assumed that the propagation speed of current pulses along the strike object is equal to the speed of light c and that the current reflection coefficients at its extremities (q_t at the top and q_g at the bottom) are constant. Further, the existence of upward-connecting leaders and any reflections at the return stroke wave front are neglected.
The bottom reflection coefficient for the current in the tower can be expressed in terms of the characteristic impedance of the tower, Z_t, and the grounding system impedance, Z_g, as follows:

$$\rho_g = \frac{Z_t - Z_g}{Z_t + Z_g} \qquad (5)$$

Similarly, the top reflection coefficient for the current in the tower can be expressed in terms of the characteristic impedance Z_t and the equivalent impedance of the lightning return stroke channel Z_{ch}:

$$\rho_t = \frac{Z_t - Z_{ch}}{Z_t + Zch} \qquad (6)$$

For a lightning return stroke initiated at the top of the strike object, the current along it and along the lightning channel for a given height z were derived by Rachidi et al. [7] and it is given by

$$i(z,t) = (1 - \rho_t) \sum_{n=0}^{\infty} \begin{bmatrix} \rho_t^n . \rho_g^n i_0 \left(h, t - \frac{h-z}{c} - \frac{2nh}{c}\right) . u\left(t - \frac{h-z}{c} - \frac{2nh}{c}\right) + \\ \rho_t^n . \rho_g^{n+1} i_0 \left(h, t - \frac{h+z}{c} - \frac{2nh}{c}\right) . u\left(t - \frac{h+z}{c} - \frac{2nh}{c}\right) \end{bmatrix} \qquad (7)$$

for $h < z < H_{tot}$:

$$i(z,t) = \begin{bmatrix} P(z-h).\,i_0\left(h, t-\frac{z-h}{v^*}\right) - \rho_t i_0\left(h, t-\frac{z-h}{c}\right) + \\ (1-\rho_t)(1+\rho_t)\sum_{n=0}^{\infty} \rho_g^{n+1}\rho_t^n i_0\left(h, t-\frac{h+z}{c}-\frac{2nh}{c}\right) \\ .\,u\left(t-\frac{h+z}{c}-\frac{2nh}{c}\right) \end{bmatrix}$$
$$.\,u\left(t-\frac{z-h}{v}\right) \qquad (8)$$

where $i_0(h, t)$ is the so-called 'undisturbed' current, defined as the current that would be measured at the top of the strike object (lightning attachment point) if both reflection coefficients qt and q_g were equal to zero, z is the height along the strike object for Eq. (7) and along the channel for Eq. (8), c is the speed of light, v is the return stroke speed, H_{tot} is the total height, obtained by adding the lengths of the lightning channel and of the elevated strike object, v* is the current-wave speed in the lightning channel, and u(t) is the Heaviside unit step function.

A. *The Modified Transmission Line model, MTLE*

Established by Nucci, Rachidi [10][15], the model MTLE corrects the defects of the TL model while keeping its simplicity by allowing an easy use in the electromagnetic radiation, based on this formulation of the space-temporal distribution along the channel of the current *i(z', t)*, defined by :

$$i(z',t) = i(0, t - z'/v)\exp(-z'/\lambda) \qquad z' \le vt$$
$$i(z',t) = 0 \qquad z' > vt \qquad (9)$$

More recently, Heidler proposed a new analytical expression to simulate the current:

$$i(0,t) = \frac{I_0}{\eta}\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n}exp(-t/\tau_2)^n \qquad (10)$$

And

$$\eta = \exp\left[-\left(\frac{\tau_1}{\tau_2}\right)\left(n\frac{\tau_2}{\tau_1}\right)^{\frac{1}{n}}\right]$$

I_0 , the magnitude of the current in the channel base
$\tau 1$, is the time-constant of the face
$\tau 2$, is the constant of decrease
η , is the factor of correction factor of magnitude and
n is an exhibitor ranging between 2 and 10.

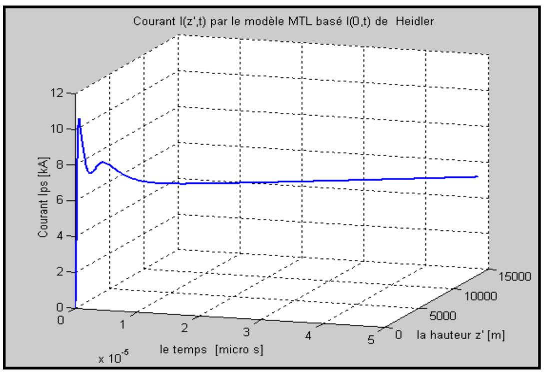

Fig. 5. Current in lightning channel of the Model MTLE with (0, t) of Heidler

For lightning to wind turbines, the previous model needs to be adapted to take into account the discontinuity between the body and the blades of the wind turbine system at the hub. The instantaneous angle of the struck blade with respect to the base may strongly influence the reflection and transmission coefficients at the discontinuity.

V. Protecting Wind Turbines

There is an unabated trend for the utilization of regenerative energy gained from wind turbines, solar, photovoltaic and biogas plants or geothermal heat. This is an enormous market potential not only for the energy industry but also for the suppliers and the electrical trade and that worldwide. It goes without saying that surges can cause considerable damage there. Due to the exposed position and the overall height, wind turbines are exposed to direct lightning effects. Multi-megawatt wind turbines with blades reach a total height up to 150 m and are therefore particularly exposed to danger. **A** comprehensive lightning and surge protection is required

A. *Lightning Protection Zones Concept LPZ*

The lightning protection zones concept is a structuring measure for creating a defined EMC environment within a structure (Figure 6). The defined EMC environment is specified by the electromagnetic immunity of the used electric equipment.

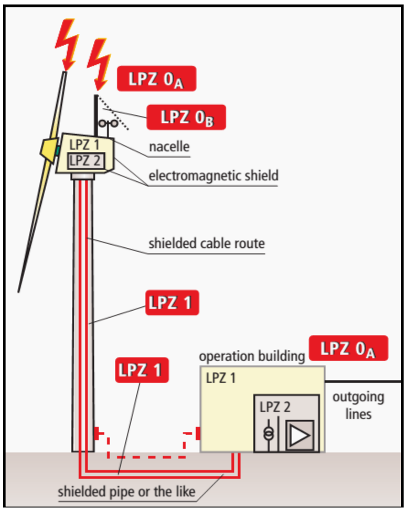

Fig 6. Lightning protection zones concept for a wind turbine

Being a protection measure, the lightning protection zones concept includes therefore a reduction of the conducted and radiated interferences at boundaries down to agreed values.

For this reason, the object to be protected is subdivided into protection zones. The protection zones result from the structure of the wind turbine and shall consider the architecture of the structure.

It is decisive that direct lightning parameters affecting lightning protection zone **LPZ 0_A** from outside are reduced by shielding measures and installation of surge protective devices to ensure that the electric and electronic systems and devices situated inside the wind turbine can be operated without interferences.

B. Shielding measures

The nacelle should be designed as a metal shield that is closed in itself. Thus a volume can be obtained inside the nacelle with considerably attenuated, electromagnetic field compared to the outside.

The connecting cables should be provided with an outer, conductive shield. With respect to interference suppression, shielded cables are effective against EMC coupling only if the shields are connected with the equipotential bonding on both sides. The shields must be contacted with encircling contact terminals to avoid long and for EMC improper**.**

C. Earthing system of a wind turbine

For earthing a wind turbine, the reinforcement of the tower should always be integrated. Installation of a foundation earth electrode in the tower base, and, if existing, in the foundation of an operation building, should also be preferred in view of the corrosion risk of earth conductors.

The earthing of the tower base and the operation building (Fig.7) should be connected by an intermeshed earthing in order to get an earthing system with the largest surface possible.

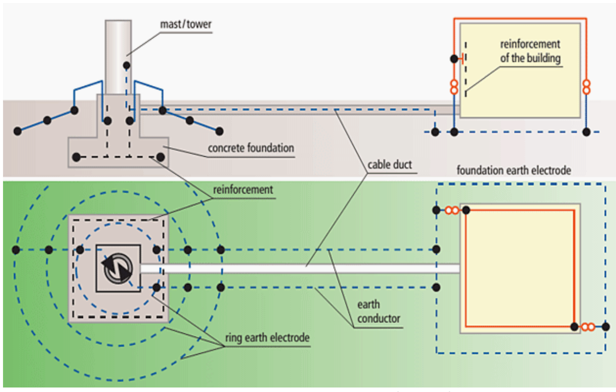

Fig.7. Earthing system with the largest surface of Wind turbine

Protective circuit for conductors at the boundary of lightning protection zone **LPZ0$_A$** to **LPZ1** and higher Besides shielding against radiated sources of interference, protection against conducted sources of interference at the boundaries of the lightning protection zones must also be provided for reliable operation of the electric and electronic devices.

At the boundary of lightning protection zone **LPZ 0$_A$** to **LPZ1** (conventionally also called lightning equipotential bonding) SPDs must be used, which are capable of discharging considerable partial lightning currents without damage to the equipment. These SPDs are called lightning current arresters (SPDs Type 1) and tested with impulse currents, wave form 10/350 µs.

At the boundary of **LPZ0$_B$** to **LPZ1** and **LPZ1** and higher, only low energy impulse currents have to be controlled which result from voltages induced from the outside or from surges generated in the system itself. These protection devices are called surge protective **devices** (SPDs Type 2) and tested with impulse currents, wave form 8/20 µs.

D. LPS on blades and working

LPS is vital for wind turbine blades as they are prone to lightning strikes due to their shape and position on the wind turbine. LPS in the present blades in this project consist of a down conductor/ receptor (Fig.8) based system. During a thunderstorm the receptor is the preferred first point of attachment to lightning leaders.

After successful interception to the lightning leader, the lightning current is safely conducted through the down conductor

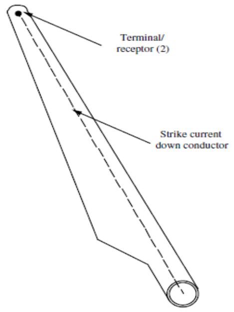

Fig.8. Zone blade conductor retrofit

VI. Influence of Carbon Reinforced Plastic, CRP

In [6], Carbon Reinforced Plastic materials are considered as electrical conductors and it is recommended to bond CRP to other conducting components for lightning protection purposes. However, this recommendation raises two questions which need to be addressed:

a. are CRP components able to conduct lightning current without being damaged ?

b. how should the bonding between CRP and LPS be made?

Another issue related to the use of CRP is their response to the static electric field below a thundercloud. It is indeed well known that the electric field E_g at ground level below thunderclouds can reach values of about -5 to -15 kV/m. It is likely that the CRP material in the blade experiences fields which vary from E_g to a value than can reach a few times E_g, due to the field enhancement effect, when the blade tip is at its highest position.

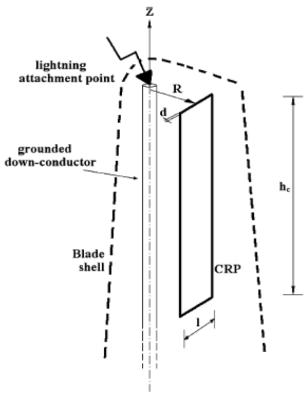

Fig 9. Geometry for the evaluation of eddy currents in a CRP laminate (Adapted from [7] _2010 IEEE)

The circulation of eddy currents results in an energy dissipation as heat, which can generate mechanical stresses. To evaluate the eddy current losses in CRP laminates, we consider the geometry presented in Fig.9. The CRP laminate is defined by a volume of thickness d, width l and length h, parallel to, and at a distance R from the lightning down conductor. The average loss due to eddy currents in a laminate is given by:

$$P(f) = \frac{k(f)df}{2} B_{\max}\ (w)^2\ \frac{\sinh(k(f)d)-\sin(k(f)d)}{\cosh(k(f)d)-\cos(k(f)d)} \qquad (11)$$

$$B_{max}(f) = \mu \frac{I(f)}{2\pi R} \frac{\tanh(\sqrt{j2\pi f\mu\sigma}\frac{d}{2})}{\sqrt{j2\pi f\mu\sigma}\frac{d}{2}}$$

$$(f) = \sqrt{\frac{2\pi f\mu\sigma}{2}}$$

l is the medium permeability and r is the conductivity of the CRP.

The energy dissipated per unit volume is given by:

$$W' = 2\int_0^{fmax} |p(f)|df \qquad (12)$$

And the total dissipated energy in the laminate is therefore:

$$W = W'.l.d.h \qquad (13)$$

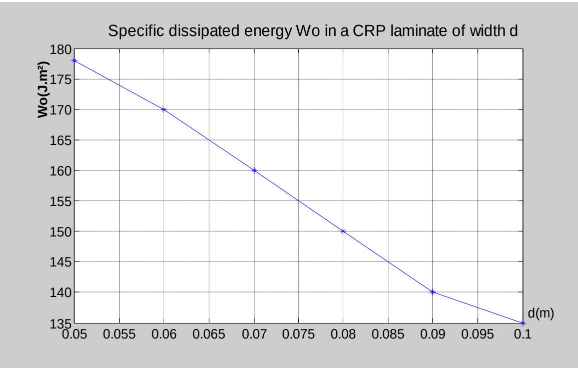

Fig. 10 . Specific dissipated energy in a CRP laminate of width d. (Adapted from [7] _2010 IEEE)

Figure.10 present the specific energy W_o = W/(l.h) in J/m^2 as a function of width d and considering the following parameters used in [7]: R = 0.2 m, σ = 7.246 9 10^4 S m^{-1} and μ_r = 1. The return stroke current corresponds to a typical first return stroke and has an amplitude of 30 kA.

VII. CONCLUSION

In the term of this work we can finish off the following conclusion and recommendations:

✓ The lightning damage is the single largest cause of unplanned downtime in wind turbines, and that downtime is responsible for the loss of countless megawatts of power generation

✓ Lightning protection of wind turbines presents a number of new challenges due to the geometrical, electrical, and mechanical particularities of the turbines. This is especially true for modern units since they are becoming taller and because carbon fiber composite materials are being used to reinforce them.

The main conclusions of the chapter are summarized here under :

➢ The risk assessment for the purpose of LPS design is based on empirical formulas for the estimation of the number of flashes to a tall object on a flat terrain. The rotation of the blades may have a considerable influence on the number of strikes to the blades of large wind turbines as these may be triggering their own lightning.

➢ The simulation results show that the influence of the height is important in the frequency of lightning on the Wind turbines where Erikson's model gives more credibility and deserves to be adopted to provide for a more efficient LPS and the transient phenomena in general. More than one receptor if necessary blades over 25 m (82 ft) in length.

➢ The presence of carbon reinforced plastics in the blades introduces a new set of problems to be dealt with in the design of the turbines' LPS

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