Lightning Protection of Wind Turbine regarding with Risk Management

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Abstract—**This paper proposes a concept of lightning protection of wind turbine from the viewpoint of risk management. Lightning protection of wind turbine including design by manufactures and maintenance by operators should be done from the viewpoint of risk management. It is important to understand damage aspects, possible causes and corresponding countermeasures to satisfy both of safety and economic operation. The concept from risk management will help to establish reasonable countermeasures depends on damage levels with appropriate cost-benefit balance, which finally realises reduction of lightning incidents and improvement of turbine availability.**

Keywords-wind power; wind energy; blade; incident level; risk management;

I. INTRODUCTION

Damages in wind turbines due to lightning vary from significantly serious incidents such as blade falling, nacelle burnout and physical injury to minor events like blade scorching and breakdowns of small electronics devices. It is not reasonable to take a single countermeasure to protect all kind of lightning damages because the levels and aspects of lightning damages range from catastrophic to minor. Lightning protection of wind turbine should be done from the viewpoint of risk management.

This paper introduces a basic concept of risk management to apply to lightning protection of wind turbine. Common understanding of the concept of risk management is important among all stakeholders of the wind industry including turbine manufacturers, device suppliers, turbine owners and developers as well as insurance and finance sectors, certification bodies and regulators.

II. BASIC CONCEPT OF RISK MANAGEMENT

The concept of risk management can be seen from the definitions of terms on risk management in ISO/Guide 73: 2009 [1]. According to the Ref.[1], "risk" is deferred as "effect of uncertainty on objectives". Table I shows the list of definitions of major terms on risk management.

The countermeasures against the various risks should be done depending upon the combination of possibility of the events and their effects. Figure 1 illustrates the simplest risk matrix, which is divided two possibilities and two magnitude of the consequence. In this matrix, the conceivable risk management is divided into four domains with "risk avoidance", "risk sharing", "risk reduction" and "risk retention" as summarised in Table II. Risk matrices can be differ in various fields and may be more complex with multiple classes.

TABLE I. DEFINITIONS OF MAJOR TERMS ON RISK MANAGEMENT

Terms	Definitions
risk	effect of uncertainty on objectives Note (*extract*): An effect is a deviation from the expected — positive and/or negative.
risk management	coordinated activities to direct and control an organization with regard to risk
risk assesment	overall process of risk identification, risk analysis and risk evaluation
risk identification	process of finding, recognizing and describing risks
risk analysis	process to comprehend the nature of risk and to determine the level of risk
risk evaluation	process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable
risk soure	element which alone or in combination has the intrinsic potential to give rise to risk
event	occurrence or change of a particular set of circumstances
hazard	source of potential harm Note 1 to entry: Hazard can be a risk source
risk matrix	tool for ranking and displaying risks by defining ranges for consequence and likelihood
level of risk	magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood
risk acceptance	informed decision to take a particular risk
rist treatment	process to modify risk Note (*extract*): Risk treatments that deal with negative consequences are sometimes referred to as "risk mitigation", "risk elimination", "risk prevention" and "risk reduction".
risk avoidance	informed decision not to be involved in, or to withdraw from, an activity in order not to be exposed to a particular risk
risk sharing	form of risk treatment involving the agreed distribution of risk with other parties
risk retention	acceptance of the potential benefit of gain, or burden of loss, from a particular risk

Note: quoted and summarised by the author from Ref.[1]

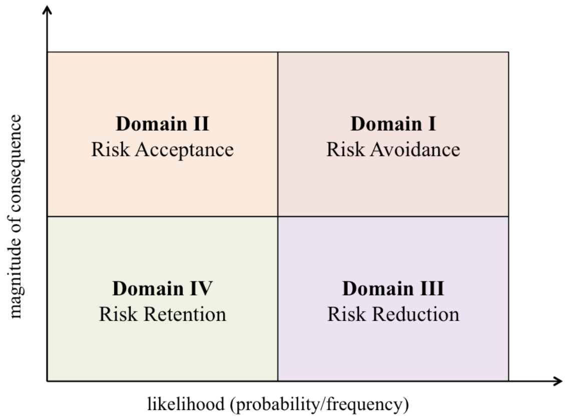

Figure 1. An Example or Risk Matrix

TABLE II. CLASSIFICATION OF RISKS AND THEIR TREATMENTS

Domain	likeli-hood	maguni-tude	level of risk	risk treatment	examples
I	high	high	intolerable	risk avoidance	approval, zoning
II	low	high	tolerable	risk acceptance	insureance, commission
III	high	low		risk reduction	quolity improvment
IV	low	low	acceptable	risk retention	periodic maintenance

III. CLASSIFICATION OF LIGHTNING DAMAGES IN TURBINE BLADES

As introduced in the previous chapter, it is important to choose the appropriate risk treatment corresponding to the appropriate risk analysis, which means the process to comprehend the nature of risk and to determine the level of risk. It is therefore important to classify damages due to lightning.

As a wind turbine has many components in itself, a blade is the most critical component against lightning damage because of several reasons:

- It is installed at the highest point of the turbine;
- It is made from relatively fragile material like glued and fibre reinforced plastics;
- It is one of the most expensive single component in a wind turbine and may need the most expensive construction to reinstall; and
- It may become the most dangerous component for public safety in case of falling debris.

Therefore, considering on blade damages is very important for risk management of wind turbine.

A classification of damages in turbine blades due to lightning has been proposed by CIGRE (The International Council on Large Electric Systems) WG C4.409 (Lightning Protection of Wind Turbine Blades, convenor: Prof. S. Yokoyama), after international discussions for several years [2]-[4]. The discussion to consensus formation is still progressing in IEC (International Electrotechnical Commission)/TC88 (Wind energy generation systems)/MT24 (Maintenance Team for "Lightning protection for wind turbines", convenor: Mr. T. S. Sørensen) in an effort to publish the second version of IEC 61400-24 within a couple of years [5]. Table III shows the latest agreed version, where a minor revision has been made from Ref.[2]-[4].

TABLE III. CLASSIFICATION OF BLADE DAMAGES DUE TO LIGHTNING

(IV) **Catastrophic incident** causing possible injury and/or death	
	(IV-a) Blade rupturing and falling
	(IV-b) Blade burnout and falling
	(IV-c) Melting and/or spark of control wire
	(IV-d) Falling of receptor or other blade component [a]
(III) **Serious incident** requiring immediate repair	
	(III-a) Cracking along bond weld
	(III-b) Tearing at blade edge
	(III-c) Melting and/or spark of down conductor
(II) **Normal event** requiring repair as soon as possible	
	(II-a) Surface stripping
	(II-b) Loss of a small part of receptor
(I) **Minor event** not requiring immediate repair	
	(I-a) Receptor vaporisation
	(I-b) Surface scorching
	(I-c) Other minor damages

a: This event can be considered as (II-b) in case neither residents nor passers-by clearly exist around the wind turbine.

The level of damage should be categorised into four levels as shown in Table III, numbering from the lowest to highest, according to damage and wearing aspects. The highest level of the blade damage is (IV) Catastrophic incident, that may cause human injury and/or death, while Level (III) Serious incident, that requires immediate repair otherwise the damage may progress worse to Level (IV), follows. Level (II) is categorised as Normal event, that requires repair as soon as possible and the lowest level is Level (I) Minor event that does not need repair before the next scheduled maintenance.

In case of offshore turbines and turbines installed in uninhabited areas, the sub-category (IV-d) "Falling or receptor or other blade component" can be demoted to (II-b) because it may not create the risk of public safety. Otherwise, it should be categorised into the highest damage level (IV) Catastrophic incident even if the dropped component is small. An incident with dropped any component in inhabited areas can easily lead a social negative impact against wind power. The negative impact due to a turbine incident and therefore decline of social acceptance of wind power should be considered as a potential huge risk not only for the relevant manufacturer and/or turbine operators but also against whole of wind power industry.

IEC/TC88/MT24 are also discussing the agreeable expression of detail aspects of damages in blades, which can be described as follows;

- rupturing – a sudden or immediate break of blade separating into two or more parts, like exfoliation of bond weld between two blade shells and/or large cracks in blade shells.
- falling – a drop of any components of blade onto ground including a whole blade, a part of blade shell, the blade tip, a receptor and so on.
- burnout – loss of the whole or part of the blade due to fire originally caused by lightning.
- air brake control wire melting – melting and breaking of a down conductor due to large joule energy of lightning current passing through it.
- down conductor melting – melt down and break down of a down conductor due to large joule energy of lightning current passing through it.
- sparking between broken wire end – electric discharge due to lightning between a gap of broken wires.
- cracking – a crack along bond weld that glue two blade shells but the bonding is still kept partly.
- tearing – a break of part of a blade shell but the broken part still contacts to the rest of the healthy part.
- surface stripping – a small break of fibres on the surface of blade.
- loss of a small part of receptor – a break of part of a metallic receptor into pieces. If the broken part is substantial and falls onto ground, the event should be categorized into Category (IV-d) depending upon the circumstances around the turbine.
- melting – a small break of receptor due to melting after being attached by lightning with large energy.
- scorching – a change of color into back of the blade surface.

IV. Possible Cuases of Blade Damage due to Lightning and their Recommended Countermeasures

Possible causes of damages in wind turbine blade due to lightning has been considerably clarified by investigations on the past turbine incidents [4]. Most of the incidents classified into (IV) Catastrophic incident have occurred in poor blades as following;

- old blade designs that have tip air brake control wires,
- poor blade designs, such as with imperfect specified mechanical bonding of receptors to the main body of the blade,
- blades with poor manufacturing quality blade, such as with imperfect glue bonding between blade shells.
- poorly maintained blades, such as oversight, neglect or underestimation of past damages.

The cause of blade rupturing and cracking is normally considered to be immediate vaporisation of water inside the blade shells, that incident merely occurs in well-designed and well-installed blade. Another possible reason of blade rupturing or cracking is inappropriate selection of LPL level. In particular, highly careful consideration should be needed to area where upward lightning with large energy are expected

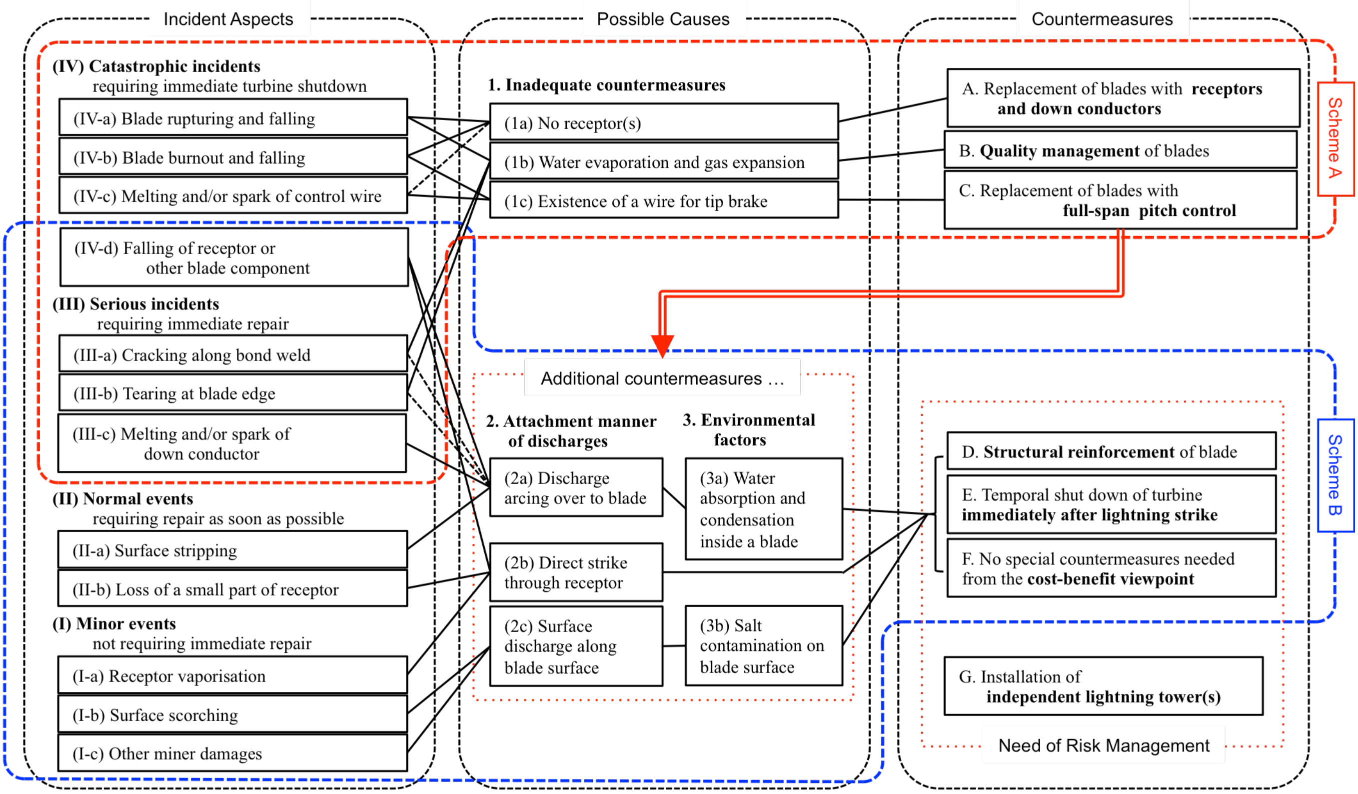

Figure 2. Recommended countermeasures schemes according to the incident classification

such us in Japan.

Corresponding the possible causes of blade damages, appropriate countermeasure should be required. To avoid the Level (IV) incidents, that may frighten public safety, many players should pay attention to clear imperfect condition; for blade manufacturer, imperfect design and/or installation should be reviewed; for wind power plant operators, appropriate inspection technique and process should be improved; for certification body and regulators, the optimal commercial/legislative scheme should be established.

Figure 2 shows the recommended countermeasures according to the classification of blade damage due to lightning. Scheme A in this figure denotes the above-mentioned appropriate countermeasures to avoid the Level (IV) incidents. Even after the appropriate countermeasures, incidents cannot be exterminated completely. Extermination of all level of incidents/events should not be aimed because the effort may not reasonable and far from the philosophy of risk management.

Temporal shut down of the damaged turbine as shown in Figure 2 may be the most realistic countermeasure to reduce the total risk of lightning damage. Immediate inspection by skilled workers, or automatic and remote inspection if possible, is recommended soon after the temporal shut down.

Actually, after the investigation and discussion on the latest subsequent wind turbine incidents in Japan by Working Group on Incident Correspondence and Structure Enhancement for New Energy Generation Facilities [6] in the Ministry of Economy, Trade and Industry (METI), Japan, the newly revised interpretation of the Ministerial Order No.1997-53 "Technical Standard on Wind Energy Generation Systems" was released by METI. In the revised interpretation by METI, which is considered as a *de-facto* standard in Japan, a requirement of the temporal shut down after lightning strike to wind turbines in winter lightning area in Japan was added [7].

Table IV also shows a matrix of risks and their countermeasures against blade damage due to lightning, taking into account of risk management. This table does not only show risks by damage of blade but also describe risks of lost profits caused by stoppage of turbine operation. Note that the length of stoppage does not always depend upon the level of incident but strictly upon quality of maintenance scheme like as following;

- availability of service personnel who are specialists of wind turbine maintenance,
- availability of spare parts,
- availability of relevant vehicles, lifts, cranes, jack-up vessels etc. as needed to repair or re-install the

TABLE IV. MATRIX OF BLADE DAMAGES DUE TO LIGHTNING, TAKING ACOUNT OF RISK MANAGEMENT

Level		**(IV) Catastrophic incident**				**(III) Serious incident**			**(II) Normal event**		**(I) Minor event**		
Damage Aspect		(a)	(b)	(c)	(d)	(a)	(b)	(c)	(a)	(b)	(a)	(b)	(c)
		Blade rupturing and falling	Blade burnout and falling	Melting and/or spark of control wire	Falling of receptor or other blade component	Cracking along bond weld	Tearing at blade edge	Melting and/or spark of down conductor	Surface stripping	Loss of a small part of receptor	Receptor vaporisation	Surface scorching	Other minor damages
Risk Management (qualitative suggestion)	Possibility of human suffering	high				slightly high			almost no		no		
	social influence	very high				low			almost to		no		
	need of blade replacement	yes			no	sometimes yes			almost no		no		
	assumed repairing method	special crane for blade replacement			crane	gondola or crane			high-place work vehicle		makeshift scaffold or rope work		
	party reasonable for repair	depends on insurance / service / contract / age of blade							local builder or ship repairer		local builder or local staff on site		
	estimated repairing cost	very high			low to high	high			medium		low		
	time for loss of generation	several months			several days	several weeks			several days		almost no (repaired in periodic maintenance)		
	lost profits	very high			low to high	high			low		almost no		
	probability	very low (depend on the area)			low	relatively low			relatively high		high		
	countermeasure cost	very high			medium	medium to high			low to medium		non to medium		

broken blade,

- appropriate contract agreements with suppliers and/or maintenance service.

V. Lightning Damages in other Components

On contrast to blades, other components inside a nacelle and a tower are not so prior for public safety unless mechanical control would be lost due to lightning. Countermeasure to protect of these components can be treated in scheme of commercial cost-benefit design/operation.

The damage classification of wind turbine components excluding blades can be also categorised in same manner as that of blades. Table V shows the classified damages into four levels with examples of damage aspects.

TABLE V. Classification of Damages in other Components due to Lightning

(IV) **Catastrophic incident**	
e.g.	• injury and/or death of workers inside/near turbine • burnout of nacelle
(III) **Serious incident**	
e.g.	• insulation breakdown of generator or transformer • break down bearings
(II) **Normal event**	
e.g.	• breakdown of earthing system • insulation breakdown of converter and other power-electronics devices
(I) **Minor event**	
e.g.	• insulation breakdown of monitoring, control or communication device

Countermeasure against lightning damage in other components can also be done in same way as that for blades. However, it should be noted that the Level (I) Minor event in other components does not always means the event that does not require immediate repair like in the classification for blade, where the viewpoint of public safety is needed. Neglecting even the minor event in monitoring, communication and control devices may occur catastrophic incident due to loss of control of the turbine.

To reduce stoppage hours and therefore lost profits, it is also recommended to take appropriate maintenance scheme where adequate preparation for unexpected incidents or events.

VI. Risk Management and Lightning Protection of Wind Turbines

Finally, in this chapter, relationship between risk management as introduced in Chapt. II and the above-mentioned lightning protection of wind turbines are discussed. While the Fig.1 is a simple matrix of risk management for general purpose, an application of the concept of risk management to the lightning protection of wind turbine blades can be considered as shown in the below sections.

A. Risk Aboidance

Domain I in Fig.1 denotes the area where the both of the magnitude of consequence and the probability of the event are expected to be high. As the risk in this case is expected to be intolerable, “risk avoidance” should be fundamentally taken. In this case, business closure or product recovery can be considered as a common treatment.

In case of wind turbines, it can be related to approvals and certifications that strictly check whether the turbines have the ability to reduce the level of risk to Domain II or III. Turbines that are planned to be installed in winter lightning area such as the costal area of the Sea of Japan are highly recommended to be considered the scheme.

Old turbines that were installed before the first half of 2000s, almost of which have tip breaks on their blades, tends to have poor countermeasures for lightning protection. As tip-break wires in their blade often used as down conductors, damages to those blades have “happened in cases where the steel wire controlling the tip brake was of insufficient cross section to conduct the lightning current from the tip shaft to the hub” [8]. It is therefore highly recommended to rebuild new blades with a full-span pitch control, corresponding to “Scheme A” in Fig.2.

Another possible countermeasure would be “repowering”, that means rebuilding a new large turbine with the latest lightning protection technique after decommissioning the multiple old turbines in the same site. Political incentives to repower the old turbines could be helpful to reduce the catastrophic incidents in insufficient turbines.

B. Risk Acceptance

Domain II in Fig.1 corresponds to the case where the magnitude of consequence is expected high but the probability of the event is low. In this case, the risk can be reduced by externalisation of the risk using insurance scheme and/or outsourcing of maintenance to the third parties.

What should be noted is the fact there would be “moral hazard” in insurance scheme, which is a disincentive when an insurance subscriber tends not to take care appropriate maintenance due to expectation of payment by insurance in case of incidents. To avoid the moral hazard, it is important to reduce “asymmetry of information” and therefore to investigate and publish the statistical data on turbine incidents as well as possible.

C. Risk Reduction

Domain III is the case where probability of the event would be high but the magnitude of consequence is low. In case, many manufactures would take risk reduction like quality improvement. For wind developers, it corresponds to a series of maintenance schemes including not only periodic inspections but also an appropriate and speedily responses to incidents.

For example, according to the investigation in the WG of METI, Japan, lack or shortage of inspections after the past minor damages due to lightning were highly suspicious as the reason of several catastrophic damages in recent Japan.

To avoid the cases, technical innovations like a fortified blade material and/or an intelligent lightning sensor systems would be needed, which correspond to the countermeasures D and E in Fig.2). It is also important to enhance political/economical supports that promote turbine owners and managers to understand importance of maintenance and invest more to reduce incidents and unexpected stoppages. The more effort to maintenance can reduce the risk the more, and *vice versa*.

D. Risk Retention

The final domain, Domain IV in Fig.1, means the case for risk retention, where neither the magnitude of consequence nor the probability of the event is significant. However, it should be noted, risk retention is completely different from ignorance of risks. Ignorance and unconcern of risks is considered as one of the highest risks. Firm periodic inspection with ordinary tasks is surely important.

In some cases like a minor breakdown in an electronic device, an ex-post measure would be better than a high-cost pre-measure from the viewpoint of cost-benefit balance (corresponds to countermeasure F in Fig.2). Even in the case, spare parts and special tools should be appropriately prepared. Also, education and deployment of well-trained staffs is important from long-term viewpoint. It is natural that a reliable and redundant fail-safe system should be installed, otherwise a minor event easily grow worse to a catastrophic incident like tower collapse or blade falling.

In this manner, the concept of risk management depending upon the damage levels and types of risks will help a reasonable lightning protection of wind turbines.

VII. CONCLUSION

This paper introduced the general concept of risk management and proposed an application to lightning protection of wind turbine. An incident of wind turbine may give significant influence to social acceptance and could be strong barriers against development of wind power, especially in Japan and other countries where wind power has not fully developed. To reduce the turbine incidents, it became more and more important that the past incident data should be statistically investigated, published and analysed to help to avoid incidents in future.

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