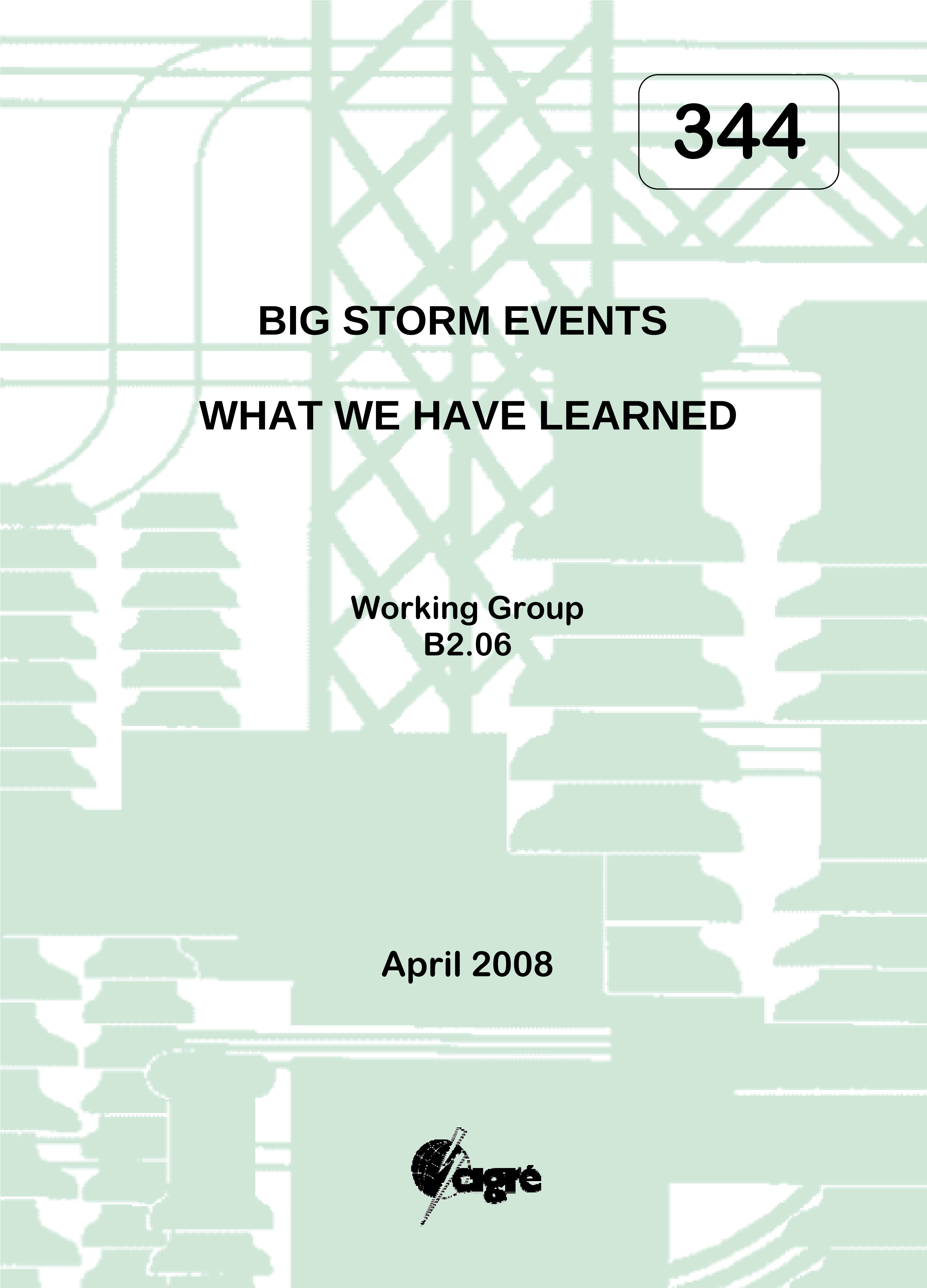

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BIG STORM EVENTS

WHAT WE HAVE LEARNED

Working Group
B2.06

April 2008

April 2008

Big Storm Events: What we have learned

Working Group B2.06

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1. Executive Summary

Introduction

After the storm events in Canada in early 1998 and again in France in late 1999, the idea to share information on the impact of severe and widespread Big Storm Events on overhead lines grew strongly in CIGRE WG B2.06.

A one page Questionnaire "Lessons to be drawn from Big Storm Events" was issued in 2006 in order to identify other similar events and to collect all information **available** to the public regarding:

- The knowledge of characteristics and origin of the storm event as well as its impact on overhead lines;
- The strategy of upgrading and adapting the network for future similar or more severe events;
- The need of improving design practices and emergency preparedness.

Initially CIGRE WG B2.06 intended to limit the subject to high synoptic winds as they correspond to the design principles of the International Standard IEC 60826 [1; 2]. However as the study progressed, information on localized High Intensity Winds, such as downdrafts and tornadoes, became available, hence those phenomena have also been considered.

Therefore, a clear definition of a Big Storm Event was needed to share and to compare the appropriate information.

General questions

There were four General Questions in the Questionnaire:

- 1. How would you **define** a "Big Storm Event"?
- 2. What would you like to see **discussed** in a CIGRE Technical Brochure?
- 3. Do you want to reply to **some questions** on a "Big Storm Event" in your country?
- 4. Are the **reports** on this "Big Storm Event" and the mitigation actions available to the public and CIGRE WG B2.06 for publication?

The following countries responded to the Questionnaire:

- Africa: Algeria, South Africa;

- Asia: China, Japan;
- Europe: Austria, Belgium, Bosnia and Herzegovina, Czech Republic, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Russia, Serbia, Spain, Sweden, Ukraine, United Kingdom;
- North America: Canada, USA;
- Oceania: Australia, New Zealand;
- South America: Brazil, Venezuela.

Criteria for the definition of a BSE

WG B2.06 suggested the following criteria for the definition of a Big Storm Event:

- Climatic load in excess of normal design load;
- Widespread climatic event;
- Major damage to the network system;
- Major outages;
- Impact on population;
- Use of emergency restoration systems;
- Upgrading of existing lines by either:
  - decreasing impact of climatic loads;
  - increasing strength of line components;
- Requiring a review of design rules for new lines;
- Other.

CIGRE WG B2.06 found it useful to ask the CIGRE Colleagues to validate the criteria of the definition of a Big Storm Event. CIGRE WG B2.06 was aware that some criteria were only consequences or lessons drawn. Nevertheless causes, consequences, mitigation and adaptation were included in the survey to ensure the appropriate definition was arrived at.

Ranking of the criteria on BSE definition

Table S.1 gives the ranking system of the criteria for the definition of a BSE according to all responders to the Questionnaire.

One can notice that the "*major damage to the network system*" and the "*climatic load in excess of normal design load*" are far away the most important criteria (respectively 93% and 90% of the votes) for the definition of a Big Storm Event.

Table S.1 – Definition of a BSE according to all responders

	Votes	Criterium
1	93 %	Major damage to the network system
2	90 %	Climatic load in excess of normal design load
3	85 %	Major outages
4	80 %	Requiring a review of design rules for new lines
5	73 %	Impact on population
6	68 %	Widespread climatic event
7	63 %	Upgrading by increasing strength of line components
8	48 %	Use of emergency restoration systems
9	43 %	Upgrading by decreasing impact of climatic loads
10	13 %	Other

As damage to the overhead lines is not always followed by an extended blackout, except when the distribution lines are also destroyed, e.g. by falling trees, the criterium on "*major outages*" was found less important (85%) than the damage itself. Nevertheless the quick and safe restoration of power to customers is one of the leading objectives for many utilities.

It is remarkable that the consequences of failures, such as damage and outages, are considered on average more important criteria than the initial causes of the line failures, such as a "*climatic load in excess of normal design load*" (90%) and a "*widespread climatic event*" (68%). Nevertheless, in countries where widespread windstorms and ice storms similar to the events in Québec (1998) and France (1999) occurred, the criteria on the causes of the event are by far the most important criteria.

If the return period of a devastating climatic event was much greater than the return period considered for the design, a Big Storm Event is generally followed by a "*review of the design rules*" (80%) for new lines. Mostly climate parameters (gust wind speed; ice load) or even loading conditions are reviewed. This is particularly true for ice loadings, which are often increased and sometimes even doubled, when more reliable statistical data on ice accretion became available.

The variety of different views expressed by the responders is illustrated in **Figure S.1.**

As a conclusion of the ranking system and the various comments received, one can establish that the definition depends mostly on the type of the climatic event. Is it either a large-scale Big Storm Event or a small-scale High Intensity Wind phenomenon?

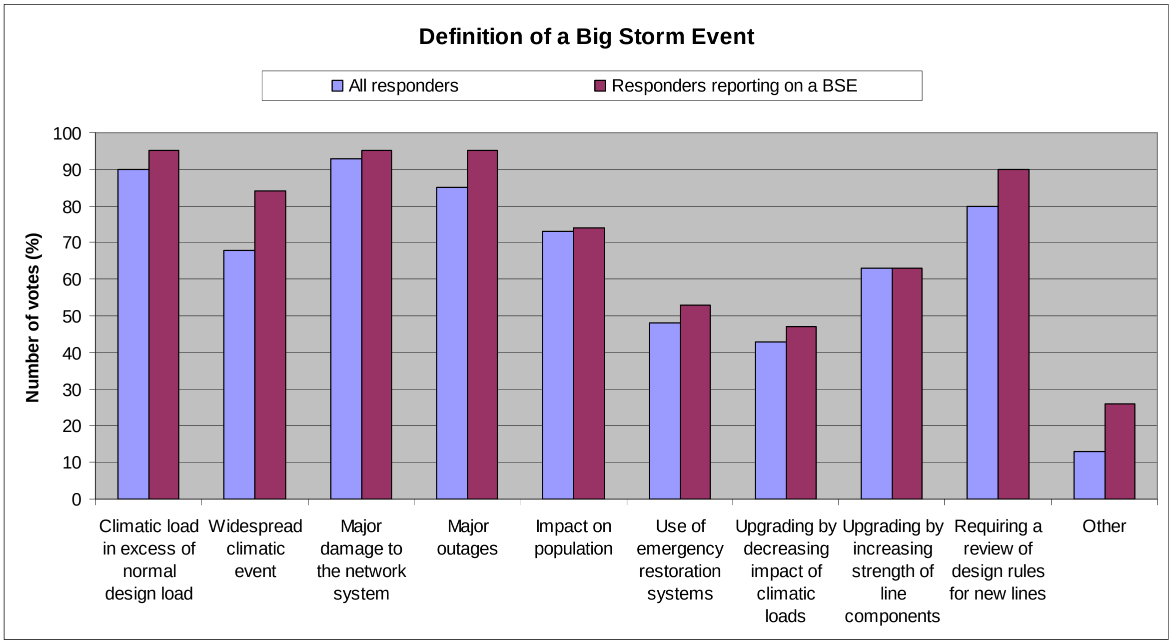

Figure S.1 – Criteria for the definition of a BSE according to all responders and responders reporting on a Big Storm Event

In this context, most European countries consider that the two following criteria are the most important ones to define a Big Storm Event:

- A climatic load in excess of normal design load;
- A widespread climatic load.

For most countries, especially outside Europe, a widespread storm event cannot be defined as a Big Storm Event. This is due to the fact that localized High Intensity Winds, such as downdrafts and tornadoes, which are locally more devastating, are small-scale phenomena compared to the European windstorms and even tropical cyclones. Therefore CIGRE WG B2.06 proposes distinguishing between these two storm event types on the basis of **severity** and **area**:

- Widespread Big Storm Events (BSE), including large-scale European windstorms and tropical cyclones (hurricanes, typhoons, cyclones);

- Localized High Intensity Winds (HIW), such as small-scale downdrafts and tornadoes.

This distinction is in line with CIGRE Technical Brochure "How Overhead Lines Respond to Localized High Intensity Winds – Basic Understanding" [3], where specific loading cases are discussed for localized High Intensity Winds, opposed to the widespread Big Storm Events that correspond to the synoptic winds considered by the International Standard IEC 60826.

Aim of the Technical Brochure

The responders identified the aim of the Technical Brochure:

- Identification and assessment of corrective and preventive actions, including design code changes for new lines;
- Comparing worldwide experience on preventive and corrective actions;
- Sharing lessons in emergency preparedness;
- Observation of the type, the cause and the destructiveness of the storm event.

According to the comments, the characteristics of the Big Storm Events and the causes of the initial and secondary failures have to be analyzed in depth before appropriate actions can be taken. Obviously those actions are linked to the type of the storm event.

Therefore the CIGRE Technical Brochure also includes background information regarding the origin and impact of the different types of storm events. It covers such topics as:

- Cause of wind storms: wind mechanism; wind speed and direction; wind shear; wind fronts; classification of wind storms;

- Different types of severe storm events: European windstorm; winter storm with freezing rain; tornadoes and downdrafts emanating from thunderstorms; tropical cyclones; coupled ocean-atmosphere phenomena;

- Effect of climate change on the magnitude, duration and frequency of Big Storm Events: climate change; global climate models; greenhouse effect; history of natural climate change; 4th Assessment Report of IPCC; projections of extreme storm events;

- Adaptation strategy to climate change.

This background information was also requested by a majority of responders to the questionnaire.

Specific regional aspects of recent BSE

Some responders provided detailed and relevant information regarding severe storm events that affected their country. All those items have been considered as available and accessible to the public. The following items are discussed country by country:

- Observation of the storm event and its consequences:
  - Type of storm, date, duration, location;
  - Extent of outages and emergency restoration of power;
  - Extent of damage;

- Assessment of the storm event and comparison between the meteorological data and the current design parameters:
    - Origin of the storm;
    - Weather data of extreme wind speed and / or ice deposits;
    - Original design parameters, if available

- New developments:
    - New strategies or policies;
    - New design rules;
    - Rebuilding, innovative solutions;

- Conclusion.

All those specific aspects, if available, are considered for the following cases:

- Windstorms: France 1999, Belgium 1990, Sweden 2005, USA 2006;
- Ice or snow storms, with or without wind: Canada 1998, Czechoslovakia 1974, Germany 2005, Japan 1980, Ukraine 2000, USA 2005;
- Tropical cyclones: Tenerife 2005, Australia 2006, USA 2004 and 2005;
- Downdrafts and Tornadoes: Canada 1996, New Zealand 2004 and 2005, Ukraine 2000, Brazil 2005.

Common features of BSE

Three recent large-scale climatic events were selected with a different loading case:

- Ice only (Canada 1998);
- Wind only (France 1999);
- Combined wind and ice (Germany 2005).

Table S.2 summarizes the characteristics of the climatic events and the impact on the area and population.

Table S.2 – Some typical climatic events

Date of event	Country	Type of climatic load	Area affected (km^2)	Inhabitants without electricity
05-09.01.1998	Canada (Québec)	Ice (freezing rain)	150 000	1 500 000
26+28.12.1999	France (North & South)	Wind only	2/3 of the territory	4 500 000
24-25.11.2005	Germany (Münsterland)	Wet snow + wind	1000	300 000

Independently of the loading case, similar climatic events lead to catastrophic widespread damage to the overhead lines and result in major outages which affected millions of customers for prolonged periods.

Comparison between the lessons learned from various climatic events with major damages and outages is difficult, because each event has its own specific characteristics. As there are strong links between causes and consequences, actions taken after such storms are mostly compatible with the type of storm.

Nevertheless, an attempt to synthesize the most relevant lessons learned has been made in the next clause.

What we have learned

Some **Utilities** decided on new policies and strategies after Big Storm Events. In some countries, all measures taken must guarantee that service should be reinstalled within a limited number of days. Power must remain supplied to all substations.

For the System **Operators**, identification of strategic lines is fundamental. The robustness of the network can be improved by better meshing and interconnection of lines. Putting strategic lines in the same corridor must be avoided, especially in zones prone to bad weather events. Strategic lines must be built far away from each other, except when the environmental requirements dominate. If needed, overhead lines are replaced with underground cables.

Big Storm Events are incentives to intensify specific **maintenance** programs. Poor condition of the weakest elements sensitive to primary failures has to be registered systematically. Vegetation management includes clearing vegetation and widening of corridors to avoid trees falling on conductors and supports, especially when fast-growing trees threaten the conductors. During severe ice events, it is recommended to keep into service all circuits to avoid additional unbalanced ice loadings.

Designers who have to check less reliable lines may rank the most sensitive supports based on the use factor, taking into account the real span, height, line angle, line direction, etc., that are in general lower than the design parameters. But by contrast, designers must be well aware that design wind speed can be exceeded due to local topography (ridges and slopes). If the climatic load was in excess of normal design load, wind speed or characteristic ice loads are reviewed on the basis of more reliable statistical data, the zone of high wind speeds or ice loads may be widened, or even new load cases may be considered such as combined wind and ice loads. Wind and ice maps are updated. Due to the lower torsion rigidity of the earth wire, it is now recommended to consider at least the same ice weight as for the single conductors. No country, except Brazil, mentioned the transfer from deterministic methods to Reliability Based Design Methods, such as the International Standard IEC 60826 [1].

In order to **limit secondary failures** by installing anti-cascade towers, by using load control devices, etc. it is necessary to distinguish secondary failures from primary failures.

Upgrading steel lattice towers is in general relatively easy, by replacing or doubling steel angles. The buckling length of primary members can be reduced by the addition of secondary members. Wood poles may be replaced with concrete poles. Other timber products such as laminated wood systems (LWS) may be used. Increasing the reliability level of overhead lines can also be realised by decreasing impact of wind or ice loads. Some innovative solutions are described in the Technical Brochure. The need for de-icing methods, ice warning systems and ice test stations is mentioned many times.

An **emergency response** plan includes not only the emergency restoration systems and spare material stocks, but also the complete organisation structure, reciprocal assistance agreements and regular classroom and field exercises to implement the emergency plan. A good balance between preventive and corrective measures is highlighted. Both are useful and complementary. The risks of identified events have to be determined, as well as the resources required for power restoration in a specified time frame.

Before taking actions, **Asset Owners** would like to understand the characteristics of the storm event that occurred. Was it an exceptional event? Can it happen again? Therefore the basic understanding of the meteorological phenomena and their impact on lines is essential. Especially continuous research on the wind profile of High Intensity Winds is needed, as those events are difficult to forecast in time and space [3]. Utilities already improved their communication with **weather stations** to be better prepared in advance by being informed regarding forecasts of severe weather phenomena.

Finally **companies** must be able to timely and accurately determine a global estimated restoration time and **communicate** that to the customers and the population.

What effect climate change can have on storm events

According to the Summary Reports of the Fourth Assessment Report (4AR) of the Intergovernmental Panel on Climate Change (IPCC) issued on February-May 2007 [4] it is likely (confidence level 66%) that future tropical cyclones (hurricanes and typhoons) will become more intense, with larger gust wind speeds and more heavy precipitation, due to further warming of sea surface temperature.

Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity and there is no clear trend in the annual numbers of tropical cyclones.

There is now 50% confidence that there is a human contribution to the observed trend of intense tropical cyclone activity increase. Wind, solar and nuclear energy are mitigation strategies for generating power in order to prevent excess greenhouse gases from being released in the atmosphere.

Adaptation strategy becomes necessary for Asset Owners as global warming will get worse before it could get better by mitigation policies, because heat trapping greenhouse gases, such as carbon dioxide, are chemically stable and long-lived atmospheric gases.

The threat of climate change is now more widely understood. Nevertheless, more research and knowledge is necessary regarding the structure, the probability, the intensity, the duration, the frequency, the extent, the location and the track of severe weather events.

Recommendations

On the basis of the lessons learned WG B2.06 recommends:

- Taking immediate aerial photos and videos on site before clearing the damaged structures after a Big Storm Event. This can facilitate the assessment of the origin of direct failures (wind or ice) and indirect failures (fallen trees), and allow designers to distinguish between the primary failures and the secondary failures, including the cascade failures;

- Collecting all meteorological data available, to analyse and to understand the storm event (type, origin, location or track, intensity, duration, and correspondence with forecast);

- Performing failure analysis (observation on site, test on samples, calculations);

- Understanding the relation between:
    - The climatic load;
    - The existing strength of line components, taking into account the condition of most sensitive elements;

- Developing strategies and policies for:
    - increasing structural and electrical reliability;
    - improving availability and continuity of service;
    - taking appropriate actions to reduce possible secondary failures and cascades;

- Finding a good balance between:
    - corrective measures to take after an unexpected storm event (quick restoration of power and services, emergency supply, rebuilding, etc.);
    - preventive measures taken before a possible storm event (new design rules, preparedness, spare parts, emergency response plan, including organisation, resources and training, etc.);

- Improving basic understanding and knowledge about climate features, their changes and their impact on overhead lines;

- Finally, facilitating transfer from deterministic to reliability based design methods of overhead lines based on the International Standard IEC 60826 [1; 2]. Loads and strengths are recognized as random variables. With statistical data, designers can associate a value of wind or ice load for any selected climatic return period or reliability level.

General conclusion

With the answers to the Questionnaire issued, CIGRE WG B2.06 was able to collect and compare worldwide information on Big Storm Events during last decades in order to share experience in adaptation strategy and emergency preparedness. WG B2.06 also provided some additional recommendations.

References

[1] IEC 60826, “Design Criteria of Overhead Transmission Lines”, Edition 3, October 2003.

[2] WG 22.06, "Probabilistic Design of Overhead Transmission Lines", CIGRE Technical Brochure No.178, February 2001.

[3] WG 22.06, "How Overhead Lines respond to Localized High Intensity Winds – Basic Understanding”, Electra Journal, to be published in 2008.

[4] Intergovernmental Panel on Climate Change (IPCC). Fourth Assessment Report, WG I. The Physical Science Basis. Paris, France, 2007.

2. Introduction and scope

The idea to share information on Big Storm Events (BSE) grew strongly after the severe and widespread storm events in Canada in early 1998 and again in France in late 1999.

Therefore a Questionnaire was issued by CIGRE Working Group (WG) B2.06 on January 27, 2006 to identify other similar events, and to collect all information **available** to the public regarding:

- The knowledge of characteristics and origin of the storm event;
- The strategy of upgrading or adapting the network;
- The need for improving design practices and lessons in emergency preparedness,

so that this information could be shared and lessons drawn. It was obvious that corrective and preventive actions are linked to the type and destructiveness of storm events.

Initially WG B2.06 intended to limit the subject to high synoptic winds as they correspond to the design principles of the International Standard IEC 60826. However as the study progressed information on localized High Intensity Winds (HIW), such as downdrafts and tornadoes, became available, hence those phenomena have also been considered.

Clause 3 introduces the Questionnaire on the Big Storm Events. In order to share the appropriate information, it was needed to provide a clear definition of a Big Storm Event. WG B2.06 preferred to submit the criteria for a definition to the responders. Clause 4 focusses on the statistical results of the enquiry and some relevant comments as well. Clause 5 clarifies what experts would like to see discussed in this Technical Brochure and it summarizes the major characteristics of the storm events that have been reported.

Clause 6 provides some useful excerpts of a previous WG B2.06 report on line failures and their causes. Clause 7 gives two approaches for Upgrading processes after big storm events.

As announced in Clause 8, the lessons learned from large-scale synoptic winds (Canada, France, Belgium, Sweden, Germany, Czech Republic, Ukraine, Japan, Spain, Australia, USA) and small-scale HIW (Canada, New Zealand, Ukraine, Brazil), especially regarding new strategies and new design criteria, are synthesized respectively in Clauses 9 and 10. Clause 11 summarizes the lessons drawn from those events. Finally, clause 12 gives some recommendations. The list of references is shown in Clause 13.

The events mentioned in Clauses 9 and 10 are fully reported respectively in Appendices A and B. According to the demand of the responders to the Questionnaire, Appendix C provides some background information on the causes of widespread Big Storm Events and localized High Intensity Winds as well as the possible consequences of climate change. Summarizing synoptic tables can be found in Appendix D. The Questionnaire is given in Appendix E.

3. Answers to the Questionnaire

3.1 General questions of the Questionnaire

There were four General Questions in the Questionnaire “Lessons to be drawn from Big Storm Events”:

- 1. How would you **define** a "Big Storm Event"?
- 2. What would you like to see **discussed** in an Electra Report and/or in a CIGRE Technical Brochure?
- 3. Do you want to reply to **some questions** on a "Big Storm Event" in your country?
- 4. Are the **reports** on this “Big Storm Event” and the mitigation actions available to the public and WG B2.06?

In general, the sub-questions in the one page Questionnaire were quite simple. The answer is mostly "yes", "no" or a specific value. The last column entitled "Comment" could be used by the responder for additional information or clarification.

The Questionnaire issued by CIGRE WG B2.06 “*Principles of Overhead Line Design*” on January 27, 2006 is given in Appendix together with the letter for additional information.

The objective of the Questionnaire was consistent with the current Terms of Reference of CIGRE WG B2.06:

*"CIGRE WG B2.06 deals with methods to **improve electrical and mechanical design** of Overhead Line systems, including Reliability Based Design methods, taking into account better knowledge of **meteorological issues**."*

3.2 Responses to the Questionnaire

In 2006, the following countries responded to the Questionnaire (the values between brackets indicate the number of answers reported if more than one):

- Africa: Algeria, South Africa;
- Asia: China (4), Japan;
- Europe: Austria, Belgium, Bosnia and Herzegovina, Czech Republic, Denmark, Estonia, Finland, France, Germany (3), Ireland, Italy (2), Netherlands, Norway, Poland, Portugal, Russia, Serbia, Spain, Sweden (3), Ukraine (2), United Kingdom;
- North America: Canada (2), USA (4);
- Oceania: Australia, New Zealand;
- South America: Brazil, Venezuela.

Synoptic Table D.1 in Appendix D gives more details about those responders and their answers in general.

3.3 Summary of the responses to the Questionnaire

The Synoptic Tables D.1 to D.7 in Appendix D are based on the responses to the 4 Questions in Questionnaire in Appendix E:

- Table D.1 – List of all (44) answers to the one page Questionnaire on “Lessons to be Drawn from Big Storm Events”;
- Table D.2 – List of the (40) answers to Questions 1 & 2;
- Table D.3 – List of the (19) answers to Questions 1 & 2 only for a widespread BSE;
- Table D.4 – List of all (44) answers to Questions 3 & 4;
- Table D.5 – List of the (27) answers to Questions 3 & 4 if a BSE is reported (1/2);
- Table D.6 – List of the (27) answers to Questions 3 & 4 if a BSE is reported (2/2);
- Table D.7 – List of the additional comments clause wise.

Number of all answers received: 44 (given in Tables D.1 and D.4);
Number of countries that responded: 31;
Number of answers to Question 1 & 2 received: 40 (given in Table D.2);
Numbers of answers only if a widespread BSE was reported: 19 (given in Table D.3);
Number of answers to Question 3 (on events) received: 27 (given in Tables D.5 and D.6);
Number of all answers received with reference to full reports on BSE or in attachment: 13.

The full reports that are available and accessible to the public are listed in Clause 13.1 “References”.

Tables D.5 and D.6 give all information on the Big Storm Events as provided by the responders reporting on a Big Storm Event.

4. Criteria for a Big Storm Event

4.1 Criteria for a definition

The idea to share information on Big Storm Events (BSE) grew strongly after the severe and widespread storm events in Canada in early 1998 and again in France in late 1999. In order to achieve this purpose it was needed to provide an appropriate definition.

CIGRE WG B2.06 suggested the following criteria for the definition of a BSE:

- Climatic load in excess of normal design load;
- Widespread climatic load;
- Major damage to the network system;
- Major outages;
- Impact on population;
- Use of emergency restoration systems;
- Upgrading by either:
  - decreasing impact of climatic loads;
  - increasing strength of line components;
- Requiring a review of design rules for new lines;
- Other.

However WG B2.06 found it useful to ask the CIGRE Colleagues to validate the criteria of the definition of a Big Storm Event. WG B2.06 was aware that some criteria were only consequences or lessons drawn. Nevertheless causes, consequences, mitigation and adaptation were included in the survey to ensure the appropriate definition was arrived at.

4.2 General ranking system of definition criteria

Table 1 below gives the ranking system of the criteria for the definition of a BSE according to all responders to the Questionnaire (based on Table D.2).

Table 1 – Definition of BSE according to all responders

	%	**Votes**	**Criterium** (The number refers to the Questionnaire)
1	93	37/40	1.3 – Major damage to the system
2	90	36/40	1.1 – Climatic load in excess of normal design load
3	85	34/40	1.4 – Major outages
4	80	32/40	1.8 – Requiring a review of design rules for new lines
5	73	29/40	1.5 – Impact on population
6	68	27/40	1.2 – Widespread climatic load
7	63	25/40	1.7.2 – Upgrading by increasing strength of line components
8	48	19/40	1.6 – Use of emergency restoration systems
9	43	17/40	1.7.1 – Upgrading by decreasing impact of climatic loads
10	13	5/40	1.9 - Other

One can notice that the "*major damage to the network system*" in general and "*to the overhead lines*" in particular as well as the "*climatic load in excsess of normal design load*" are far away the most important criteria (respectively 93% and 90% of the votes) for the definition of a Big Storm Event.

As damage to the overhead lines is not always followed by an extended blackout, except when the distribution lines are also destroyed, e.g. by falling trees, the criterium on "*major outages*" is still less important (85%) than the damage itself to the operation system.

Some responders declared that major damages and outages are only consequences of the events. Sven Hoffmann (United Kingdom) stated "*a widespread occurrence of loads in excess of the normal design loads would be highly likely to cause major damage, resulting in major outages and a significant impact on population*". He also explained that "*other events may lead to the same or similar outcomes*". They may be combined with widespread occurrences of poor asset condition.

If the return period of a devastating climatic event was much greater than the return period considered for the design, a Big Storm Event is generally followed by a "*review of the design rules*" (80%).

The review of design rules for new lines has been considered as a lesson learned from Big Storm Events. Mostly climate parameters (gust wind speed; ice accretion) or even loading conditions are reviewed. This is particularly true for ice loadings, which are often increased and sometimes even doubled. Ice load needs a longer observation period than wind load in order to obtain as reliable statistical data as wind speed. If appropriate, combined wind and ice loading conditions can be considered for particular regions. It may also flow out of a Big Storm Event, that minor changes to designs could limit any damage. Nevertheless going through a progressive review of the design loads may also lead to the conclusion that the current reliability levels are still reasonable and practical.

It could be surprising that the "*impact on population*" is considered only as the fifth most important criterium (73%). This is probably due to the perception that this criterium does not deal with the consequences of the outages, but rather with the fact that the number of deaths and injuries due to overhead line failures is mostly negligible compared with other catastrophic events. Nevertheless the quick and safe restoration of power to customers is one of the leading objectives for many utilities.

As a number of responders did not suffer "*widespread climatic events*" but only localized High Intensity Winds, such as downdrafts and tornadoes, this criterium is qualified 68%.

Upgrading of the damaged lines "*by increasing strength of line components*" (63%) is still more usual than "*by decreasing impact of climatic loads*" (43%). Certain countries hold the view that increasing structural reliability would depend on whether the extreme event was likely to reoccur or whether it could be classified as a once off "act of God". Depending on the view point taken, it may be or may not be necessary to consider this new climatic load for future line designs. For Sven Hoffmann (United Kingdom) "*the criteria on increasing* *structural reliability (upgrading) are not criteria necessarily defining a BSE*". He continues: "*In the case of any failure of an OHL component I would expect the cause of that failure to be reviewed and appropriate actions taken in the light of the results of the findings, including a review of design criteria following significant climatic events*".

Only a limited number of utilities consider that damage to the overhead lines due to a Big Storm Event does not necessitate the provisional restoration of the line by "*using Emergency Restoration Systems*" (48%). The criterium on Emergency Restoration Systems is ranked nearly in the last place. Probably a more general criterium such as "*Preparedness*" or "*Emergency Planning*" should have a much better qualification. One responder argued that such systems are important but generally not available in enough quantity for an extended Big Storm Event. However they are still necessary to reinstate quickly. Emergency Restoration Systems are more useful if the number of towers failed is limited, especially when only one tower collapsed, for instance due to flooding. However, in France, the distance between anti-cascading towers equals the length of their emergency restoration lines, so that a provisional restoration is often possible.

Finally there are only a very few other criteria mentioned for Big Storm Events that were not foreseen by WG B2.06. Man made pollution and salt sea with wind on composite or glass coated insulators have been mentioned and falling trees on distribution lines as well.

The variety of different views expressed by the responders is illustrated in **Figure 1** below.

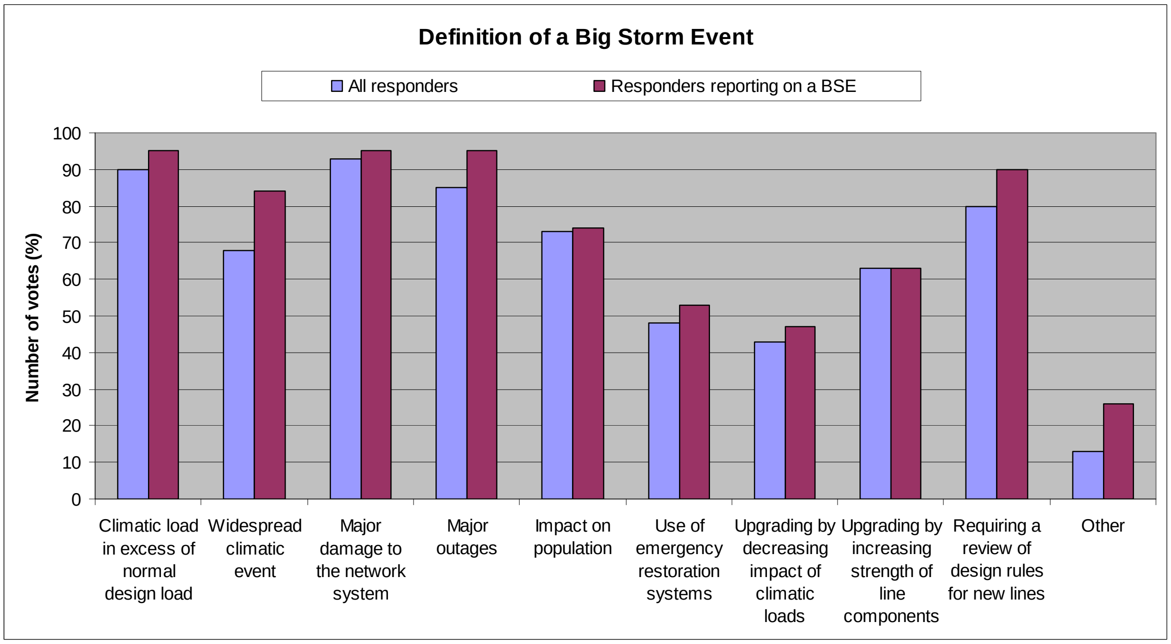

***Figure 1** – Criteria for the definition of a BSE according to all responders and responders reporting on Big Storm Events*

4.3 Ranking of definition criteria if the BSE reported was widespread

Some responders found that "*climatic loads in excess of normal design loads*" and "*widespread climatic load*" are clearly the most important criteria for a Big Storm Event. Nevertheless the criterium "*widespread climatic load*" was, generally, qualified relatively low. Therefore the initiative was taken to examine the change in the ranking system when only responders reporting on a widespread Big Storm Event were selected. According to Table D.3, 19 responders were selected.

Table 2 below gives the ranking system according to the responders reporting on a widespread Big Storm Event (based on Table D.3).

Table 2 – Definition of BSE according to responders reporting on a widespread BSE

	%	**Votes**	**Criterium** (The number refers to the Questionnaire)
1	95	18/19	1.3 – Major damage to the system
1	95	18/19	1.4 – Major outages
1	95	18/19	1.1 – Climatic load in excess of normal design load
4	90	17/19	1.8 – Requiring a review of design rules for new lines
5	84	16/19	1.2 – Widespread climatic load
6	74	14/19	1.5 – Impact on population
7	63	12/19	1.7.2 – Upgrading by increasing strength of line components
8	53	10/19	1.6 – Use of emergency restoration systems
9	47	9/19	1.7.1 – Upgrading by decreasing impact of climatic loads
10	26	5/19	1.9 - Other

"*Major damage*" (95%) and "*major outages*" (95%) are now the leading criteria for the definition despite they are still consequences of a Big Storm Event. Those criteria are now as important as "*climatic load in excess of normal design load*" (95%). They are directly followed by the criteria on "*requiring a review of design rules for new lines*" (90%) and on the "*widespread character of the climatic load*" (84%).

This ranking seems more logical according to the conclusions of the Biggest Storm Events ever that happened on January 1998 in Québec, Canada and on December 1999 in France. Nevertheless the consequences are considered more important than the causes of the events.

We also note that the appreciation of the five most important criteria (84% to 95%) is now higher than for the general response (73% to 93%) above in Clause 4.2. The qualification for "*Requiring a review of design rules for new lines*" increases from 80% to 90%.

As a conclusion of this second comparison, one can establish that the definition depends mostly on the type of climatic event. Is it either a widespread Big Storm Event (BSE) or a localized High Intensity Wind (HIW) phenomenon? In both cases the "*major damages leading to major outages*" are the first criterium according to the responders. In the case of widespread wind or ice storms the initial cause "*widespread climatic loads in excess of* *normal design loads*” is still a secondary criterium compared to the direct consequences such as major damage and outages.

Figure 1 also illustrates the shift in opinion of respondents reporting on a widespread Big Storm Event. The trend of responses follows the same general pattern as before.

4.4 Comments and final conclusions on the definition of BSE

Prof. Liang Xidong (China), who responded to the WG B2.06 Questionnaire, stated *“There is still a lack of clear definition of a storm event from the point of view of transmission line design*”.

Sven Hoffmann (United Kingdom) provided an interesting comment on the definition: “*To my mind, a "**Big Storm Event” should be defined by the event itself** - the cause. For criterium 1, criteria 1.3 to 1.9 of the Questionnaire deal more with the effects of an event.*

I think this is a very important distinction to make - as it helps put comparisons of mitigation measures into context. To my mind, a "Big Storm Event" describes a major climatic event such as a hurricane or an ice storm that covers a significant geographic area. However, whether this event causes the effects described in criteria 1.3 to 1.9 might depend on two issues - the actual loads seen by the assets, and the actual (as opposed to design) strength of the assets.

On the one hand, a relatively minor event (with loads less than design strength) might cause widespread damage and outages if assets are in a poor condition. Mitigation in this case might be achieved with an improved asset management program. On the other hand, loads significantly in excess of design loads may have occurred, and in this case it would be expected that widespread damage would occur, regardless of asset condition. Mitigation measures in this case would almost certainly be more complex.

Furthermore, there are occasions where a storm event causes damage to assets not by direct mechanical action, but by secondary effects. For example trees affecting distribution lines. Mitigation measures may not be required from a mechanical design point of view, but with an improved vegetation management programme.

Lastly, and just to confuse matters a little, the effects of a "Big Storm Event" listed in criteria 1.3 to 1.5 might be realised by events not thought of as "storms", such as geomagnetically induced currents, which I believe caused widespread damage to North American power systems some years ago. This event might be described as a "Big Storm Event" in terms of the criteria of criteria 1.3 to 1.5, but caused by electrical, rather than mechanical effects.

*So on balance, … I would define a "Big Storm Event" primarily according to the **severity** and **area** of effect of mechanical loads developed, while acknowledging that other criteria could also be used depending on the circumstances.”*

In this context, most European countries consider that the two following criteria are the most important ones to define a Big Storm Event:

- A climatic load in excess of normal design load;
- A widespread or a large-scale climatic load.

For most countries outside Europe the widespread character of a storm event does not necessarily characterize a Big Storm Event. This is due to the fact that localized High Intensity Winds, such as downdrafts and tornadoes, which are locally more devastating, are small-scale phenomena compared to the European windstorms and even tropical cyclones. In simple words: a localized HIW is a very strong wind in a small area; a widespread BSE will cover a much larger area than a localized HIW.

Therefore WG B2.06 suggests to distinguish two storm type events by **severity** and **area** for the use by OH line operators:

- Widespread Big Storm Events (BSE), including large-scale European windstorms and tropical cyclones (hurricanes, typhoons, cyclones);

- Localized High Intensity Winds (HIW), such as small-scale downdrafts and tornadoes.

This distinction is in line with CIGRE Technical Brochure "How Overhead Lines Respond to Localized Intensity Winds – Basic Understanding", where specific loading cases are discussed for localized High Intensity Winds (CIGRE, 2008), opposed to the widespread Big Storm Events that correspond to the synoptic winds considered by the International Standard IEC 60826.

As most lessons drawn from both storm events are relatively similar, both types of wind are considered in this CIGRE Technical Brochure.

5. Aim of the Technical Brochure

5.1 Criteria for the aim of the TB

The aim of the CIGRE Technical Brochure is to identify Big Storm Events occurred during last decades, to collect meteorological parameters, to compare innovative actions and to share lessons in preparedness.

In order to know exactly what the responders would like to see discussed in the Technical Brochure, we suggested 4 criteria:

- To observe mitigation actions rather than the storm event;
- To compare worldwide experience on mitigation actions;
- To identify and assess pro- and re-active actions, including design code changes for new lines;
- To share lessons in emergency preparedness.

5.2 General ranking system of the criteria for the aim of the TB

Table 3 gives the ranking system of the criteria for the aim of a Technical Brochure according to all responders (based on Table D.2).

Table 3 – Aim of the Technical Brochure according to all responders

	%	**Votes**	**Criterium** (The number refers to the Questionnaire)
1	98	39/40	2.2 - To compare worldwide experience on mitigation actions
2	93	37/40	2.3 - To identify and assess pro- and re-active actions, including design code changes for new lines
3	90	36/40	2.4 - To share lessons in preparedness
4	68	27/40	2.1 - To observe mitigation actions rather than the storm event
5	30	12/40	2.5 - Other

The three criteria 2.2, 2.3 and 2.4 of the Questionnaire are ranked very high (90% to 98%). It could be strange that only 68% agrees on the first criterium 2.1. It probably means that for a lot of responders the assessment of the cause of the storm event is as important as the mitigation actions. Some reactions are clear: “*Both are important*”; “*It is always good to put the reaction in the context*”; “*We need to know the main characteristics of the event*”. Moreover “*causes of events vary greatly from country to country*”.

Does it mean that a majority of utilities are still convinced to be confronted with very exceptional phenomena and that they would like to understand those phenomena before taking appropriate actions?

5.3 Ranking of aim criteria if the BSE reported was widespread

Table 4 gives the ranking system according to responders reporting on a widespread Big Storm Event (based on Table D.3).

Table 4 – Aim of Brochure according to responders reporting on a widespread BSE

	%	**Votes**	**Criterium** (The number refers to the Questionnaire)
1	95	18/19	2.2 - To compare worldwide experience on mitigation actions
1	95	18/19	2.3 - To identify and assess pro- and re-active actions, including design code changes for new lines
1	95	18/19	2.4 - To share lessons in preparedness
4	58	11/19	2.1 - To observe mitigation actions rather than the storm event
5	32	6/19	2.5 - Other

There is more willingness “*To share lessons in preparedness*” when a BSE already occurred. This criterium 2.4 is now ranked in the first place (95%) together with the criteria on “*To compare worldwide experience on mitigation actions*” and “*To identify and assess pro- and re-active actions, including design code changes for new lines*”.

There is a general agreement on all criteria (95%), except for the first criterium 2.1 “*To observe mitigation actions rather than the storm events*” (58%). Probably a criterium such as “*To observe mitigation actions taking into account the characteristics of the storm event*” would be more successful.

5.4 Comments and conclusion on the criteria on the aim of the TB

According to the comments, the characteristics of the Big Storm Events and the causes of the initial and secondary failures have to be analyzed in depth before appropriate actions are taken.

Some other items that responders would like to be discussed are:

- Experience or feedback on remedial actions undertaken or not with existing lines and codes;
- Comparing design strategies;
- Discussing efficiency of anti-cascading measures.

5.5 Answers regarding Big Storm Events that occurred

Table 5 below summarizes the responses to Questions 3 and 4 (see Tables D.5 and D.6 in Appendix D) regarding the Big Storm Events that occurred in the country of the responders.

The number of events with only wind load (41%) is nearly as high as the number of events with combined wind and ice load (44%). However, the number of events with ice only is very low (11%).

All utilities reporting on a Big Storm Event provided full information on:

- Extent of the damage to towers, poles and lines;
- Loading characteristics from wind and/or ice load.

Table 5 – Summary of the responses to Questions 3 and 4

	%	**Votes**	**Question** (the number refers to the Questionnaire)
1	44	12/27	3.1.3 – Combined wind and ice load?
2	41	11/27	3.1.1 – Wind load only?
3	11	3/27	3.1.2 – Ice load only?
4	4	1/27	Other?
	100	27/27	Total
	100	27/27	3.2 to 3.7 – Information on date of event, location, gust wind speed, ice thickness and density or ice mass per unit length, extent of event, number of towers/poles/lines failed and reference to original design code?
	41	11/27	3.8 – Any re-calculation of structure strength with use factors?
	48	13/27	3.9 – Any innovative solutions for increasing reliability?
	52	14/27	3.10 – Was a review of strength coordination undertaken?
	67	18/27	3.11 – Have new design rules been considered since the event?
	0	0/27	3.12 – Did you collect ice data according to the ice observation sheets of CIGRE Technical Brochure 179 (TF 22.06.01)?
	37	10/27	3.13 – Any other relevant data/circumstances?
	48	13/27	4 – Are there relevant reports available? Are they updated and accessible to the public? And can they be forwarded for integration in the present report?

The number of utilities that recalculate the strength with use factors and applied innovative solutions for increasing reliability is relatively high (41% to 48%).

In addition to the above, the following innovative solutions are also mentioned by responders:

- Ranking of the most sensitive towers and elements taking into account the real use factor and risk assessment;
- Implementation of generic reinforcement solutions, also referred to as “Kits”;

- De-icing methods;
- Ice load warning systems;
- Adoption of snow accretion resistant means such as snow-resistant plastic rings and smooth-body conductors with fins, which are described in 1997 CIGRE Sendai Colloquium paper;
- Replacing overhead distribution lines with underground cables.

It is important to mention that 52% of the responders reviewed their design codes or practices after a Big Storm Event. When the return period was considered outside reasonable level, no review was necessary. However subsequent review was sometimes planned for any combination of towers and line directions, to ensure that no similar situation exists.

No utility collected ice data according to the ice observation sheets of CIGRE Technical Brochure No. 179 (TF 22.06.01). Nevertheless two utilities confirmed that they collected ice data but not exactly according to the TB 179.

Ten responders (37%) reported on other relevant data and circumstances:

- Presumably wind downburst from field observations and limited witness accounts;
- Impact of tower age;
- Impact of terrain at an altitude of more than 600 m;
- Extreme combination of line direction for the worst possible transverse load, lee effect, location of line in wide valley, types of towers, severity of storm;
- No frozen soil (permafrost) at certain time of the year (due to climate change) - New type of forest, fast growing trees but not so strong;
- Extreme ice with many broken conductors not considered in the standard.

Finally 13 responders (48%) provided a lot of relevant reports on their events.

As those reports are available to the public, they have been introduced in Clause 8 and synthesized in Clauses 9 and 10.

The full reports country by country are given in Appendices A and B.

Lessons drawn from these events are summarized in Clause 11.

Additional recommendations are provided in Clause 12.

6. Previous analyses of WG B2.06 on line failures

6.1 Introduction

A survey on transmission line failures was already conducted in the past by WG B2.06. One of the ideas was to classify the failures according to their causes, especially those failures prone to be treated on a statistical basis.

Unfortunately, the review of the many reports received, showed that most of them failed to uncover the real and significant causes of the failures. That is the reason why in the present Questionnaire the real causes of the line failures have not been requested. Lessons drawn have been emphasized.

Some of the more significant results of this study are given below. For the complete report we refer to CIGRE Technical Brochure No. 109 "Review of IEC 826 – Loading and Strength of Overhead Lines", Chapter III "Analysis of Recent Transmission Line Failures", João Felix Nolasco [6].

6.2 Difficulty to uncover the real and significant causes of failure

Most of the reports received failed to uncover the real and significant causes of the failures. It was noticed that:

- In a few of the failures reported, foundations were indicated as having been the triggering mechanism;
- It was beyond the scope of the report to include failures of other line components. Such failures are mainly originated by:
    - Mechanical phenomena (vibration, fatigue, etc.);
    - Electrical occurrences (power arcs, short-circuits, punctures, etc.);
- Failures resulting from defects in raw materials or from inadequacies in the design have seldom occurred.

6.3 Some cases of failures related to climatic events – Lessons learned

Some typical examples of failures related to climatic events mentioned in the CIGRE Technical Brochure No. 109 are given here under, as well as lessons learned.

- No change in the design criteria was performed as a return period of 1000 years was determined for a high intensity thunderstorm where two towers collapsed;
- Due to cascading of a 220 kV line, new design criteria were adopted for containment of the longitudinal loads;

- Skewed winds were added to the design rules after skewed winds caused two tower failures;
- A failure that occurred in a 138 kV line provided with semi-elastic towers proved that the earth wire did not act as considered in the design. The towers were then guyed to prevent further failures;
- A localized HIW caused two big failures on a 380 kV line. As the return period of the HIW was found less than the original forecasts, new wind measurements were used, so that the tower deficiencies could be corrected;
- The secondary loads were neglected in the initial tower design of a 500 kV line. After an analysis based on a statistical basis and on risk assessment, the reinforcement of 1400 towers could be reduced to 120 towers;
- After suffering tower cascades, new design criteria were adopted for a 400 kV line: the wind pressure was multiplied by 1,33 and ice thickness of 0 and 20 mm was changed to 10 and 30 mm;
- Excess of ice caused 5 line failures. The new ice loads changed from 12 kg/m to 27 kg/m;
- The design guide was changed after two 154 kV lines and one 66 kV line in the same region failed under extreme wet snow load on the conductors;
- As a consequence of failures due to extreme ice on towers and conductors, anti-torsion dampers and snow resistant rings were applied to the conductors of the lines;
- Eight failures in several old lines of the same region led to the utility to change the design criteria concerning ice accretion. The towers were reinforced and the foundations enlarged.

6.4 Conclusions of the failure analysis

- The report recommends to improve and increase the number of measurement stations of the climatic variables (wind speed, snow and ice accretion), in order to improve the statistical data;
- There are only a very low percentage of foundation failures announced. It seems that too high safety factors have been generally assigned to the foundation design;
- Coordination of strength seems to be adequate and therefore shall be kept as it is;
- The great majority of the failures occurred in lines which were only deterministic treated;
- Changes of the design criteria for new lines are mostly based on the statistical re-evaluation of the failures;
- The calculation of the use factor may lead to savings on the required reinforcements;
- The change of design criteria, especially regarding ice loads, has occurred frequently, as a consequence of failures. It seems that ice load criteria have been often defined in the past without having enough climatic measurements.
- The combined ice and wind loading was considered for a long time as being covered by the cases wind only and ice only.

7. Two approaches for Upgrading after Big Storm Events

The next text is an extract of the CIGRE WG B2.06 Technical Brochure No. 294 on "How OH Lines are Re-designed for Uprating and/or Upgrading – Analysis of the Answers to the Questionnaire". The Summary Report has been published in the Electra Journal, June 2006 issue.

"Upgrading an overhead line means an improvement in its structural reliability level. Reliability is a result of the combination between load and strength of the overhead line. It is obvious that reliability can be increased either by decreasing climatic loads or increasing strength of line components (Ghannoum, 2003). The main methods and tools to upgrade overhead lines are summarized in the **Table 6** here under."

Table 6 - Main methods for Upgrading

	Method	Tool
Upgrading	Reducing impact of climatic loads	Compact/smooth conductor
		Decreasing ice accretion
		Decreasing number of sub-conductors
		Decreasing number of circuits
	Increasing characteristic strength	Support: leg members
		Support: bracings
		Foundation: uplift
		Foundation: compression

8. How to learn from Big Storm Events

The lessons learned from some Big Storm Events are synthesized in the following Clauses 9 and 10. They show how we can be better prepared to face similar storm events.

Clauses 9 and 10 are respectively dealing with specific regional aspects of:

- Widespread Big Storm Events (BSE);
- Localized High Intensity Winds (HIW).

The following format has been applied for Clauses 9 and 10:

- Storm event, small description;
- New strategy;
- New design rules.

The specific regional aspects, if available, are considered for the following countries:

- Windstorms: France 1999, Belgium 1990, Sweden 2005, USA 2006;
- Ice or snow storms, with or without wind: Canada 1998, Czechoslovakia 1974, Germany 2005, Japan 1980, Ukraine 2000, USA 2005;
- Tropical cyclones: Tenerife 2005, Australia 2006, USA 2004 and 2005;
- Downdrafts and Tornadoes: Canada 1996, New Zealand 2004 and 2005, Ukraine 2000, Brazil, 2005.

Some responders provided detailed and relevant information regarding severe storm events that affected their country. Only information that is not confidential is given in this Technical Brochure.

In the Appendices A and B the following items are discussed country by country in more detail. All those items have been considered as available and accessible to the public:

- Observation of the storm event and its consequences:
    - Type of storm, date, duration, location;
    - Extent of outages and emergency restoration of power;
    - Extent of damage;

- Assessment of the storm event and comparison between the meteorological data and the current design parameters:
    - Origin of the storm;
    - Weather data of extreme wind speed and/or ice deposits;
    - Original design parameters, if available

- New developments:

  - New strategies or policies;
  - New design rules;
  - Rebuilding, innovative solutions;

- Conclusion.

Table 7 below provides the list of storms events considered country by country as well as the Clauses and the Appendices where the information can be found.

Table 7 – List of Big Storm Events reported

Storm event			Type storm event		Clause, Appendix, Ref, Fig			
Country	**Date**	**Year**			**Cl.**	**App.**	**Ref.**	**Fig.**
Canada	January 5-9	1998	BSE	Ice	9.1	A.1	7-9	1, 2
France	Dec. 26, 27-28	1999	BSE	Wind	9.2	A.2	13-16	3, 4
Belgium	Jan 25; Feb 26	1990	BSE	Wind	9.3	A.3	2-4, 20	-
Sweden	January 8	2005	BSE	Wind	9.4	A.4	24-25	-
Germany	November 24-25	2005	BSE	Ice & Wind	9.5	A.5	17	5, 6
Czech Rep.	January 15-20	1974	BSE	Ice & Wind	9.6	A.6	11-12	-
Ukraine	November 24-30	2000	BSE	Ice	9.7	A.7	26	-
Japan	December	1980	BSE	Wet snow	9.8	A.8	18-19	-
Spain	November 28	2005	BSE	Cyclone	9.9	A.9	23	-
Australia	March 20	2006	BSE	Cyclone	9.10	A.10	Bartlett	-
USA	‘04-‘05 Seasons	2005	BSE	Hurricane	9.11	A.11	28-33	-
USA	December 14-16	2005	BSE	Ice	9.12	A.12	34-38	-
USA	August	2006	BSE	Wind	9.13	A.13	Engel	-
Canada	September 5	1996	HIW	Microburst	10.1	B.1	10	-
New Zealand	January 9	2004	HIW	Downdraft	10.2	B.2	22	-
	March 25	2005	HIW	Downdraft			21	-
Ukraine	July 4-5	2000	HIW	Tornado	10.3	B.3	26	-
Brazil	June 14	2005	HIW	Tornado	10.4	B.4	5, 6	-

Clause 11 summarizes the lessons drawn from those events.

Clause 12 gives some final recommendations.

The background information on the causes of those Big Storm Events and High Intensity Winds is provided in Appendix C. This Appendix C also explores whether storm events in the future will be more frequent and severe due to climate change.

9. What we learned from widespread Big Storm Events

9.1 Canada – Ice storm on January 5-9, 1998

January 1998 ice storm

The ice storm of 1998, also known as Ice Storm ’98, caused massive damage to trees and electrical infrastructure, leading to widespread power outages. A shut down of activities in large cities like Montreal and Ottawa led to an unprecedented reconstruction effort of the power grid [7].

Five days of freezing rain precipitation in southern and western Quebec caused the collapse of several transmission lines owned by Hydro-Québec. Among installations rated 49 kV and more, over 2 000 wood portal structures and 617 steel lattice towers were destroyed or sustained. About 1,5 million customers were without power for periods ranging from a few hours to over 30 days. A large surface area of 150 000 km^2 was affected. There were eight major cascade collapses among structures of the 735 kV transmission network.

It was observed that the breakage of conductors and failures of towers supporting them, occurred toward the end of the periods of freezing rain. The quantities of accumulated ice were then at their peak and moderate winds were blowing in the disaster area, with gusts reaching 50 km/h.

Most of the broken poles and crossarms were observed for spans greater than 50 m and for structures having to support a 3-phase system. In both cases, the weight of the ice was clearly greater than the capacity of the vertical (poles) and horizontal (crossarms) structures to withstand the ice.

At no time during the storm were the generation plants affected. Except for a few minor elements, the substations all resisted the freezing rain.

Freezing rain is common in Canada. Typically, a warm air mass will come up along the Mississippi Valley and overrun a shallow layer of cold air trapped at the surface.

On January 4, 1998, two extremely unusual phenomena occurred simultaneously [8; 9]:

- The low pressure system of warm, moist air mass was larger than during a normal winter, due to the weather system called “El Niño” coming from the Gulf of Mexico;

- The normal drift from west to the east was stopped for a few days because of the presence for of a large stationary high pressure system above Newfoundland and Labrador.

Snow is produced at upper level in such a winter storm system but it eventually melts into rain in the warm layer, above freezing temperature, associated with the overrunning. When that rain touches the ground in the cold air below, the droplets freeze on contact creating accumulations of ice.

Prior to the 1998 storm, the last major ice storm to hit Montreal (1986) deposited around 30 to 60 mm of ice. However, the 1998 storm left deposits twice as thick.

The amount of build-up varied from one transmission line to the next and from span to span. This variation could be attributed to different causes:

- Random nature of freezing rain;
- Protection offered by wooded areas;
- Torsional rigidity of conductors;
- Wind direction.

Moreover the shape of the ice deposits is also important to assess the wind loads, since it has a direct impact on the drag coefficient.

New strategy

Following the 1998 ice storm in Canada, Hydro-Québec drew up a three-part intervention strategy [7]:

- Emergency restoration of critical lines;
- Restoration of collapsed lines before the next winter peak;
- Reinforcement of the transmission system over the medium and long term.

All these aspects of the ice storm and its repercussions were covered under a study conducted by a government enquiry commission, called “Commission Nicolet” (A.14) [8; 9].

The ice storm in Canada, 1998 brought up a number of issues [7]:

- The relevance of identifying future strategic lines with high mechanical strength;
- The possible revision of some current design criteria and parameters such as combining wind with major icing loads.

Hydro Quebec no longer accepts more than two strategic lines in a same corridor.

New design criteria

Following the collapse of transmission towers in 1969 and 1973 where high icing loads destroyed about thirty 735 kV towers on each occasion, Hydro-Quebec (HQ) revised its design criteria upward. Until 1973 HQ followed the CSA-C22.3 (produced by the Canadian Standards Association).

After the 1969 and 1973 ice storms, the new standard considered separate climatic loads, with a return period of at least 50 years, similar to the reliability based design methods of IEC Technical Report 826 (replaced with International Standard IEC 60826 in 2003), such as:

- maximum ice without any wind;
- high wind without any ice.

The combined wind and ice loads were increased by about 50%.

Due to the lower torsion rigidity of the earth wire, it is now recommended to consider at least the same ice weight (and not the same ice thickness) as for the single conductors, independently of the earth wire diameter.

Several scenarios were defined involving imbalanced loads and phase failures. The use of anti-cascading structures was provided to limit potential damage. A network of 150 monitoring stations with icing-rate meters was set up in the 1970s to gather information on freezing rain.

New load levels

Considering the urgent need to rebuild certain strategic connections while ensuring public safety, HQ established transitional loads for these projects with higher levels of reliability.

The load levels retained were 55 mm and 65 mm, defined based on the geographic area where each project is located, so that the reliability of the rebuilt lines was comparable. For all projects, the chosen load level had to have a return period of more than 150 years.

The specifications stipulated very high reliability criteria for these restoration projects corresponding to levels 55 mm and 65 mm, while existing standard tower types were designed for loads about equivalent to level 45 mm.

Innovative rebuilding solutions

Before the application of a revised standard, transitional measures were adopted for the restoration of the collapsed lines.

Regarding the rebuilt lines described in the Canadian report, two different innovative approaches resulted in a substantial increase in the prior reliability while maintaining very tight draft-design and construction schedules.

After considering various solutions, the chosen strategy was to replace the current twin bundle with a single large conductor for a 220 kV line offering an adequate electrical performance. With this solution there was no need to modify the towers and foundations, considering that a single conductor, even with a larger diameter, is subject to less ice buildup than a bundle of two small conductors, due to a lower sum of diameters (- 28%).

Figure 1 - January 1998 ice storm in Canada (HQ)

Figure 2 - January 1998 ice storm in Canada (HQ)

However this solution could not be applied to 750 kV lines considering the electrical problems. An acceptable but more costly solution was obtained by designing additional suspension towers.

Commission Nicolet

The Commission Nicolet [8; 9], set up after the January 1998 ice storm in Canada, was mandated to analyse the features of the 1998 ice storm and its consequences and impacts in order to draw as many lessons as possible for the future. This Commission was designated as a scientific and technical commission.

This Commission Nicolet proceeded in three steps for the assessment of upgrading the network system:

- The main characteristics and design criteria;
- The behaviour of the network when subjected to the unpredictable event;
- The possible reinforcements.

According to the Commission Nicolet, two characteristics had serious impact on the outages:

- A low mesh level;

- A limited number of interconnections.

Interconnections should play a larger role in helping difficulties encountered during disasters as the ice storm. The construction of strategic lines, meeting much more stringent standards than regular lines, is a convincing way of upgrading the network.

The major results of the Commision Nicolet are summarized in Appendix A.14.

9.2 France – Windstorm on December 26 and 27-28, 1999

December 1999 windstorm

In December 1999, France suffered two major storms bringing exceptionally high winds and causing extensive damage to transmission and distribution networks [13; 16].

After the two storms 3 450 000 customers in 90 French districts were left without electricity. Within 24 hours, electricity was restored to 1 500 000 households. The last few customers were finally re-supplied on mid January, 2 000. All the substations and industrial customers were reconnected in less than 4 days.

In all, 70 000 people worked to re-establish service. Equipment resources were acquired in matching proportions: more than 5 000 generator sets of all power levels, 2 500 tons of supports, 4 000 km of conductors and 900 000 connection parts were used. A number of 11 emergency lines including 4 from abroad were installed on 8 links [3].

The overhead lines have been rebuilt on the same routes. However, the mechanical strength of some damaged structures has been improved immediately, as it was noticed that the wind speeds were 10 km/h higher than foreseen by the design standards.

The storms of December 26 and 27-28, 1999 caused unprecedented damage to the French electrical network. The territorial extent of both storms (approximately 2/3 of France) and the violence of the wind were truly exceptional. During the storm, wind speeds exceeded 150 km/h, and in some areas speeds reached from 180 to 200 km/h. Woods and forest in France, Germany and Switzerland were devastated by the storms. In France, an estimated 4% of the forests were destroyed, translating into roughly 90 000 000 m^3 of timber.

Both storms propagated from separate Atlantic depressions loaded with warm air, which strengthened both as they made landfall and met with a cold air mass. Temperature contrast caused extreme turbulence along the weather front, creating the first storm. The second storm issued from a similar but different Atlantic system. The wind speeds were generally not as high as those from the first storm. This storm, however, carried a lot of moisture, and damage stemmed not only from wind speeds but also from rain and subsequent flooding. Each of both storms was associated with an intense jet stream aloft and benefited from latent heat release through atmosphere-ocean exchange processes. Both storms were extratropical cyclones and had a hurricane-like shape, with an eye at the center.

Figure 3 - December 1999 windstorm in France (RTE)

Figure 4 - December 1999 windstorm in France (RTE)

New strategy

RTE realised the importance of accurately recording the scale and type of damage that had occurred. At each location the following methodology was applied:

- Inspection and recording of the scale and type of damage at each site;
- Collection of meteorological data;
- Technical verification of the structures;
- Assessment of the chronology of the events.

RTE noticed the good behaviour of towers built after 1991.

After the December 1999 storms, RTE decided a new policy for strengthening the transmission network to meet two main goals when atmospheric events comparable to those of December 1999 occur [15]:

- To guarantee the safety of people and property;
- To ensure the continuity of supply to customers and safety of system operation.

An action plan over 15 years was developed to ensure the objectives would be met:

- Having an emergency organization, capable of proposing solutions which can be implemented in under five days. RTE added further support resources:

    - by rescaling the stock of emergency lines available;
    - by reciprocal assistance agreements with other European grid operators;
- Upgrading weak points on the network:
    - By clearing stretches of forest land making it impossible for trees to fall on power lines;
    - By upgrading towers with "insufficient mechanical strength";
- Securing HV and EHV overhead lines on a longer timescale:
    - Anti-cascade towers installed every 5 km;
    - All substations connected to at least one more reliable HV or EHV line;
    - All major communication route crossings made more secure.

To reach this goal the following measures were taken:

- Installation of "anti-cascade" towers every ten spans in order to limit secondary failures. The distance of ten spans was selected as this is the length of overhead line which can be restored using the emergency restoration systems available;
- Ensure that every transmission substation was linked with at least one overhead line designed to the higher reliability level.

Since the transmission system in France consists of standard tower families, the optimal solution from a technical and financial point of view was to design standard reinforcement kits. Therefore, RTE decided to develop a single generic kit per tower type [14] .

New design criteria

New design criteria were incorporated into the French Technical Regulations. These revisions include the following:

- Extension of the geographical areas where higher wind pressures are applied;
- Higher standard wind pressure for the other area.

9.3 Belgium – Windstorm on January 25 and February 26, 1990

The 1990 twin storms

The intensity of the wind storms that affected in 1990 the overhead lines in the western part of Belgium was probably comparable with the 1999 windstorm in France (Clause 9.2). Even the relative extent of the windstorms in comparison with the total surface of the country was similar. Fourteen circuits were out of service and 69 self-supporting lattice towers collapsed (35 towers for 380 kV). As the distribution lines were not affected and additional power generation was available in time, the households were still supplied [2].

Two important connections between the Netherlands and the nuclear power station Doel in Belgium were destroyed due to the first windstorm of January 25, 1990. As a result of the bilateral exchange agreement between Belgium and the Netherlands, a Belgian and a Dutch emergency line were installed [20]. During the operation period of both emergency lines, the second severe storm occurred on February 26, 1990. Some other towers in the country were again destroyed, but fortunately not on the emergency line.

New strategy and design criteria

Due to the failure of some towers in 1985, less than 5 years before the 1990 storm, the wind loading conditions had already been reviewed and new design methods implemented.

After the urgent reconstruction of the damaged OH lines in 1990, the Belgian utility decided to select the towers built before 1985 to reinforce according to some simple criteria:

- high towers with long wind span lengths;
- unprotected towers in open terrain;
- towers next to roads, railways and residential areas.

The severe wind storms in France at the end of 1999, that didn't affect the Belgian network, were at the basis of the decision in 2000 to analyse the strategic 380 - 220 - 150 kV lines, and to modify them where necessary.

In order to avoid serious incidents as much as possible, the Belgian Utility Elia conducted a study with the following scope:

- identification of the components of the HV grid most vulnerable to wind load;
- the upgrading works needed to increase the reliability of the overhead network in bad weather;
- the development of an Emergency Plan.

As towers are standard products in overhead lines, towers installed in site are always underutilised with respect to the basic hypotheses of the design calculations of the standard tower. However due to local topography (ridges and slopes) wind speed can be amplified.

The calculation of the actual use factor enables to rank the towers most sensitive to the prevailing winds for each strategic line.

9.4 Sweden – "Gudrun" windstorm on January 8, 2005

The "Gudrun" windstorm, 2005

Windstorm "Erwin", also called "Gudrun" in the Nordic region, hit northern Europe from Ireland to Russia on January 7-9, 2005. Forest damage in the southern part of Sweden was the worst recorded in recent history and caused disruption of power supplies, phone lines and railway traffic on January 8th, 2005 [24; 25].

In Sweden, a numberless amount of wooden poles from 0,4 –10 kV distribution lines failed. There was also an extensive damage on 40-50 kV lines. The severity and extent of the widespread storm can be characterized by the failure of 250 000 000 trees over an area of 40 000 km^2 with 75 000 000 m^3 storm felled forest. As a comparison, the total yearly production in Sweden is 85 000 000 m^3 and in the affected areas, 3 to 4 years of production were lost.

In 1969, Sweden was already hit by two storms, causing damage of respectively 25 000 000 and 10 000 000 m^3 of fallen trees. Since then, the moist ground due to the mild and wet winter was a factor that has contributed to the global damage. At the time of the “Gudrun” storm, there was no frozen soil in southern part of Sweden so that there were new types of forests and trees growing very quickly (probably due to climate change).

In the afternoon of January 7, 2005, Gudrun began as a perturbation on the polar front in a region just west of Ireland. At the same time, cold air masses from Greenland started to move southward colliding with very mild and moist air masses located further south. The location of the jet stream together with a very large temperature difference between the air masses allowed the storm to generate a large amount of energy, affecting the speed and the direction of the wind.

New strategy

It was considered that no overhead line could withstand a natural disaster such as Gudrun. Therefore the following preventive measures were taken:

- Widening of corridors for 40-50 kV overhead lines;
- Cabling of networks in rural and forest areas;
- Replacing overhead lines with underground cables for links to customer houses;
- Using European standard equipment;
- Installation of emergency power;
- Optimization of the network structure;
- Improving forecasts and communication regarding severe weather events.

The robustness of the network had to be increased. Investments must be based on risk analysis to ensure the viability of the network.

New design rules

No new design requirements were required as the more than 20 years old distribution system has been designed according to a national code with more than 80 years good experience.

9.5 Germany – Wet snow storm on November 24-25, 2005

The 2005 wet snow event

In the region of Münsterland, western Germany, in an area close to the Netherlands, there were heavy ice loads on power lines on November 24-25, 2005. Five 110 kV lines owned by the utility RWE were damaged with 83 steel lattice towers failed. The wind and ice storm event also affected the Netherlands and Belgium.

In report [17], it was stated that the towers failed due to an exceptional climatic event. The ice overload on conductors was the result of three simultaneous factors:

- Excellent adherence of the snow to the conductor due to a high liquid-water content;
- A strong wind increasing the flux of snow;
- A constant temperature of nearly 0°C.

Moreover, it was noticed that unbalanced ice loading may increase failure probability by torsion of tower, especially when one circuit is out of service during severe ice events or when circuit is not installed.

New strategy and design criteria

The failed lines were built between 1950 and 1990 using the German standards valid at the time of erection. No additional load assumptions had been considered since severe ice loads had never been observed in this area. The German National Committee for Overhead Lines analyses this event with the consequence to review the Standard for ice loads. The main changes will be a ice load map with ice load zones for Germany. In a first step this map will be informative.

Figure 5 - Wet snow storm on November 24-25, 2005, Germany (E.ON)

Figure 6 – Snow accretion after the wet snow storm on November 24-25, 2005, Germany (E.ON)

9.6 Czechoslovakia – Ice and wind storm on January 15-20, 1974

The 1974 ice and wind storm

On January 15-20, 1974 the hitherto most serious ice storm on overhead lines in the former Czechoslovakia occurred.

The ice storm was caused by rapid formation of ice deposits passing successively into formation of glaze on conductors, towers and poles of transmission and distribution lines, combined with strong wind gusts with the velocity of up to 100 km/h [11].

Due to the extent of the storm and the major consequences, the Czechoslovak government ordered to take necessary measures, including a detailed analysis of the disaster. The measures adopted were divided into two groups:

- Short-term measures: to put the damaged lines into the initial state, to confront the present situation with the current design standards and to check up the applicability of de-icing methods;
- Long-term measures: to improve the availability when clearing the failures and to review the design standards:
    - The ice chart was revised resulting in a fourth (critical) area with more onerous ice loads;
    - A new combined ice and wind loading was introduced (where the wind speed is half the value of load case with wind only).

New strategy and design criteria

The ice storm initiated the development of :

- Methods of de-icing;
- The revision of design standards, especially combined ice and wind loading;
- The improvement of the accuracy of the ice chart;
- The experimental investigation of the impact of the diameter, the torsion rigidity, and the height of the conductor above ground level on ice accretion.

For the last purpose, a special ice-measuring stand was built at Studnice [12], the most exposed location of the Czech-Moravian Highlands.

Cooperation with meteorological institutes, especially in forecasting icing situations was deepened. In winter periods, a regular daily exchange of information took place.

9.7 Ukraine – Ice storm on November 24-30, 2000

The November 2000 ice storm

There was a considerable amount of overhead line failures during the broad-scale icing storm on November 24-30, 2000 in southeast Ukraine. It was the greatest natural catastrophe since a century that struck Ukraine. The type of intensive icing was freezing rain with smog [26]. The icing resulted in the damage of 300 000 reinforced concrete poles and 20 000 steel towers.

Over 80% of the damaged supports were due to cascades because of conductor breakage. It seemed that cascade failures tend to increase with voltage level.

The intensive icing was the consequence of the interaction between cold arctic air mass from northeast with the warm and moist air mass from southeast.

A lot of researchers in Ukraine and Russia noted an increase of natural catastrophes in recent years. Based on the data of various researches the frequency of wind storms increased by a factor of 1,6 to 2,5.

New strategy and design criteria

The main conclusions of the Ukrainian study for the November 24-30, 2000 ice storm were the need for:

- The review of the design criteria, in particular:
  - Ice deposits in function of the height above ground and the conductor diameter;
  - Unbalanced ice loading in the adjacent spans of a tower;
- The development of de-icing and anti-cascading methods.

9.8 Japan – Wet snow storm on December, 1980 – De-icing

Wet snow event, 1980

In December 1980, Tohoku area suffered serious damage caused by heavy wet snow accretion around conductors [18; 19]. The heavy wet snow was brought by rapidly developed low atmospheric pressure with high wind and heavy snowfalls.

New strategy

After the wet snow event, various measures have been taken to reduce the damage:

- Increasing design load of snow accretion;
- Strengthening the conductors;
- Inserting additional tower steel members to resist torsion load caused by unbalanced snow accretion between neighbouring spans;
- Adopting various de-icing measures.

9.9 Tenerife, Spain – Tropical Cyclone Delta on November 28, 2005

Tropical Cyclone Delta, 2005

On November 28, 2005 the remains of tropical storm Delta arrived at the northeast coast of Tenerife, Spain [23].

Measured wind speed at the leeward side of the island close to the shoreline varied from 134 km/h to 209 km/h, where the mountains are steeper. The wind speed measured on the northeast coast was lower than 100 km/h, but wind speeds on the highest point of the mountain ridge reached 248 km/h. Usually storms and hurricanes formed in the Carribean arrive weakened to the Canary Islands with wind speeds not exceeding 90 km/h.

All lines damaged were situated on the leeward side of the island. No support damages were reported on the northeast side.

9.10 Australia – Larry Cyclone storm on March 20, 2006

The March 2006 Larry Cyclone

On the morning of March 20, 2006, cyclone Larry crossed the coastline of tropical Far North Queensland, Australia. It was reported that Larry was the most severe cyclone to hit the coast of Queensland since 1931 (Bartlett, 2007).

New strategy

A full review of the response to Cyclone Larry was carried out and identified some opportunities for improving procedures. Among the strengths in the emergency response were:

- Cooperative interaction with other key organizations;
- Establishing a local base for all the emergency and communication managers;
- Drawing on the knowledge and expertise of locally based staff;
- Availability of highly skilled staff to support the Emergency Management Team.

9.11 USA – Hurricane season 2004-2005

The 2004-2005 hurricanes

The majority of increases in outage time of hurricane-affected areas are attributed to the significant damage Hurricanes Katrina and Wilma caused to overhead lines in Florida [28; 29; 30; 31; 32; 33].

New strategy

In 2006 the Florida Public Service Commission (FPSC) has approved rules requiring Florida's investor-owned electric utilities to cost-effectively strengthen, or storm-harden, the state's electric infrastructure [29].

Each utility in Florida will be required to file storm-hardening plans, updated every three years. The plans must identify critical infrastructure and the utility's deployment strategy for strengthening electric service in their service areas, addressing measures to reduce outages and restoration time, including:

- accelerating tree trimming cycles;
- developing more detailed storm data;
- strengthening existing transmission structures;
- initiating collaborative university research on the effects of extreme winds and storm surges on electric facilities;
- increasing coordination with local governments to facilitate more effective

communication on an ongoing basis;
- inspecting wooden distribution poles once every eight years.

Each year, FPSC requires electric utility companies in the state to report on the reliability of their service the previous year.

The last report of Florida Power and Light Company (FPL) submitted to FPSC indicates that absent any hurricanes, the company expects service reliability to be further enhanced in 2007 through its “Storm Secure” program and its reliability and maintenance program.

“Storm Secure” is a comprehensive plan, launched in 2006, aimed at providing customers with a more reliable and robust electrical infrastructure under future storm conditions. It is a long term commitment to make the system more resilient to future hurricanes.

The 2007 “Storm Secure” [29; 32] plans call for upgrading main lines that serve health facilities and major thoroughfares with community services. Overhead circuit highway crossings will be retrofitted to make them more storm-resilient. Other initiatives include:

- Vegetation Management – Clearing vegetation and trimming of "hot spots" where fast-growing trees threaten to intrude on conductors, especially for main distribution lines and also for their lateral lines;
- Concrete or steel structures – Upgrading program for transmission structures that will allow it to inspect nearly 17 percent of its transmission structures every year;
- Wood structures – Replacing wood structures with concrete poles;
- Poles – More frequent pole inspection. Based on the outcome of the inspection, poles may be treated, reinforced with a steel truss, or replaced if required;
- New technologies – Evaluating new products and technologies to efficiently make the infrastructure more resilient to hurricanes in the future;
- Thermovision – Investment in state of art technology, allowing the detection of potentially faulty equipment through an infrared inspection and replacement of equipment before it causes a power interruption.

FPL is engaged in collaborative research with other utilities to study the effects of hurricane winds and storm surge to better equip electrical infrastructure. A permanent post-storm forensic team has been established to analyze damage to the electrical system and improve grid design and equipment.

9.12 USA – Ice storm on December 14-16, 2005

Ice storm, 2005

The ice storm of December 14-16, 2005 was triggered by a deep low pressure system formed over the Gulf of Mexico on December 14. At the same time, cold arctic air from northern Canada penetrated deep into the central USA and lowered the temperatures at the surface while warm air from the Gulf Stream remained at the coast [34].

The ice storm left over 700,000 people in the dark in and near the Appalachians. It took over a week to restore power.

Other ice storm occurred recently in the USA: November 30 and December 1, 2006, in Illinois [35]; the New Year's ice storm, 2007, in Nebraska [36; 37]; January 11-24, 2007: the North American ice storm was a severe ice storm that impacted a large swath of North America from the Rio Grande Valley to New England and south-eastern Canada [38]; the Midwest winter storm, February 24, 2007, in Iowa [39; 40].

New strategy

The most frequent concern expressed during public hearings was the length of time without power and not knowing when power was to be restored.

In response to the concerns the South Carolina Office of Regulatory Staff (ORS) released a review of the performance regarding the service outage during the week immediately following the storm.

The focus of the review was to identify areas where there may be room for improvement in the infrastructure, operations, and response mechanisms.

One of the most notable recommendations involves an underground conversion mechanism, since the vast majority of outages resulting from the storm were due to overhead distribution lines being affected by falling trees or limbs.

The ultimate goal in conducting this review was to ensure that customers and of all regulated utilities receive reliable and high quality service, even during times of extreme weather to better respond to major outages.

Utilities must plan, prepare and respond to widespread and prolonged power outages. Utilities have a proud tradition of mutual assistance, coming to each other's aid during power emergencies.

9.13 USA – Wind storm on August, 2006

The wind storm, 2006

In August 2006, Midwest Energy (Hays, Kansas, US) experienced a windstorm that blew down a 3 km stretch of wood transmission and distribution poles in western Kansas. All poles broke at the ground line (Engel, 2007).

Design criteria

The area is located in what the National Electrical Safety Code (NESC) designates as the Heavy Loading District. It seems likely that the wind loadings simply exceeded structure design strength. An important lesson is that localized weather effects can result in winds much stronger than those recorded at nearby weather stations.

New strategy

Upgrading infrastructure for high wind is an emerging but important topic. Ideally, a utility can compare the cost of various upgrading options and the cost of the expected damage reduction that will result from each of these options. This process allows for decisions to be made based on quantifiable costs and benefits. Possibilities for strengthening transmission and distribution lines include:

- Stronger poles;
- Upgraded poles;
- Shorter spans;
- Smaller conductors;
- Storm guying;
- Push braces;
- Less pole-mounted equipment;
- Fewer third-party attachments;
- Aggressive tree removal;
- A multitude of other options.

Achieving the proper level of infrastructure performance during high winds at the lowest possible cost is a daunting task, but will increasingly be demanded of utilities by their regulators and customers.

10. What we learned from localized High Intensity Winds

10.1 Canada – HIW storm on September 5, 1996

The microburst storm on September 1996

In the early hours of September 5, 1996 a severe thunderstorm moved through the rural area immediately northwest of Winnipeg. Nineteen guyed steel towers of the HVDC transmission line collapsed, causing the complete failure of the Radisson – Dorsey Transmission System carrying 2020 MW. In addition another 3 steel towers and 18 wood pole structures were damaged [10]. In spite of the extensive loss of power and damage, customers were not affected.

A number of modes of failures were observed suggesting that the towers did not fail all at the same time. It was not possible to clearly establish what parts of each tower failed first. However, it could be concluded that no cascading action occurred. Towers outside the affected area withstood the high winds and the unbalanced conductor loadings, caused by failed towers and broken conductors.

Conductors were damaged at some locations but none were broken. Phase conductor clamp, spacer damper and insulator damage was observed at some tower locations with no consistent damage pattern. Broken insulator strings were not found. It is not mentioned whether these damages are initial failures or consequences of the tower collapses.

The storm is believed to have been a microburst that produced extremely High Intensity down pressure and lateral Winds (HIW). The high winds moved through a narrow strip, approximately 2 km wide. Analysis of damage, supported by the radar data, suggested that a straight line wind associated with a microburst storm occurred. Based on the damage evidence, it was estimated that low end F1 winds (116-179 km/h) occurred in the area.

Design review

A review of the design parameters and the ultimate capacities of various components of the HVDC transmission lines confirmed that the original design was adequate. Considering the low frequency of occurrences of microbursts, the very localized effects, the unpredictability of the magnitude of this type of wind storm, and the cost of strengthening the transmission lines, it was judged that for the existing lines it was more economic and practical to develop an efficient emergency plan to minimize down time from extreme weather events such as this one, than to upgrade these transmission lines.

New strategy

In spite of adequate restoration, the following was recommended:

- The emergency response plan should be updated to include both temporary and permanent restoration schemes;
- A future line should be located away from the existing lines to avoid loss of all lines at the same time;
- Weather patterns should be monitored to detect any climatic changes;
- Research should be carried out to study HIW and their impact on overhead lines.

10.2 New Zealand – HIW storm on January 9, 2004 and March 25, 2005

The downdrafts on January 2004

On January 9, 2004, three towers of the BEN-HAY A 500 kV d.c. line collapsed under extreme winds exceeding 230 km/h. Nevertheless, this line was already upgraded after towers were blown over under severe wind gusts of 160 km/h on August 1, 1975 and October 15, 1988. The failure of the 3 towers was attributed to extremely high winds with a return period of about 1300 years. The high localised wind gusts were generated by lee effect, that was not considered for strengthening [22].

The downdrafts on March 2005

Two towers of the EDG-TRK A 220 kV transmission line near Manawahe collapsed on March 25, 2005. After an aerial survey of some of the area, it seemed clear that much of the damage was due to many downdrafts from the thunderstorm clouds [21].

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New design criteria

The conclusion drawn from the investigation of the tower failures in New Zealand was the need to further increase the reliability for any upgraded towers with:

- The adoption of site specific wind speeds;
- Improved knowledge of localised HIW behaviour (e.g. lee zone effects).

10.3 Ukraine – HIW storm on July 4-5, 2000

The July 2000 HIW

During a micro cyclone on July 4-5, 2000, 67 towers of the 330-750 kV network collapsed. The cyclone arose in the western part of Ukraine and moved to the Black Sea coast. The maximum wind speeds were observed over a width of 10 to 20 km. Along the edges of the cyclone some tornadoes were observed [26]. These tornadoes were the main reason of the overhead line damages.

Analyses of the wind storm consequences showed that more than 80% of damage was due to cascades in open flat terrain.

The same climatic conditions with tornadoes were the main reason of other damages of overhead lines since 1992. Eleven events were mentioned with a mean value of 2 towers damaged per event.

New strategy and new design criteria

The main conclusions of the Ukrainian study for the July 2000 HIW storm were:

- Climate change should be the main cause of the wind storms with tornadoes;
- The vertical wind profile during high intensity wind storms does not correspond with the current design methods for synoptic winds. Practically in half of the cases a rotational wind was observed;
- Frequency and gust factor of high intensity wind storms must be defined on statistical data of observations.

10.4 Brazil – HIW storm on June 14, 2005

Various HIW events

A significant number of tower failures associated to a great variety of climatic phenomena occurred in the south and southeast areas of Brazil, rather than of a unique large scale storm event. Since 1982, eleven accidents have occurred in the AC and three in the DC lines of the 765 kV Itaipu Transmission System in the State of Paraná in Brazil caused by strong winds of short duration and restricted to small areas [5].

The June 14, 2005 HIW

During a more recent storm event on June 14, 2005, 8 guyed towers and one self-supporting tower of the Itaipu transmission system failed after a super-cell formation in the area. Due to the number of failed towers, it seemed that the wind front was extremely large, contrary to the usual assumption that strong winds have a narrow front. Unfortunately it was probably not possible to detect the track and the intensity of the tornadoes due to the absence of trees.

New strategy and design criteria

The south of Brazil, as well as Argentine and Paraguay, is subjected to the formation of High Intensity Winds like downdrafts and tornadoes. Such phenomena, due to their narrow front, normally are not registered in meteorological stations, and there is no relevant statistic in Brazil.

When the study of the 1st Brazil – Argentine 500 kV Interconnection has begun in the end of the last decade, the differences of wind loading criteria adopted in Argentine and Brazil have been clearly displayed. Loadings due to High Intensive Winds (with speed up to 240 km/h), including tornadoes, were already considered in the Argentine transmission lines, resulting in wind pressures much higher than the ones adopted in Brazil.

Finally in 2000, ANEEL, the Brazilian Electrical Energy Agency, responsible for the energy transmission concession market, launched a specification determining that the mechanical design of the transmission lines under concession should follow the International Standard IEC 60826 for synoptic winds. Also recommendations for the adoption of loadings due to High Intensive Winds will be stated in the new standard edition, which will result in wind loadings higher than the ones prescribed before.

Conclusion

Ruy Carlos Ramos de Menezes (2006) stressed that records of wind speeds from synoptic winds and High Intensity Winds may not be mixed as well as the correction ratio between wind speeds measured during respectively 3 seconds and 10 minutes. The records of wind speeds during HIW should be removed from the data collection and processed independently. It is misleading to average the wind speed of HIW over 10 minutes as this event lasts only over a very short time. In Brazil it is recommended to follow IEC 60826 for synoptic winds. However it is suggested to introduce suitable loading cases to account for HIW events.

11. Summary of lessons learned

This Clause summarizes what lessons were learned from the most recent Big Storm Events.

Some **Utilities** decided on new policies and strategies after Big Storm Events. In some countries, all measures taken must guarantee that service should be reinstalled within a limited number of days. Power must remain supplied to nearly all substations.

For the System **Operators**, identification of strategic lines is fundamental. The robustness of the network can be improved by better meshing and interconnection of lines. Putting strategic lines in the same corridor must be avoided, especially in zones prone to bad weather events. Strategic lines must be built far away from each other, except when the environmental requirements dominate. If needed, overhead lines are replaced with underground cables.

Big Storm Events are incentives to intensify specific **maintenance** programs. Poor condition of the weakest elements sensitive to primary failures has to be registered systematically. Vegetation management includes clearing vegetation and widening of corridors to avoid trees falling on conductors and supports, especially when fast-growing trees threaten the conductors. During severe ice events, it is recommended to keep into service all circuits to avoid additional unbalanced ice loadings.

Designers who have to check less reliable lines may rank the most sensitive supports based on the use factor, taking into account the real span, height, line angle, line direction, etc., that are in general lower than the design parameters. But by contrast, designers must be well aware that design wind speed can be exceeded due to local topography (ridges and slopes). If the climatic load was in excess of normal design load, wind speed or characteristic ice loads are reviewed on the basis of more reliable statistical data, the area of high wind speeds or ice loads may be increased, or even new load cases may be considered such as combined wind and ice loads. Wind and ice maps are updated. Due to the lower torsion rigidity of the earth wire, it is now recommended to consider at least the same ice weight (and not the same ice thickness) as for the single conductors, independently of the earth wire diameter. No country, except Brazil, mentioned the transfer from deterministic methods to Reliability Based Design Methods, such as the International Standard IEC 60826 [1].

In order to **limit secondary failures** by installing anti-cascade towers, by using load control devices, etc. it is necessary to distinguish secondary failures from primary failures.

Upgrading steel lattice towers is in general relatively easy, by replacing or doubling steel angles. The buckling length of primary members can be reduced by the addition of secondary members. Wood poles may be replaced with concrete poles. Other timber products such as laminated wood systems (LWS) may be used. Increasing the reliability level of overhead lines can also be realised by decreasing impact of wind or ice loads.

Some innovative solutions are described in the Technical Brochure. The need for de-icing methods, ice warning systems and ice test stations is mentioned many times.

An **emergency response** plan includes not only the emergency restoration systems and spare material stocks, but also the complete organisation structure, reciprocal assistance agreements and regular classroom and field exercises to implement the emergency plan. A good balance between preventive and corrective measures is highlighted. Both are useful and complementary. The risks of identified events have to be determined, as well as resources required for power restoration in a specified time frame.

Before taking actions, **Asset Owners** would like to understand the characteristics of the storm event that occurred. Was it an exceptional event? Can it happen again? Therefore the basic understanding of the meteorological phenomena and their impact on lines is essential. Especially continuous research on the wind profile of High Intensity Winds is needed, as those events are difficult to forecast in time and space.

Utilities already improved their communication with meteorological or **weather stations** to be better prepared in advance by being informed regarding forecasts and tracks of severe weather phenomena.

Finally, **companies** must be able to timely and accurately determine a global estimated restoration time and **communicate** that to the customers and the population.

12. Final recommendations

With the answers to the Questionnaire received from CIGRE SC B2 members and various SC B2 Working Groups, CIGRE WG B2.06 was able to collect and compare worldwide information on Big Storm Events during the last decades in order to share experience in corrective and preventive actions and lessons in preparedness.

On the basis of the lessons learned, WG B2.06 recommends:

- Taking immediate aerial photos and videos on site before clearing the damaged structures after a Big Storm Event. This can facilitate the assessment of the origin of direct failures (wind or ice) and indirect failures (fallen trees), and allow designers to distinguish between the primary failures and the secondary failures, including the cascade failures;

- Collecting all meteorological data available, to analyse and to understand the storm event (type, origin, location or track, intensity, duration, and correspondence with forecast);

- Performing failure analysis (observation on site, test on samples, calculations);

- Understanding the relation between:
  - The climatic load;
  - The existing strength of line components, taking into account the condition of most sensitive elements;

- Developing strategies and policies for:
  - Increasing structural and electrical reliability;
  - Improving availability and continuity of service;
  - Taking appropriate actions to reduce possible secondary failures and cascades;

- Finding a good balance between:
  - Corrective measures to take after an unexpected storm event, such as quick restoration of power and services, emergency supply, rebuilding;
  - Preventive measures taken before a possible storm event, such as new design rules, preparedness, spare parts and emergency response plan, including organisation, resources and training, according to CIGRÉ SC B2 WG 13 (2005);

- Improving basic understanding and knowledge about climate features, their changes and their impact on overhead lines.

Facilitating transfer from deterministic to reliability based design methods of overhead lines based on the International Standard IEC 60826. Loads and strengths are recognized as random variables. With statistical data, designers can associate a value of wind or ice load for any selected climatic return period or reliability level.

13. References

13.1 References to clauses 9 and 10 on Big Storm Events

Reports accessible to the public			
Country	**Provided by**	**Report**	**Ref**
Australia	Henry Hawes e.a.	Letchford, C. W., Hawes, H., 2000. Risk assessment to improve reliability of transmission facilities exposed to sub-tropical high wind events. CIGRE Session paper 22-104, Session 2000, Paris, France.	1
Belgium	Eric Cloet; Jan Rogier	Cloet, E. and Rogier, J., 2004. Securing strategic overhead transmission lines in the Belgian grid. Symposium "Securing Critical Infrastructures", October, 2004, Grenoble, France.	2
	Jan Rogier	Rogier, J. and Gille, A., 2002. Participation belge au dépannage du réseau français : un exemple de solidarité entre électriciens européens. SEE, Workshop "Les réseaux électriques face aux phénomènes climatiques exceptionnelles", Paris, France.	3
		Rogier, J., 2004. De verwachtingen van de elektrotechnici betreffende het in rekening brengen van de invloed van de meteorologische omstandigheden – on line of voorspeld – op de sturing van hun netten. Cigré bijdragen (The expectations of the electriciens regarding the considerations of the weather conditions – by monitoring or by reporting – for power grid management. Cigré contributions). Revue E, 1/2004, Brussels, Belgium.	4
Brazil	Rogerio P. Guimarães	Answer to Question 3.11 of the Special Reporter, CIGRE Session 2004	5
Brazil	João Felix Nolasco	Analysis of recent transmission line failures, CIGRE WG B2.06 Technical Brochure 109 "Loading and strength of overhead lines"	6
Canada	Normand Bell e.a.	Bell, N., Binette, L., Lemieux, N., Sabarin, G., 2000. Increasing the reliability of transmission lines rebuilt after the January 1998 ice storm. CIGRE Session paper 22-106, Session 2000, Paris, France.	7
	Ghyslaine McClure	Nicolet, R., e.a., 1999. Facing the unforeseeable. Lessons from the Ice storm of '98. Commission Nicolet, Les Publications du Québec, Québec, Canada.	8
		Nicolet, R., e.a., 1999. Les conditions climatiques et l'approvisionnement en énergie. Commission Nicolet, Les Publications du Québec, Québec, Canada.	9

	Zibby Kieloch	Review of emergency response, restoration and design of these lines – Wind storm failure on Sept. 5, 1996.	10
Czech Republic	Jiří Hrabánek, Pavel Froněk	Popolanský, F., Hrabánek, J., 1974. Analysis of catastrophic storm in Czechoslovakia in 1974.	11
		Popolanský, F. Historical Survey of ice investigation on the territory of the Czech Republic.	12
France	Fabien Rancoule	Letscher, P., Haberstich, P., Dalle, B., 2002. Strengthening RTE overhead transmission lines following the storms of December 1999, CIGRE Session paper 22-105, Session 2002, Paris, France.	13
		Transmission system security – Reinforcement kits for anti-cascade towers, RTE.	14
		Power grid security – The RTE security plan – RTE.	15
		Storms of 1999: two major events for the network–RTE.	16
Germany	Hubert Brüninghoff	Thierau, G., 2006. Kurzfassung zur Ermitlung der Schadensursache der am 25/26.11.2005 in westlichen Münsterland geschädigten Stahlgittermaste des Hoch- und Mittelspannungsnetzes. Universität Duisburg-Essen, Essen, Germany.	17
Japan	Koji Fukami	Snow accretion resistant methodology, files ring1.jpg and ring2.jpg.	18
		Additional information, February 6, 2006	19
Netherlands	Bert Rhebergen e.a.	Rhebergen, B., Boone, M., Walter, R., Rogier, J., 1998. Experiences with 400 kV and 150 kV emergency restorations in Belgium and the Netherlands. CIGRE Session paper 22-205, Session 1998, Paris, France.	20
New Zealand	Robert Lake	Winds near Kawerau on 25 March 2005 and transmission line damage, 13.05.05	21
		Severe winds near Molesworth on 9 January 2004, September 2004.	22
Spain	Angel Gallego	Effects of the tropical storm Delta on transmission lines in Canary Islands	23
Sweden	Leif Söderberg †	Hurricane “Gudrun” - Background – Consequences – Aftermath, Slides, January 8, 2005.	24
	Curt Lindqvist	Lindqvist, C. The devastating effect on the supply in Sweden due to a storm/hurricane in January, 2005; Political response; Design principles. Cigré Opening panel on “Impact of Natural Phenomena on the Design & Operation of Power Systems” to CIGRE Session 2006, Paris, France.	25
Ukraine	Sergey Turbin	Turbin, S., 2003. Damageability of overhead line elements in Ukraine during wind and ice with wind storms, Draft report B2-03 (WG06) August 15, 2003	26
USA	Keith Lindsey e.a.	Schweiner, R. J., Twomey, K. E., Lindsey K. E., 2002. Transmission line emergency restoration philosophy at Los Angeles Department of water and power. CIGRE Session paper 22-101, Session 2002, Paris, France.	27

	T & D	Florida Power and Light strengthens grid, advances storm plan. Transmission and Distribution, November 28, 2006.	28
		Florida Commission approves rules to strengthen state’s electric infrastructure. Transmission and Distribution, December 6, 2006.	29
		Florida Power & Light Company – Report: Florida's transmission system is reliable. Transmission and Distribution, February 21, 2007.	30
		Florida Power & Light Company improves reliability after unprecedented hurricane seasons. Transmission and Distribution, March 6, 2007.	31
		FPL conducts ‘dry-run” by simulating arrival of a major hurricane. Transmission and Distribution, May 10, 2007.	32
		Tampa Electric Prepares Year-Round for Hurricane Season. Transmission and Distribution, June 5, 2007.	33
		South Carolina Agency releases review of Duke’s power response to 05 Ice Storm. Transmission and Distribution, February 2, 2007.	34
		ComEd Releases More Than 180 Employees, Contractors to Help Ameren Restore Downstate Customers. Transmission and Distribution, December 7, 2006.	35
		Nebraska Public Power District Developing Long-Term Restoration Strategy. Transmission and Distribution, January 3, 2007.	36
		Nebraska Public Power District Finishes Storm Restoration. Transmission and Distribution, May 15, 2007.	37
		Winter Storms Bring Power Outages Across the Nation. Transmission and Distribution, January 17, 2007.	38
		Interstate Power and Light Submits Major Winter Storm Restoration Report to Iowa Utilities Board. Transmission and Distribution, April 2, 2007	39
		Interstate Power and Light Co. Completes Rebuild of 345-kV Transmission Line. Transmission and Distribution, Augustus 2, 2007	40

13.2 References to other clauses, especially to Appendix C

Alexandersson, H., Schmith, T., Iden, K., and Tuomenvirta, H. (1998). Long-term variations of the storm climate over NW Europe. *Global Atmosphere and Ocean Systems*, **6**, 97-120.

American Meteorological Society (AMS) (2007). Climate Change – An Information Statement of AMS. *Bulletin American Meteorological Society*, **88**, Washington, US.

American Society of Civil Engineers (ASCE) (2005). Guidelines for electrical transmission line structural loading, draft revision 2005. ASCE Manual No. 74, New York, US.

Atlantic Oceanographic and Meteorological Laboratory (NOAA) (2005). Frequently Asked Questions. NOAA, Hurricane Research Division, Update October 19, 2005.

Bartlett, S. (2007) Australia responds to cyclone Larry. Powerlink Queensland's emergency-management procedures expedite disaster-recovery efforts. Transmission and Distribution, 5, May 2007, pp. 56-64.

Chan, J. C. L., and Liu, S. L. (2004). Global warming and western North Pacific typhoon activity from an observational perspective. *J. Climate*, **17**, pp. 4590-4602.

Chan, J. L. C., and Shi, J.-E. (1996). Long-term trends and interannual variability in tropical cyclone activity over the western North Pacific. *Geophys. Res. Lett.*, **23**, pp. 2765-2767.

CIGRÉ SC 22 WG 06 (2000). Load control devices of overhead transmission lines. CIGRÉ Technical Brochure No. 174, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC 22 WG 06 (2001). Probabilistic Design of overhead transmission lines on current practices regarding frequencies and magnitude of high intensity winds. CIGRÉ Technical Brochure No. 178, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC B2 WG 06 (2006). Reliability based design methods for overhead lines - Advantages, applications and comparisons. CIGRÉ Technical Brochure No. 289, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC B2 WG 06 (2006). How overhead lines are re-designed for Uprating-Upgrading – Analysis of the answers to the Questionnaire, CIGRE Technical Brochure 294, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC B2 WG 06 (2008). How Overhead Lines respond to Localized High Intensity Winds – Basic Understanding, CIGRE Technical Brochure, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC B2 WG 13 (2003). Assessment of existing overhead line supports, CIGRE Technical Brochure 230, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC B2 WG 13 (2005). Guidelines for emergency resource planning for overhead transmission line asset owners, Electra Journal No. 222, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC B2 WG 16 (2004). Report on current practices regarding frequencies and magnitude of high intensity winds. CIGRÉ Technical Brochure No. 256, International Council on Large Electric Networks, Paris, France.

CIGRÉ SC B2 WG 16 (2006). Guidelines for meteorological icing models, statistical methods and topographical effects, CIGRE Technical Brochure 291, International Council on Large Electric Networks, Paris, France.

Easterling, W., Hurd, B., and Smith, J. (2004). Coping with global climate change: The role of adaptation in the United States, Pew Centre on Global Climate Change.

Emanuel, K. A. (1987). The dependence of hurricane intensity on climate. *Nature*, **326**, pp. 483-485.

Emanuel, K. A. (2000). A statistical analysis of tropical cyclone intensity. *Mon. Weather Review*, **128**, pp. 1139-1152.

Emanuel, K. A. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, pp. 686-688, August 4, 2005.

Emanuel, K. A. (2005). Hurricanes and climate. American Meteorological Society, Seminar "Hurricanes: Are they changing and are we adequately prepared for the future?".

Emanuel, K. A. (2006). Anthropogenic Effects on Tropical Cyclone Activity.

Engel, M., Brown, R., Phillips, E., and Bingel, N. (2007). Extreme winds test wood pole strength. Midwest Energy investigates cause of failure in the aftermath of a significant meteorological event. *Transmission and distribution*, **5**, May 2007, pp. 34-38.

Environment Canada. Ice storm 1998. A closer look at a rare situation.

Environmental Protection Agency (2007). Climate change – Science. Washinton D. C., US.

Europe Quality Expertise (2000). Lothar and martin, 100 year event. January 6, 2000.

European Environment Agency (2005). Vulnerability and adaptation to climate change in Europe. EEA Briefing 3, Copenhagen, Denmark.

Ghannoum, E. (2003). Increasing Structural Reliability and Security using IEC 60826 Principles. Report R9-03, Colloquium on Overhead Lines Revitalization, Belgrade, May 6-10, 2003.

Glick D. (2004). Global warming. Geosigns. *National Geographic*, September 2004, Vol. 206, No. 3.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D. W., and Medina-Elizade, M. (2006). Global temperature change. Proceedings of the National Academy of Sciences of the USA.

Hayden, T. (2006). Super Storms. No end in sight. National Geographic, August 2006, pp. 66-77, USA.

Holland, G. J. (1993). Global Guide to Tropical Cyclone Forecasting. WMO/TC-No. 560, Report No. TCP-31, World Meteorological Organization, Geneva, Switzerland.

Intergovernmental Panel on Climate Change (IPCC) (2001). Third Assessment Report of the IPCC, Working Group I: The Scientific Basis, Paris, France.

Intergovernmental Panel on Climate Change (IPCC) (2007). Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Climate Change 2007: The Physical Science Basis. Summary for Policymakers. IPCC, Paris, France.

Intergovernmental Panel on Climate Change (IPCC) (2007). Contribution of Working Group II to the Fourth Assessment Report of the IPCC, Climate Change 2007: Climate Change - Impacts, Adaptation and Vulnerability. Summary for Policymakers. IPCC, Paris, France.

International Electrotechnical Commission (IEC) (2003). Design criteria of Overhead Transmission Lines, International Standard 60826, Technical Committee 11, 2nd Ed., ISO, Geneva, Switzerland.

Kluger, J. (2005). Global Warming: The Culprit. *Time Magazine,* October 3, 2005, No. 40.

Kluger, J. (2007). Global warming: Mitigation. *Time Magazine*, April 9, 2007, No. 15.

Knutsen, T. R., and Tuleya, R. E. (2004). Impact of CO_2-induced warming on simulated hurricane intensity and precipitation - Sensitivity to the choice of climate model and convective parameterization. *J. Climate*, **17**, pp. 3477-3495.

Landsea, C. W., Nicholls, N., Gray, W. M., Avila, L. A. (1996). Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophys. Res. Lett.*, **23**, pp. 1697-1700.

Landsea, C. W., Pielke Jr., R. A., Mestas-Nuñez, A. M., and Knaff, J. A. (1999). Atlantic basin hurricanes - Indices of climatic changes. *Climate Change*, **42**, pp. 89-129.

Langlois, S. (2006). Effect of high intensity winds on overhead transmission lines. McGill University, Department of Civil Engineering and Applied Mechanics. Structural Engineering Series. Report no. 2006-02, 68 p.

Mann, M. and Emanuel, K. A. (2006). Atlantic hurricane trends linked to climate change. EOS, 87, 233-241.

McCibben, B. (2007). Confronting Carbon. *National Geographic*, October 2007, Vol. 212, No. 4.

McDonald, J.R., and Mehta, K.C. (2006). A recommendation for an Enhanced Fujita Scale (EF-Scale). Technical Report submitted to The National Weather Service. Wind Science and Engineering Center, Texas Tech University, Texas, USA.

National Academy of Sciences (NAS) (2001). Climate Change Science – An Analysis of some Key Questions. National Academy Press, Washington, US.

National Center for Atmospheric Research (NCAR). Overview of NCAR research on climate change.

National Oceanic and Atmospheric Administration (NOAA) (2000). How much energy does a hurricane release.

National Oceanic and Atmospheric Administration (2006). Evolution of the National Weather Service. Climate Change Science – An Analysis of some Key Questions. National Academy Press, Washington, US.

National Oceanic and Atmospheric Administration (2006). Tornado Monitoring; Update August 17, 2006, Ashville, US.

National Oceanic and Atmospheric Administration (2006). Global Warming. Frequently asked questions. Update February 3,2006, Ashville, US.

National Research Council (NRC) (2001). Climate change Science: An analysis of some key questions. National Academy Press, Washington, DC, US.

National Research Council (NRC) (2006). Surface temperature. Reconstructions for the last 2000 years. National Academy Press, Washington, DC, US.

Nolasco, J. F. (1996). Analysis of recent transmission line failures. CIGRÉ Technical Brochure No. 256, Review of IEC 826: Loading and strength of overhead lines (pp. 87-98). Paris, France.

Pielke Jr., R. A., Landsea, C., Mayfield, M., Laver, J., and Pasch, R. (2005). Hurricanes and Global Warming. *Bulletin of American Meteorological Society*, November 2005, pp. 1571-1575.

Schade, L., and Emanuel, K. (1999). The ocean's effect on the intensity of tropical cyclones: Results from a simple coupled atmosphere-ocean model. *Journal Atmospheric Science*, 56, pp. 642-651.

Simmonds, I., and Keay, K. (2000). Variability of Southern Hemisphere extra-tropical cyclone behavior, 1958-97. *J. Climate*, **13**(3), 550–561.

Stern, N. (2006). Stern Review on the Economics of Climate Change.

Stern, N. (2006). Unchecked Global Warming a Massive Threat to US and Global Economies. Stern Report Global Warming, Washington.

Trenberth, K. (2002). The evolution of ENSO and global atmospherictemperatures. *J. Geophys. Res.*, **107**, 4065.

WASA Group (Von Storch et al.), (1998). Changing waves and storms in the Northeast Atlantic? *Bull. Am. Met. Soc.*, **79**, 741-760.

Webster, P. J., Holland, G. J., Curry, J. A., and Chang, H.-R. (2005). Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment. *Science*, **309**, pp. 1844-1846.

World Meteorological Organization (WMO) (2006). El Niño/la Niña Update. Geneva, Switzerland.

World Meteorological Organization (WMO) (2006). Link between climate change and tropical cyclone activity – More research necessary. Press release No. 766, December 11, 2006, Geneva, Switzerland.

World Meteorological Organization (WMO) (2006). Statement on tropical cyclones and climate change. WMO International Workshop on Tropical Cyclones, IWTC-6, November 2006, San Jose, Costa Rica.

Zhang, Y., and Wang, W. C. (1997). Model-simulated northern winter cyclone and anticyclone activity under a greenhouse warming scenario. *J. Climate*, **10**, 1616-1634.

Appendices

A. Specific regional aspects of some widespread BSE

A.1 Canada – Ice storm on January 5-9, 1998

January 1998 ice storm

The ice storm of 1998, also known as Ice Storm ’98, caused massive damage to trees and electrical infrastructure all over the area, leading to widespread power outages. Millions were left in the dark for periods varying from days to weeks and a shut down of activities in large cities like Montreal and Ottawa led to an unprecedented reconstruction effort of the power grid [7].

Five days of freezing rain precipitation in southern and western Quebec caused the collapse of several transmission lines owned by Hydro-Québec. Among installations rated 49 kV and more, over 2 000 wood portal structures and 600 steel lattice towers were destroyed or sustained. About 1,5 million customers were without power for periods ranging from a few hours to over 30 days. A large surface area of 150 000 km^2 was affected. According to Environment Canada’s data [7], there was up to 100 mm of ice on the ground.

Outages – Power restoration

On January 6, about 700 000 clients were without electricity. The number of clients affected went down to 500 000 on January 7, then rose to over a million on January 8. The maximum number of clients without electricity was reached on January 9. On that date, 1 400 000 clients were deprived of service, which represents approximately 3,5 million people, that is, half the population of Québec.

While the power failure in 1989 lasted 8 hours, this time half of the clients affected were without electricity for two and a half days, and some of them for more than thirty days. On January 17, about 250 000 clients were still without electricity.

It was observed that the breakage of conductors and failures of towers supporting them, occurred toward the end of the periods of freezing rain. The quantities of accumulated ice were then at their peak and moderate winds were blowing in the disaster area, with gusts reaching 50 km/h.

Damage

Freezing rain caused the collapse of:

- 617 towers, of which 194 were for 120 kV lines, 234 for 230 kV lines, 53 for 315 kV lines, 129 for 735 kV lines and 7 for interconnection purposes. To add to this

- 1100 wood and steel support structures carrying 120 kV lines and 1500 wood poles carrying 49 kV lines.

There were eight major cascade collapses among structures of the 735 kV transmission network.

Most of the broken poles and crossarms were observed for spans greater than 50 m and for structures having to support a 3-phase system. In both cases, the weight of the ice was clearly greater than the capacity of the vertical (poles) and horizontal (crossarms) structures to withstand the ice. More than 16 000 poles were replaced.

At no time during the storm were the generation plants affected. Except for a few minor elements, the substations all resisted the freezing rain.

Origin of the January 1998 ice storm

Freezing rain is common in Canada. Typically, a warm air mass will come up along the Mississippi Valley and overrun a shallow layer of cold air trapped at the surface.

On January 4, 1998, two extremely unusual phenomena occurred simultaneously [9;10]:

- The low pressure system of warm, moist air mass was larger than during a normal winter, due to the weather system called “El Niño” coming from the Gulf of Mexico (Appendix C.3.5) over the Great Lakes toward the upper St. Lawrence Valley;

- The normal drift from west to the east was stopped for a few days because of the presence for of a large stationary high pressure system above Newfoundland and Labrador, unusually strong for winter time, keeping an Easterly flow of very cold air near the surface. No one was able to explain why this air mass was blocked over such an abnormally long period of time.

As a consequence of these two phenomena, the first occurrence of freezing rain registered on January 5, was followed by a second one on January 7, and then by a third rainfall on January 8.

Snow is produced at upper level in such a winter storm system but it eventually melts into rain in the warm layer, above freezing temperature, associated with the overrunning. When that rain touches the ground in the cold air below, the droplets freeze on contact creating accumulations of ice (Appendix C. 3.2).

Problems of observation and quantification

Exact data concerning the amount of ice accumulated on the ground following the January storm was not readily available [8]. It was even more difficult to determine the amount of ice that accumulated on overhead conductors in particular. Moreover the automatic gauges used at most meteorological stations were not able to distinguish between freezing rain and ice pellets, so that the instrument converted everything into the equivalent water depth. When freezing rain was falling, the air masses in movement are all at a temperature close to the freezing point, so that the temperature only has to vary slightly to modify the freezing rain in rain precipitation, ice pellets or even melting snow.

Data about ice deposits

The Montreal area typically receives freezing rain between 12 and 17 times a year, averaging between 45 and 65 total hours of rain. In Quebec, standards were reinforced after a storm left 30 to 40 mm of ice over Montreal in 1961.

Prior to the 1998 storm, the last major ice storm to hit Montreal (1986) deposited around 30 to 60 mm of ice. However, the 1998 storm left deposits twice as thick, downing power lines all over the region, damaging most of the trees in Montreal, and leaving streets covered in a thick impassable layer of ice.

Although it is difficult to make direct measurements of the ice build-up on conductors, two methods may be used to assess it:

- Calculation using empirical, semi-empirical or analytical models, such as Chaîne, Stokes, Makkonen models (CIGRE WG16, 2006);
- Direct measurement on the icing-rate meters installed at the monitoring stations.

The amount of build-up varied from one transmission line to the next and from span to span. This variation could be attributed to different causes:

- Random nature of freezing rain;
- Protection offered by wooded areas;
- Torsional rigidity of conductors (varying with the diameter of the single conductor or the outside diameter of the conductor bundle. The ice deposits on the earth wires were usually more cylindrical in form due to the lower torsional rigidity which allows them to rotate around more easily);
- Wind direction (line sections running parallel to the wind sustained twice as less damage than the perpendicular sections).

Moreover the shape of the ice deposits is also important to assess the wind loads, since it has a direct impact on the drag coefficient. Current standards generally consider drag coefficients of about 1,0 to 1,1 if the ice deposit is perfectly cylindrical in shape. However, highly non-symmetrical deposits were noted during the ice storm. Wind-tunnel tests conducted on similar profiles showed that the actual drag coefficients ranged from 1,2 to 2,4, and the diameter considered for the wind load could be 20% higher compared with a cylindrical ice profile with the same mass per unit length.

History of design criteria

Following the collapse of transmission towers in 1969 and 1973 where high icing loads destroyed about thirty 735 kV towers on each occasion, Hydro-Quebec (HQ) revised its design criteria upward. Until 1973 HQ followed the CSA-C22.3 (produced by the Canadian Standards Association). It stipulated only one load level, namely a combination of 12,7 mm of ice and 0,383 kPa of wind pressure, along with one broken conductor. A safety factor was added to these loads.

After the 1969 and 1973 ice storms, the new standard considered separate climatic loads, similar to the reliability based design methods of IEC Technical Report 826 (replaced with International Standard IEC 60826 in 2003), such as:

- maximum ice load without any wind;
- high wind load without any ice.

The combined wind and ice loads were increased by about 50%.

The aim was to obtain lines capable of withstanding loads with a return period of at least 50 years.

Several scenarios were defined involving imbalanced loads and phase failures. The use of anti-cascading structures was provided to limit potential damage.

As in southern Quebec the average duration of freezing-rain precipitation is 25 to 50 hours a year, a network of 150 monitoring stations with icing-rate meters was set up in the 1970s to gather information on freezing rain.

New load levels

Considering the urgent need to rebuild certain strategic connections while ensuring public safety, HQ established transitional loads for these projects with higher levels of reliability.

The load levels retained were 55 mm and 65 mm, defined based on the geographic area where each project is located, so that the reliability of the rebuilt lines was comparable. For all projects, the chosen load level had to have a return period of more than 150 years.

The specifications stipulated very high reliability criteria for these restoration projects corresponding to levels 55 mm and 65 mm, while existing standard tower types were designed for loads about equivalent to level 45 mm (**Table A.1**).

Due to the lower torsion rigidity of the earth wire, it is now recommended to consider at least the same ice weight (and not the same ice thickness) as for the single conductors, independently of the earth wire diameter.

Table A.1 – Example of three levels of climatic load for restoration projects

Load	Original loads		Loads for restoration			
Return period	> 50 years		> 150 years based on the geographic area			
Load level	Level 45 mm		Level 55 mm		Level 65 mm	
	Ice mm	Wind km/h (Pa)	Ice mm	Wind km/h (Pa)	Ice mm	Wind km/h (Pa)
Freezing rain only	45	-	55	-	65	-
Combined freezing rain and wind	20	80 (600)	25	85 (680)	30	85 (680)
Maximum wind only	-	110 (1140)	-	120 (1360)	-	120 (1360)
Return period of freezing rain only	50 years		100 years		150 years	

New strategy

Following the 1998 ice storm, HQ drew up a three-part intervention strategy:

- Emergency restoration of critical lines;
- Restoration of collapsed lines before the next winter peak;
- Reinforcement of the transmission system over the medium and long term.

Before the application of a revised standard, transitional measures were adopted for the restoration of the collapsed lines.

All these aspects of the ice storm and its repercussions were covered under a study conducted by a government enquiry commission, called "Commission Nicolet" (See Appendix A.14) [8; 9].

Rebuilding collapsed lines

Upgrading 230 kV double circuit Boucherville – St. Césaire line

The double circuit line Boucherville – St. Césaire sustained considerable damage during the ice storm. More than half of the transmission towers on the 42 km line were destroyed or heavily damaged. It was originally designed to withstand level 45 mm climatic loads, corresponding to a return period of 50 years for ice events. Considering the line's strategic importance, the objective was to rebuild the line by considerably increasing its structural strength so that it could withstand level 65 mm loads, about 3 times the return period of the original line.

After considering various solutions, the chosen strategy was to replace the current twin bundle with a single large conductor offering an adequate electrical performance. With this solution there was no need to modify the towers or reinforce the foundations, considering that a single conductor, even with a larger diameter, is subject to less ice build-up than a bundle of two small conductors, due to a lower sum of diameters (-28%).

This type of approach usually presents disadvantages from an electrical standpoint. However, the slight reduction of the thermal capacity remains acceptable (-21%) as the conductivity of the single large conductor was roughly equivalent to that of the twin bundle. Moreover, audible noise and radio interference are usually not critical at the voltage level of 230 kV.

The conductor bundle 2 Curlew 524 A1/S1A 54/7 was replaced with 1 Geant 1060 A1/S1A 54/19. For similar climatic conditions the single large conductor induces less mechanical unit loads (-39% for vertical loads with 65 mm ice and -43% for transverse loads of 680 Pa on 30 mm sleeve) (**Table A.2**).

Table A.2 – Characteristics of conductor bundles and unit loads (N/m) under same climatic conditions

Characteristics			Original	Used	Diff.
Description of arrangement			2 Curlew 524 A1/S1A 54/7	1 Geant 1060 A1/S1A 54/19	
Physical properties	Total of diameters	mm	63,2	45,0	- 28%
	Transmission capacity	MVA	1420	1120	- 21%
65 mm freezing rain only	Vertical load per phase	N/m	387,1	237,5	- 39%
30 mm ice with 680 Pa wind	Transverse load per phase	N/m	124,6	71,4	- 43%

The analysis of the loads originating from the new conductor shows that most of the loads are similar or less than the original design loads, especially the transverse loads (-17% for a span length of 400 m) (**Table A.3**) which control most of members in suspension towers. There are a few minor overruns (about +3%), but which do not have any repercussions due to the frequent under-utilization of the towers and because some of these loads do not control the size of the tower leg members.

Table A.3 – Comparison of loads (kN) before and after modification for a 400 m span

Characteristics			Original	Used	Diff.
Description of arrangement			2 Curlew 524 A1/S1A 54/7	1 Geant 1060 A1/S1A 54/19	
Load level			45	65	
Freezing rain only	Vertical load per phase	kN	92,0	94,8	+ 3%
Ice with wind	Transverse load per phase	kN	34,4	28,6	- 17%
Phase failure	Longitudinal load per phase	kN	47,4	48,7	+ 3%
Freezing rain	Sag	m	19,6	19,8	0%
Bare at 95°C	Sag	m	16,4	16,4	0%

The selected conductor has roughly the same sag behaviour as the original bundle so that tower heights and foundations could be maintained without strengthening the structures.

However, to increase the line's reliability, the existing optical earth wire had to be replaced with a new sturdier earth wire and modifications had to be made to the towers' overhead wire peak. To limit the extent of the modifications to the other parts of the towers, the height of the peaks was slightly decreased so that the original angle of protection is now 30° instead of 25°.

Rebuilding two 735 kV lines

Among the 735 kV lines surrounding and supplying the island of Montreal, the lines Nicolet – Hertel and Boucherville – Hertel had been partially destroyed. Their capacity was below the current requirements of level 45 mm since both collapsed lines had been built according to the CSA Standards [7].

An initial strategy consisted in applying the same approach as for the 230 kV Boucherville – St. Césaire line, namely to replace the existing ACSR quad bundle of 36 mm conductors with a bundle of two or three larger conductors. Unfortunately, this solution was not adequate for the voltage level involved. In fact, the electrical and electromagnetic criteria would have called for diameters in excess of 50 mm. The total loads are then roughly the same as those from the original quad conductor bundle for the same climatic conditions. A quad bundle therefore had to be used.

Several other solutions for increasing the existing reliability were also assessed, taking into account the necessity to limit the modifications so that the lines could be put back into service within a few months' time:

- relaxation of the existing conductors using the standard towers with shorter spans;
- restoration of the collapsed towers at the same locations with additional towers at mid-span;
- use of new high strength conductors to reduce sag;
- optimization and design of a new conductor bundle and tower type;
- design of a single new optimized suspension tower for level 55.

The last solution was retained since it was found a good compromise between the first four solutions. Only a few minor reinforcements were also required on the angle and dead-end towers. **Table A.4** shows how the new suspension tower resulted in a considerable increase in the allowable weight spans and wind spans for levels 55 mm and 65 mm.

This solution was not necessarily the most optimal one over the long term, however it allowed project schedules to be met at an acceptable cost while supplementing a standard category of tower.

Table A.4 – Utilization criteria for 735 kV suspension towers at each load level						
Load Level	Level 45 mm		Level 55 mm		Level 65 mm	
Span length	Wind span (m)	Weight span (m)	Wind span (m)	Weight span (m)	Wind span (m)	Weight span (m)
Current tower	450	580	350	450	310	350
New tower	650	700	530	590	440	470
Increase	44%	21%	51%	31%	41%	34%

Conclusion

Following the 1998 ice storm, HQ drew up a three-part intervention strategy:

- Emergency restoration;
- Final restoration of collapsed lines;
- Reinforcement of the transmission system over the medium and long term.

The 1998 ice storm brought up a number of issues:

- the relevance of identifying future strategic lines with high mechanical strength;
- the possible revision of some current design criteria and parameters such as combining wind with major icing loads.

Regarding the rebuilt lines described in this report, two different innovative approaches resulted in a substantial increase in the prior reliability while maintaining very tight draft-design and construction schedules.

A.2 France – Windstorm on December 26 and 27-28, 1999

December 1999 windstorm

In December 1999, France suffered two major storms bringing exceptionally high winds and causing extensive damage to transmission, communication and distribution networks, buildings and monuments, trees and shrubs, etc. [13; 16].

Damage observed on the RTE transmission network was 50% due to trees falling on conductors or supports, to the direct effects of wind on the structures (up to 180 km/h inland), short-circuits due to miscellaneous projectiles on the lines (tree limbs, etc.) or excessive swaying of the conductors.

Electricity networks in the majority withstood these storms fairly well, despite some losses due to pollution from saline mists carried by violent winds on and around the coastlines. In spite of the extent of damage to all of the networks, RTE emphasizes that the balance of electricity generation and consumption remained fairly stable throughout all those events.

Automatic protections and service resumption devices operated satisfactorily, as did the network observation and command capabilities and routing of safety communications.

Outages – Power restoration

After the two storms 3 450 000 customers in 90 French districts were left without electricity. Within 24 hours, electricity was restored to 1 500 000 households. The last few customers were finally re-supplied on January 13, 2000.

All the substations and industrial customers were reconnected in less than 4 days.

In all, 70 000 people (EdF agents, workers from firms in the electricity sector, the French army and foreign contractors from Belgium, Germany the Netherlands and Spain) worked to re-establish service, including nearly 50 000 in logistics, telephone reception, relations with local communities or equipment suppliers.

Equipment resources were acquired in matching proportions: more than 5 000 generator sets of all power levels, 2 500 tons of supports, 4 000 km of conductors and 900 000 connection parts were used.

A number of 11 emergency lines including 4 from abroad were installed on 8 links [3]. More than 60 helicopters have been used, and more than 10 km of temporary roadway have been installed to give access to towers. Contacts with the Ministry of Transport led to the publication of orders authorizing lorries carrying equipment to travel on the motorways on two consecutive Sundays.

The overhead lines have been rebuilt on the same routes. However, the mechanical strength of some damaged structures has been improved immediately, as it was noticed that the wind speeds were 10 km/h higher than foreseen by the design standards.

Damages

The storms of December 26 (from 02h00 to 11h00) and 27-28 (from 16h00 to 04h00), 1999 caused unprecedented damage to the French electrical network, due to worsening depression conditions (960 hPa). The territorial extent of both storms (approximately 2/3 of France) and the violence of the wind were truly exceptional. The zones affected were much broader than in October 1987 (in Brittany) and February 1990. During the storm, wind speeds exceeded 150 km/h, and in some areas speeds reached from 180 to 200 km/h.

The exceptional wind speeds created by these two storms inflicted heavy and widespread damage, which was amplified by the flood and avalanche losses following the storms. Woods and forest in France, Germany and Switzerland were devastated by the storms. In France, an estimated 4% of the forests were destroyed, translating into roughly 90 000 000 cubic meters of timber.

After the relative lack of activity since 1990, the December 1999 storms are a shocking reminder that Europe is frequently exposed to violent winter storms which cause widespread damage throughout northwest Europe. While the consequences are massive, the damage suffered is not uncommon, and can be expected to occur again in this century.

The severity and the extension of the wind storm can be illustrated by the quantity of forest destroyed: $139 \cdot 10^6$ m^3 or ten times the loss in 1982 (and 1990).

Damages to the lines and supports

The following numbers of failures have been registered:

- 400 kV:
  - 38 / 447 (8,5%) lines were out of service (16 seriously);
  - 119 / 26 300 (0,4%) towers collapsed (of which 6% built before 1970; 75% built between 1970 and 1978; 19% built between 1978 and 1991);
- 225 kV:
  - 81 / 1 421 (5,7 %) lines were out of service;
  - 121 / 53 200 (0,2%) towers collapsed (of which 22% built before 1958; 53% built between 1958 and 1970; 14% built between 1970 and 1978; 11% built between 1978 and 1991);
- 63 and 90 kV:
  - 421 / 5 093 (7,6%) lines were out of service;
- 90 kV: 90 / 45 00 (0,2%) towers collapsed;
- 63 kV: 259 / 123 100 (0,2%) towers collapsed;
- For 90 and 63 kV: 73% of the damages were due to the fall of trees/branches on the lines;
- 184 / 4 406 (3,9%) substations for supplying customers and industries were out of service on December 27, 1999.

Towers mostly failed due to the buckling of a main leg member, some tower tops and crossarms were broken. Failures of foundations were due to geotechnical or intrinsic weakness.

For the damages to the HV and EHV network, only one quarter was due to the wind speeds that were superior to the design wind speed for towers. The rest of the damages was mostly due to cascade and old or inadequate design.

A low number of towers failed, if the following towers are excluded from the total number: towers with low safety margin, foundations with drilled massive and towers failed by cascade: in this case only 66 towers 225 and 400 kV failed or 66 / 79 500 = 0,08%.

RTE noticed the good behaviour of towers built after 1991.

Origin of the windstorm

According to EQE (Europe Quality Expertise) the two storms “Lothar” and “Martin” propagated from separate Atlantic depressions loaded with warm air, which strengthened both as they made landfall and met with a cold air mass. Temperature contrast caused extreme turbulence along the weather front, creating the first storm “Lothar”. The remarkable aspect was the geographical spread of high wind speed as the atmospheric system crossed Europe.

The second storm “Martin” issued from a similar but different Atlantic system. The wind speeds were generally not as high as those from the first storm. The storm, however, carried a lot of moisture, and damage stemmed not only from wind speeds but also from rain and subsequent flooding. As a result the Alps in southeast France, Switzerland, Austria and northern Italy were covered with heavy snow fall and a large number of avalanches took place.

Each of both storms was associated with an intense jet stream aloft and benefited from latent heat release through atmosphere-ocean exchange processes. "Lothar" and “Martin”, were extra-tropical cyclones and had a hurricane-like shape, with an eye at the center (Appendix A.3.1).

EQE, in cooperation with Swiss Re, developed a new Storm Severity Index, which combines:

- storm duration;
- the area affected by the storm;
- the maximum wind speed,

in order to better reflect the nature of European windstorms.

Based on its research of European windstorm activity of the past century, EQE estimates Lothar and Martin storms to be respectively one in a 100 years (150 years for Paris and Colmar) and one in a 50 year event (100 years for Clermont Ferrand).

Maximum wind speed

According to **Table A.5** the wind speeds vary from one meteorological station to another. The speed of the displacement of the air masses was nearly 100 km/h. They went from west to east without any weakening.

Methodology for feedback of experiences

RTE realised the importance of accurately recording the scale and type of damage that had occurred. At each location the following methodology was applied:

- Inspection and recording of the scale and type of damage at each site;
- Technical investigation and verification according to:
    - The original methods;
    - The current design rules;
    - The limit state using special tools;
- Assessment of the chronology of the events from observations on site, estimated wind speed and results of the technical investigations.

Table A.5 – Maximum wind speed observed per weather station, December 28, 1999

	Weather station	Max gust wind speed observed (km/h)
1	Lann Bihioué	162
2	Alençon	166
3	Orly (airport)	173
4	Colmar	165
5	Pointe du Raz (coast)	162
6	Pointe de Graves	200
7	Cap Ferret	173
8	Biscarosse	166
9	Limoges	148
10	Clermont Ferrand	159
	Mean value	165
	Standard deviation	11

New strengthening policy

RTE decided a new policy for strengthening the transmission network. This policy was developed to meet two main goals when atmospheric events comparable to those of December 1999 occur [15]:

- To guarantee the safety of people and property;
- To ensure the continuity of supply to customers and safety of system operation.

To improve safety of people and property in case of exceptional climatic events, RTE adopted measures for the installations located near inhabited areas and major communication lines.

Once the policy was implemented, RTE would be able to deliver on the following commitments:

- In case of events similar to those of December 1999, power remains supplied to nearly all substations;
- For even more powerful storms, service should be restored within 5 days.

To reach this goal, each substation of the transmission network will be equipped with at least one mechanically reliable supply line to guarantee that the installation can withstand the newly defined climatic conditions.

The new technical measures adopted to secure the line considered are described below:

- Implementing “anti-cascade” towers in order to limit the spatial extent of structural collapse in the network in case of exceptional climatic events. On the average, the “anti-cascade” towers have to be installed every ten spans, or approximately 5 km at 400 kV. This distance was selected as this is the length of overhead line which can be restored using the emergency restoration systems available so that they can be set up in 5 days [14].

- Mechanical reinforcement using the new design criteria, according to the French Technical Regulation of May 17, 2001. The revisions included the following:
    - The geographical areas where higher wind pressures were applied have been extended;
    - For the rest of the country, the regulated wind pressure used as a reference has been raised significantly.

Since the transmission system in France consists of standard tower families, the optimal solution from a technical and financial point of view is to design standard reinforcement kits. Therefore, RTE decided to develop a single generic kit per tower type [14]. The advantages of this generic kit solution are:

- Only one single kit per support type with only one associated calculation model;
- Standardization of the elements to be provided and of the operation on site;
- Optimization of delay and costs of supplying, assembling and insertion a given kit.

Consideration of these requirements led to the following upgrading solutions:

- Using more resistant nuts;
- Adding cross-bracing trusses;
- Replacing current steel angles with high strength steel angles;
- Doubling tower leg members.

As it was a very ambitious program, upgrading and insertion of "anti-cascade" towers have been scheduled over a 15-year period (**Table A.6**).

Table A.6 – Deadlines for implementation of the strengthening program

	Priority substations and local line sections to ensure safety of people and property	Other substations
Installation of "anti-cascade" towers	2003	2006
Mechanical upgrading to meet new dimensioning hypotheses	2008	2015

A number of 18 000 anti-cascading towers had to be inserted, either:

- By reinforcement or
- By replacement.

They were distributed as follows (**Table A.7**):

Table A.7 – Number of anti-cascade towers

Voltage level	Number of anti-cascade towers to be inserted
63-90 kV	13 000
225 kV	3 500
400 kV	1 000
Total	18 000

Immediate effective actions were:

- Review of the management of wood-felling corridors for forest line routes;
- Reinforcement of anti-cascade system;
- Elimination of identified weak points (tower and foundation types).

Previous and new design rules

According to the wind area, the wind pressures (**Table A.8**) on conductors and flat surfaces of poles and steel angles (given between brackets) have been reviewed in the French Technical Regulation of 2001:

- In the so-called Normal Wind Areas (NWA), the wind pressure is increased by approximately 19%. The new and upgraded installations are now able to resist wind speeds of 160-170 km/h versus 150-155 km/h previously. The NWA area is reduced due to the increase in size of the other wind areas.
- The wind pressures applied to installations located in Strong Wind Areas (SWA) remain unchanged. However the geographical scope of this area is extended to cover all of Brittany, the Cottentin and the Pas de Calais regions. Moreover all coastal areas (including Corsica) are extended from 15 to 20 km inland.
- The High Wind Pressure (HWP) areas, previously included only in the RTE technical guidelines, are now included in the 2001 Technical Regulation. Those areas are extended to all coastal areas up to 2 km inland, to the estuaries and to the banks of the Rhone river up to Lyon.

Table A.8 – New design rules for wind loading on conductors and steel angles

		1991 Technical Regulation				2001 Technical Regulation			
		Wind pressure* on		Wind speed	Width area	New wind pressure* on		New wind speed	Width area
		Cond.	Angles			Cond.	Angles		
		Pa	Pa	km/h	km	Pa	Pa	km/h	km
HWP	High Wind Pressure	720	1515	180-190	1	unchanged			2
SWA	Strong Wind Area	640	1330	170-180	15	unchanged			20
NWA	Normal Wind Area	480	1030	150-155	Rest	570	1200	160-170	Rest

* Safety coefficient = 1,8

Table A.9 below gives the history of dimensioning.

Table A.9 – History of dimensioning

	Area	< 1958	1958	1972	1978	1991	2001
HWP	High Wind Pressure	X	-	EdF	EdF	Regulation	Area extended
SWA	Strong Wind Area	-	-	-	X	X	Area extended
NWA	Normal Wind Area	-	X	X	X	X	Wind pressure increased

Furthermore, some other changes were included in the Technical Regulation of May 17, 2001:

- The stability coefficient for foundations is 2,0 (versus 1,5 previously or 1,2 for wide-angle supports);
- The strength coordination is checked: the mechanical coordination coefficients are as follows: 1,2 for terminal supports; 1,1 for anti-cascade supports and 1,0 for all other supports.

Preparedness

A fast intervention team FIRE (Force d'Intervention Rapide Electricité) was installed. The objectives of FIRE are:

- The complete and fast supply of people without electricity when climatic catastrophes occur;
- Improvement of the strength of all electrical networks to the climatic events;
- Permanent disposal of necessary means to manage such crises.

Conclusion

After the December 1999 storms, RTE decided a new policy for strengthening the transmission network to meet two main goals when comparable atmospheric events occur:

- To guarantee the safety of people and property;
- To ensure the continuity of supply to customers and safety of system operation.

After the implementation, RTE would be able to deliver on the following commitments:

- Power remains supplied to nearly all substations;
- Service should be restored within 5 days.

RTE decided to develop an action plan over 15 years, to ensure the following three objectives would be met:

- Having a plan for proper RTE emergency organizational capacity;
- Refurbishment of weak points on the network:
    - By clearing stretches of forest land making it impossible for trees to fall on power lines;
    - By upgrading towers with "insufficient mechanical strength";
- Securing HV and EHV overhead lines on a longer timescale:
    - By the installation of anti-cascade towers;
    - By connecting all substations to at least one HV or EHV line;
    - By making all major communication route crossings more secure.

For new overhead lines the wind pressures have been reviewed in the French Technical Regulation principally by:

- Extending the High Wind Pressure areas;
- Increasing the wind pressure in the Normal Wind Pressure Areas.

A.3 Belgium – Windstorm on January 25 and February 26, 1990

The 1990 twin storms

The intensity of the wind storms that affected in 1990 the overhead lines in the western part of Belgium was probably comparable with the 1999 windstorm in France. Even the extent of the windstorms in comparison with the total surface of the country (1/6 of France) was similar. The first windstorm started in the northern part of France next to the border with Belgium, so that additional power stations could be started in time to avoid major outages on the distribution network [2].

The "storm of the century" on January 25, 1990 was followed one month later by a similar storm on February 26, 1990.

Outages – Power restoration

As the households were still supplied with electricity, there was no need to divulge information as there was no impact on the public.

Two important connections between the Netherlands and the nuclear power station Doel I in Belgium were destroyed due to the first windstorm of January 25, 1990. Four consecutive towers 400/150 kV collapsed. Directly after the failure the possibilities for restoration were investigated and bypass trajectories were explored for both 400 and 150 kV circuits. After approval of the trajectories for both circuits, the emergency towers were erected in spite of wind speeds of 70 km/h [4; 20].

As a result of the bilateral exchange agreement between Belgium and the Netherlands, Belgium was able to appeal to the Netherlands to also provide and install the Dutch emergency restoration line for the second circuit.

During the period that both emergency lines were in operation the second severe storm occurred on February 26, 1990. Some other towers in the country were again destroyed, but fortunately not on the emergency line.

Damage

The damage to the 150 and 380 kV network was disastrous:

- 69 self-supporting lattice towers collapsed (35 towers for 380 kV);
- 14 circuits were out of service (3 circuits for 380 kV);
- 37,5 km of lines were useless (20,6 km for 380 kV).

Origin of storm - Gust wind speed

The Belgian meteorological stations registered gust wind speeds from 115 km/h to 168 km/h. The return period of the climatic event was about 50 years and in two extreme cases even 200 years. With the experience of the wind storms 10 years later in France, it is obvious that those Belgian 1990 storms were also similar and exceptional, especially when the extent is considered, and probably a forerunner of the French 1999 windstorms (Appendices A.2 and C.3.1). Nevertheless, some lattice tower failures couldn't be explained, except by local topography.

Current design rules for wind loading

After the 1990 storms, there was no need to review the design standards. Due to the failure of some towers in 1985, less than 5 years before the 1990 storm, the wind loading conditions had already been reviewed and improvements implemented. The regulated dynamic base wind pressure before 1985 was 750 Pa up to a height of 25 m. This corresponded with a gust wind speed of 126 km/h. Taking into account the safety factor, the effective wind speed was more than 150 km/h. Since 1985, an exceptional maximum wind pressure of 1 500 Pa (or a gust wind speed of 178 km/h) was applied. At the same time the tower calculation according to ECSS (European Convention for Steel Structures) was introduced. After the 1990 wind storms, the Belgian government accepted the 1985 design standards.

Policy of upgrading after the Belgian 1990 twin storms

After the urgent reconstruction of the damaged OH lines, the Belgian utility decided to select the towers built before 1985 to reinforce according to some simple criteria:

- high towers with long wind span lengths;
- unprotected towers in open terrain;
- strategic towers (next to roads, railways and residential areas).

These tower reinforcements were performed by incorporation of additional steel angles and by replacement of existing steel angles with new ones in the bracings. Only one anti-cascade tower was added as the line sections (between tension towers) in Belgium are very short due to the high density of population and the dispersion of houses along the roads.

Check after the French 1999 windstorms

The severe wind storms in France at the end of 1999, that didn't affect the Belgian network, were at the basis of the decision in 2000 to analyse the strategic 380 - 220 - 150 kV lines, and to modify them where necessary. A line was considered to be strategic if the loss of the line, i.e. fallen towers, meant that the demanded power could no longer be supplied [2].

In order to avoid serious incidents as much as possible, the Belgian Utility Elia conducted a study with the following scope:

- identification of the components of the HV grid most vulnerable to wind load;
- the upgrading works needed to increase the reliability of the overhead network in bad weather;
- the development of an Emergency Plan.

As towers are standard products in overhead lines, towers installed in site are always underutilised with respect to the basic hypotheses of the design calculations of the standard tower. This is because:

- primarily, in practice the actual span in site is less than the calculated standard span (major gain of up to around 50%);
- the actual tower height is less than the maximum height (only a limited gain of max. 7%);
- the drag coefficient and/or diameter of the full-lock coil conductors of the Aero-Z type is lower for high wind speeds (very high gain up to 50%, especially for large conductor diameters);
- the line orientation is more favourable with respect to the prevailing winds (SW) (gain up to 30%).

There is thus a significant but variable reserve in the reliability level of the majority of the existing towers. In order to avoid a long, detailed and fastidious calculation program, the verifications of the tower strength have been limited:

- by using a simple and consistent calculation model that only uses available data, easy to implement [2];
- only for tower elements that present the greatest risk for failures.

Observations gained from different storms and the results of the tower strength calculations made it possible to identify the weakest elements of the lattice towers. These are:

- the outer main legs of the lowest K bracing: in axial compression (possible failure through buckling). In general, the safety coefficients decrease from top to bottom;

- the steel stub: simultaneously under a compression force and a bending moment. The height of the stub – or the distance between the concrete of the foundation chimney and the theoretical point (point of concurrence of the lower main leg and the diagonal angle) is limited in accordance with the specifications. The weakest point of the stub is at the entrance to the concrete (where the bending moment is the maximum) and depends on its height;
- the outer main legs of the middle part of the tower.

The consequences of the failure of a lower main leg, and above all of a steel stub, may be more severe than for the main leg of the middle part of the tower due to a:

- possible detachment from the foundation (with longer repair times for the foundation);
- tower fallen over a greater area (more damage possible around the tower);
- greater probability of cascading of towers (due to the greater differential longitudinal loads on adjacent towers).

For the reasons mentioned above, the actual use factor of an existing tower in site is less than that of a corresponding tower under the theoretical standard conditions.

The calculation of the actual use factor enables to rank the towers most sensitive to the prevailing winds for each strategic line. But by contrast, designers must be well aware that design wind speed can be exceeded due to local topography (ridges and slopes).

In order to verify the reliability of the data transmission network in a storm, lines equipped with a transmission earth cable were also examined.

Parallel lines and crossovers

In addition to the strategic lines, a study of parallel lines and crossovers on the 380 kV and 150 kV networks was done in 4 successive stages.

- In the first stage, a complete inventory of parallel lines and crossovers was made. On the basis of this inventory, only those whose simultaneous loss implies a very critical situation for the grid were selected.

- In the second stage, an analysis of the relative arrangements of the lines with respect to the prevailing wind enabled certain lines to be excluded from the study such as a parallel line that is behind the first line with respect to the prevailing wind.

- In the third stage, a geometric study showed that certain parallel lines did not present a real danger in the event of a fallen tower.

- The last stage of the study determined the use factors of the towers according to the method previously adopted.

Conclusion

After the 1990 windstorms in Belgium and the 1999 windstorms in France, the Belgian Utility Elia conducted a study with the following scope:

- Selection of the upgrading works needed to increase the reliability of the overhead network against severe weather based on:
  - Identification of the weakest elements of lattice towers by using the failure analysis of previous damages due to severe storm events;
  - Identification of strategic lines according to their importance for the network taking into account their relative position and orientation;
  - Ranking of the towers in a line according to their vulnerability to wind load on the basis of their use factor
- Development of an Emergency Plan.

A.4 Sweden – "Gudrun" windstorm on January 8, 2005

The "Gudrun" windstorm, 2005

Windstorm "Erwin", also called "Gudrun" in the Nordic region, hit northern Europe from Ireland to Russia on January 7-9, 2005. The Nordic region was the most affected area. According to meteorologists, the Gudrun windstorm was one of the worst to hit the region in years. Forest damage in the southern part of Sweden was the worst recorded in recent history and caused disruption of power supplies, phone lines and railway traffic on January 8th, 2005. The storm was called a hurricane. Probably the definition "hurricane" may be wrong, but unfortunately all reports used that word [24; 25].

Outages

A lot of traffic roads and railways were blocked. 400 000 households were without electricity and 200 000 households without teleconnection. After one week 200 000 households had their electricity back. Only on February 12, nearly all households were connected. About 10 000 homes were still without power after three weeks.

In Ireland the storm winds left around 150 000 homes without electricity. Power was cut to 30 000 homes in Carlisle (UK). In the Baltic state of Latvia 1 400 000 people (or 60% of the population) were deprived of power. In Estonia the severe weather left tens of thousands of people without power.

Restoration

The following resources were involved for restoration:

- 4 520 people working during 6 weeks;
- 600 lines men from Swedish contractors;

- 400 linesmen from international contractors (Finland, Norway, Denmark, Poland, Germany, UK).

Damage

In Sweden, a numberless amount of wooden poles from 0,4 –10 kV distribution lines failed. There was also an extensive damage on 40-50 kV lines. The severity and extent of the widespread storm can be characterized by the failure of 250 000 000 trees over an area of 40 000 km^2 with 75 000 000 m^3 storm felled forest. As a comparison, the total yearly production in Sweden is 85 000 000 m^3 and in the affected areas, 3 to 4 years of production were lost.

The Danish forests were affected with 20-30 km^2 of lost woods. In the Baltic state of Latvia, the powerful winds toppled up to 5 000 000 m^3 of wood; thousands of electricity poles were downed.

In 1969, Sweden was hit by two storms, causing damage of respectively 25 000 000 and 10 000 000 m^3 of fallen trees. Since then, the moist ground due to the mild and wet winter was a factor that has contributed to the global damage. At the time of the “Gudrun” storm, there was no frozen soil in southern part of Sweden so that there were new types of forests and trees growing very quickly.

Origin of the storm

In the afternoon of January 7, 2005, Gudrun began as a perturbation on the polar front in a region just west of Ireland. At the same time, cold air masses from Greenland started to move southward colliding with very mild and moist air masses located further south. The very strong winds of the jet stream in the troposphere, around 9 km up, were further accelerating to the northeast just aloft of the surface storm in its initial phase. In this situation, the strong upper-level winds, located right above the low-pressure system at the surface, draw the air from below, intensifying the pressure reduction. The resulting upward motions helped form clouds and precipitation (Appendix C.3.1).

The location of the jet stream together with a very large temperature difference between the air masses allowed the storm to generate a large amount of energy, affecting the speed and the direction of the wind.

The storm moved rapidly to the northeast. When the windstorm reached Norway and Sweden, the strong winds above the cyclone descended in the dry slot and made the surface beneath it a blustery place. After the storm was formed, strong winds developed in large areas of northern Germany, Denmark and western Sweden.

The mean wind speed measured at the weather stations in Sweden on January 8, 2000, 22h00 was 10-29 m/s, the maximum gust wind speed was 42 m/s at the southeast coast. In Jutland (Denmark) gust wind speeds of more than 45 m/s were recorded and in the Baltic state of Latvia up to 38 m/s.

After its climax, the storm started slowly to fill out but retained much of its strength for at least another twelve hours, while it continued moving eastward.

New strategy

In agreement with the Government the following objectives were adapted [26]:

- Single failure: max 24 hours of interruption time at load of less than 2 MW;
- Comprehensive or rare failures: max 24 hours of interruption time at load of less than 50 MW.

It was considered that no overhead line could withstand a natural disaster such as Gudrun. Therefore the following preventive measures were taken:

- Widening of corridors for 40-50 kV overhead lines;
- Development of new overhead conductors:
  - 0,4 kV with double insulation and breaking mechanism;
  - 10 kV with breaking mechanism;
- Cabling of networks in rural and forest areas;
- Replacing overhead lines with underground cables for links to customer houses;
- Using European standard equipment, independent of the manufacturer. To change damaged (or old) material with another manufacturer is of strategic and commercial importance;
- Installation of emergency power;
- Special requirements for cities and urban areas, based on risk analysis;
- Optimization of the network structure by:
  - Fewer voltage levels;
  - Redundancy/radial network.

For broadening the corridors of the overhead lines the permission procedures with the landowners started in 2006. Mutual understanding was needed. The total length considered was 28 000 km. The minimum width of the new corridor will be larger than 35-40 m. The volume of trees to cut was about 500 000 m^3. The corridors will be finished end 2007.

New design rules

No new design requirements were required as the more than 20 years old distribution system has been designed according to a national code with more than 80 years good experience.

Conclusion

The vulnerability of the society has been increased by widespread and heavy windstorms. Therefore the robustness of the network has to be increased. Investments must be based on risk analysis to ensure the viability of the network:

- Improving forecasts and communication regarding severe weather events;

- Widening line corridors so that all lines over 25 kV should be tree secured line corridors after 2007;
- Cabling of networks in rural and forest areas;
- Changing from overhead line to underground cable in forest areas;
- Optimization of the network structure;
- Supporting the Government on clear requirements for the security of supply;
- Convincing the Regulator to promote investments in increased security of supply.

A.5 Germany – Wet snow storm on November 24-25, 2005

The 2005 wet snow event

In the region of Münsterland, western Germany, in an area close to the Netherlands, there were heavy ice loads on power lines on November 24-25, 2005. Five 110 kV lines owned by the utility RWE were damaged. The wind and ice storm event also affected the Netherlands and Belgium. In Belgium many lines were out of service; only one tower failed next to the busiest freeway from Brussels to Ghent, so that it was blocked for hours.

Outages

Approximately 250 000 people had been without electricity, some for several days.

Damages

Five 110 kV lines, built in 1950, 1951, 1960, 1984 and 1990, were damaged with 83 steel lattice towers broken. Line sections oriented NW-SE were affected by perpendicular wind.

Exceptional event

In a report prepared by the Institut für Baumechanik-Baustatik of the Universität Duisburg-Essen, Essen [17], it was stated that the towers failed due to an exceptional climatic event and not due to possible deterioration of the towers. The ice overload on conductors was the result of three simultaneous factors (Appendix C.3.2):

- Wet snow due to a high liquid-water content that is responsible for the excellent adherence of the snow to the conductor;
- A strong wind increasing the flux of snow. Without wind a snow flake drops with a vertical wind speed of only 0,2-1,0 m/s. However, with wind speed of 10 m/s, snow flux is multiplied by a factor 10-50;
- A constant temperature of nearly 0°C.

Moreover, it was noticed that when one circuit is out of service during severe ice events, unbalanced ice loading may increase failure probability.

Ice thickness measured and calculated

At the weather station of Legden the measured thickness of the snow layer was 350 mm. This was comparable with the maximum value ever measured in Münsterland on January 28, 1897: 380 mm. At the airport of Münster – Osnabrück 250 mm of ice was measured where normally no more than 50 to 100 mm is expected in 24 h.

The following **Table A.10** shows the overloading factors for ice diameters of 150 mm (measured) and 210 mm (calculated) according to original design code VDE 0210. Even with the new standard DIN EN 50342-1 and DIN EN 50341-3-4, the overloading factors are extremely high. The return period of the event was considered 100 years.

Table A.10 – Overload of conductors

Ice diameter	Real ice mass	Design ice mass	Overload factor according to	
mm	kg/m	kg/m	VDE 0210	DIN EN 50341
170	6,8			
150	5,3 (measured)	0,85 (<1968)	6,3	3,6
210	10,5 (calculated)	0,73 (>1969)	14,4	7,1

Some scientists believe that this recent wet snow event in Europe (Germany, the Netherlands, Belgium) on November 24-25, 2005 indicate higher failure rates on smaller conductors than on larger ones. Smaller conductors are designed for less ice, but accrete more due to the twisting of single conductors. The effect from freezing rain is less certain if larger conductors collect more glaze due to larger cross sections.

It is interesting to note that the snow mass has been calculated using the values measured of the sag under snow load. The unbalance was assessed by the obliqueness of the insulator strings.

Conclusion

The failed lines were built between 1950 and 1990 using the German standards valid at the time of erection. No additional load assumptions had been considered since severe ice loads had never been observed in this area. RWE will investigate whether increased ice loads in the area have to be considered. The German National Committee for Overhead Lines analyses this event with the consequence to review the Standard for ice loads. The main changes will be a ice load map with ice load zones for Germany. In a first step this map will be informative.

A.6 Czech Republic – Ice and wind storm on January 15-20, 1974

The 1974 ice and wind storm

On January 15-20, 1974 the hitherto most serious ice storm on overhead lines in the former Czechoslovakia (i.e. in the Czech Republic and the Slovak Republic now) occurred. It was concentrated in areas supplied by the East-Bohemian, South-Moravian, North-Moravian and partly by the West Slovakian distribution companies.

The ice storm was caused by rapid formation of ice deposits passing successively into formation of glaze on conductors, towers and poles of transmission and distribution lines, combined with strong wind gusts with the velocity of up to 100 km/h [11].

Outages – Power restoration

Many villages and towns remained unsupplied with electricity even for several days. The greatest accumulation of supply interruptions appeared on January 17, 1974, when 702 villages and towns remained unsupplied. The majority of failures was cleared in such a way that the electricity supply could be restored till January 21, 1974. A total number of 400 persons participated in the liquidation of the damaged equipment. The last repaired line (420 kV) was put into operation on February 10, 1974.

Damages

Heavy failures originated on overhead lines of the EHV and HV transmission network (420 kV, 110 kV, 35 kV and 22 kV) and of the local distribution networks (230/380 V) in the areas affected by the ice storm. A total line length of 110 km was damaged during the ice storm from January 15th to 20th, 1974.

The most damaged line in the 420 kV system was the line Hradec – Prosenice. A total number of 18 towers were destroyed and 13 towers were damaged over a distance of 13 km. Several lines were also damaged in the 110 kV system. The line Havlíčkův Brod – Opočinek with 6 destroyed towers was damaged most seriously.

The failure of the LV and HV equipment were predominantly caused by broken steel towers and wooden and concrete poles, broken cross-arms and disrupted conductors.

Origin of the storm

The disaster originated as a result of the combination of the in-cloud and precipitation ice storm, further combined with a strong wind.

The demarcation line between the cold front and the warm front moving eastwards from western and central Bohemia passed across the Czech-Moravian Highlands. There were frosts over the territory of Eastern Europe while the western part of the continent had warm and humid weather. The interface between both air masses was marked by an isotherm of

0°C. The warm air mass was active and the cold air mass was forced to get away. The first signs of the incipient disaster were already observed on January 13, 1974. The advection ice deposits and glaze joined with the frontal glaze. Their mutual effects (horizontal and vertical precipitations) and the retarding effect of the Highlands on the progression of the warm front were the main reasons of the severe ice storm .

Weather data

The resulting density of ice deposits was 600 kg/m^3, the highest ice mass per unit length on the overhead line conductors was 12-15 kg/m, the speed of wind gusts amounted to 100 km/h.

Measures adopted

Due to the extent of the storm and the major consequences, the Czechoslovak government ordered to take necessary measures, including a detailed analysis of the disaster. The measures adopted were divided into two groups:

- Short-term measures: to put the damaged lines into the initial state, to confront the present situation with the current design standards and to check up the applicability of de-icing methods;

- Long-term measures: to improve the availability when clearing the failures and to review the design standards:
  - The ice chart was revised resulting in a fourth (critical) area with more onerous ice loads;
  - A new combined ice and wind loading was introduced (where the wind speed is half the value of load case with wind only).

New developments

The ice storm initiated the development of :

- Methods of de-icing, especially by heating and their application in practice;
- The revision of design standards for overhead lines, especially combined ice and wind loading;
- The improvement of the accuracy of the ice chart;
- The experimental investigation of other parameters such as the influence of conductor diameters, torsion properties of the conductor, icing of the bundle conductors, as well as the influence of the height of the conductor above ground level.

For the last purpose, a special ice-measuring stand was built at Studnice [12], the most exposed location of the Czech-Moravian Highlands. Methods of measurement were studied and developed. The activities are still under way.

Cooperation with meteorological institutes, especially in forecasting icing situations was deepened. In winter periods, a regular daily exchange of information took place. This daily contact proved itself as very fruitful.

A.7 Ukraine – Ice storm on November 24-30, 2000

The November 2000 ice storm

There was a considerable amount of overhead line failures during the broad-scale icing storm on November 24-30, 2000 in southeast Ukraine. It was the greatest natural catastrophe since a century that struck Ukraine. The type of intensive icing was freezing rain with smog [26].

Outages

The ice storm paralyzed the activity of nearly five thousand settlements in twelve regions. Almost 4 000 000 people found themselves under extreme conditions living with no electricity and heat, gas and water supply for a week and in some places for four months.

Damages

The icing resulted in the damage to:

- 20 931 overhead transmission and distribution lines;
- 300 000 reinforced concrete poles;
- 20 000 steel towers.

It was observed that for 110 kV lines the ratio of failed poles was 7 times as large as that of the steel towers.

From the 330 to 750 kV overhead lines 17 lines and 507 supports were damaged of which:

- 268 reinforced concrete poles (96 poles collapsed; 65 poles inadmissibly displaced; 21 cross-arms and 86 peaks bent);
- 239 steel towers (167 towers collapsed; 56 cross arms and 16 peaks bent).

It is interesting to note that 71 earth wire spans were damaged against 127 conductor spans.

Over 80% of the damaged supports were due to cascades because of conductor breakage. It seems that cascade failures tend to increase with voltage level. The number of suspension tower collapses due to conductor breakage is over 20% for 110 kV lines while it is greater than 60% for 750 kV lines.

The dynamic loading on overhead line towers arising under conductor breakage turned out as a serious maintenance problem, especially for ice overloads. The great number of breakages of conductors can be explained by damage of wires due to aeolian and sub-span vibration.

It was also mentioned that cascade of towers could be prevented by the reduction of the carrying capacity of insulators. For instance, there was a breakage in span 740-741 of the 750 kV line Yuzhnoukrainskaya – Dneprovskaya. On the adjacent towers 736-739 and 741-745 only the cross-arms were bent.

Origin of the ice storm

Intensive icing with freezing rain in southeast Ukraine on November 2000 was the consequence of the interaction between cold arctic air mass from northeast with the warm and moist air mass from southeast. Icing deposits grew during 10 to 12 hours, and in the next 4-5 days only little increasing of ice was observed. Suddenly on November 28-29 the ice accretion was 2 to 4 times more than ever observed in Ukraine. The air temperature was - 2°C to 0°C, practically without any daily trends. The icing covered an area of 226 000 km^2 with broad-scale damages on overhead lines, trees and winter crops (Appendix C.3.2).

Ice deposits

The maximum diameter of ice observed on ice measurement devices was:

- Weather station Khmel'nitsky: Ø 61 mm (min: - 3,2°C; max: - 1,1°C);
- Weather station Zatish'e: Ø 197 mm (min: - 2,7°C; max – 0,3°C),

with a density of 800 kg/m^3. In the southern part, the situation was worse as the wind speed was 14 to 17 m/s. The situation was so exceptional that theoretical return periods were found from 200-400 years up to 100 000 years.

Recent wind storms

A lot of researchers in Ukraine and Russia noted an increase of natural catastrophes in recent years. Based on the data of various researches the frequency of wind storms increased by a factor of 1,6 to 2,5. During 1961-2000 it was observed in Ukraine that the mean annual temperature increased with 0,7 °C.

Conclusions

The main conclusions of the Ukrainian study for the November 24-30, 2000 storm were:

- Review of the design criteria, in particular the ice deposits in function of the height above ground and the conductor diameter;
- Unbalanced ice loading in the adjacent spans of a tower that has to be included in tower design codes;
- The development of de-icing and anti-cascading methods that is essential for Ukraine.

A.8 Japan – Wet snow storm on December 1980 – De-icing

Wet snow event, 1980

In December 1980, Tohoku area (Northern part of Honshu Island in Japan) suffered serious damage caused by heavy wet snow accretion around conductors [18; 19].

Damages and outages

The outline of the damage to overhead lines was as follows:

- Transmission lines affected: 70 lines;
- Collapsed towers: 62 towers;
- Maximum outage power: 1,3 million kW (caused by transmission line failure);
- Longest outage duration: 125 hours.

Origin of the wet snow storm

The damage was caused by heavy wet snow accretion brought by rapidly developed low atmospheric pressure with high wind and heavy snowfalls (Appendix C.3.2).

Snow accretion around conductor was as follows:

- Diameter: 80-150 mm;
- Density: 400 kg/m^3.

Check of tower strength

Tower types are applied with some margin to the actual load condition on site (e.g. a tower design type for 400 m wind and weight span length and a line angle of 20° is applied to a site with real 378 m span length and a real line angle of 17°). After the storm the strength of the collapsed towers was calculated taking into account the actual site condition for the purpose of pursuing the cause of the failure as well as assessing the strength of the existing towers.

Measures taken

After the wet snow event, various measures have been taken to reduce the damage:

- Increasing design load of snow accretion;
- Strengthening the conductors (from HDCC to ACSR);
- Inserting additional tower steel members to resist torsional load caused by unbalanced snow accretion between neighbouring spans;
- Adopting various de-icing (wet snow) measures.

De-icing measures

Since the construction of transmission lines, it has been a primary task to reduce snow accretion. A variety of investigations and research has taken place at home and overseas.

Today, active preventive measures against snowfalls are as follows:

- Route design by avoiding snowy regions;
- Snow-proof design requirements for conductors and supports;
- Removal of accumulated snow by using snow ploughs, cable vibrators and manual shock;
- Equipping conductors with de-icing tools to melt snow by using a powerful magnetic wire (a heating wire wound around a conductor to dissipate snow or ice by heat; in this case an electric wire provides the snow-melting current);
- Suppressive tools for conductor snow accretion by using:
    - Snow-resistant rings attached around the conductor to baffle snow in sliding down along the conductor. Rings at least 6 mm thick can serve the purpose as wet snow can drop off in contact with the ring. They are spaced at double stranding pitch of the outermost wire layer. Snow-resistant rings are available in two types: a built-in ring to be attached to the conductor, and a conductor made with snow-resistant rings already in the surface. Its profile and mass will induce increments of less than 1%, respectively in aerodynamic draft and gross weight, when attached to a conductor;
    - Anti-twist counterweights. When spaced along a single conductor, they can prevent twisting due to eccentric snow loading and, in the end, covering with a cylinder of snow.

A.9 Tenerife, Spain – Tropical Cyclone Delta on November 28, 2005

Tropical Cyclone Delta, 2005

On November 28, 2005 the remains of tropical storm Delta arrived at the northeast coast of Tenerife, Spain. Tenerife is the largest island of the seven volcanic islands of the Canary Archipelago, located in the Atlantic Ocean in front of Morocco coast [23].

Usually storms and hurricanes formed in the Carribean arrive weakened to the Canary Islands with wind speeds not exceeding 90 km/h.

Damages

One 220 kV tower and 47 towers of a 66 kV line were damaged. Hundreds of supports of lower voltage lines fell down.

All lines damaged were situated on the leeward side of the island. No support damages were reported on the northeast side.

Weather data

Measured wind speed at the leeward side of the island close to the shoreline varied from 134 km/h to 209 km/h, where the mountains are steeper. The wind speed measured on the northeast coast was lower than 100 km/h, but wind speeds on the highest point of the mountain ridge reached 248 km/h.

No high wind speeds nor support damages were reported in the other islands of the Archipelago, although wind speeds of 100 km/h were measured in all islands.

All those lines were calculated for a wind speed of 120 km/h with a safety factor of 1,5.

A.10 Australia – Larry Cyclone storm on March 20, 2006

The March 2006 Larry Cyclone

On the morning of March 20, 2006, cyclone Larry crossed the coastline of tropical Far North Queensland, Australia. It was reported that Larry was the most severe cyclone to hit the coast of Queensland since 1931 (Bartlett, 2007).

The intensity of the cyclonic winds battered the township and the countryside over an area extending hundreds of kilometers in all directions. Wind speeds were reported in excess of 220 km/h (137 mph) with wind gust speeds exceeding 300 km/h, leaving in its wake a trail of destroyed homes and buildings, stripped vegetation and damaged infrastructure.

Outages

The high winds and flying debris forced the first of Powerlink's 132 kV lines out of service. In a sequence of trips on the 132 kV network, bulk electricity supply was cut to Cardwell, Tully, Innisfail, Kareeya and Kamerunga substations.

Due to the damage to Powerlink's transmission network and very extensive damage to the local distribution network, more than 140 000 customers in the area stretching 200 km along the coast and up to 60 km inland were without power supply.

Damage

In the cyclone aftermath, seven 132 kV transmission lines, spanning more than 300 km, were out of service. These were mostly double-circuit transmission lines where both circuits had tripped due to wind-carried vegetation and fallen trees, particularly where the lines passed through World Heritage rainforests. In that locale, five high-voltage substations were out of service as the cyclonic winds had totally collapsed five steel transmission towers and badly damaged another two towers.

Where tower failures had occurred, there was extensive damage to the ACSR conductors. The aluminum strands were cut mainly due to abrasion against tower steel work, but the steel strands remained intact, a factor that may have prevented the possible cascade failure of additional towers.

Power restoration

It was critical that the electricity supply be restored quickly to the devastated areas to power essential services such as water supply and sewerage, and to facilitate the cyclone-relief efforts.

Transmission line field crews from across Queensland were quickly transported to the affected areas to assess the damage, diagnose the problems and begin on-ground works, working all the while in very wet conditions. They undertook the task of inspecting some 800 transmission towers and 300 km of transmission line to locate and remove cyclone-carried debris and fallen trees, and to repair broken phase and earth conductors.

By the second day, two transmission lines along the more easily accessible coastal plains had been returned to service enabling power to be restored to four substations.

Bulk electricity supply had been fully restored to the cyclone-devastated communities of Far North Queensland within five days. Only one 132 kV line remained out of service: the Kareeya to Innisfail circuit, an aged line that had sustained severe damage, including four collapsed towers and further damage deep within a rugged rain-forested region where access by field crews was still not possible.

Specialized live-line stringing techniques were employed to install temporary conductors over the live 132 kV bus bar at Woree Substation.

Assessment of the emergency response

A full review of the response to Cyclone Larry was carried out and identified some opportunities for improving procedures. Among the strengths in the emergency response were:

- Cooperative interaction with other key organizations;
- Effective scheduling of the restoration works;
- Establishing a local base for all the emergency and communication managers;
- Drawing on the knowledge and expertise of locally based staff;
- Availability of highly skilled staff to support the Emergency Management Team.

The performance to support the Emergency Management Team in managing the restoration efforts was strongly supported by the cooperative assistance and efforts of other organizations involved in the cyclone response.

A.11 USA – Hurricane season 2004-2005

Impact of 2004-2005 hurricanes on reliability

The residual impact produced by the hurricanes in 2004-2005 triggered a higher number of outages. Reliability in the hurricane-affected areas dipped in the first five months of 2006 and returned to average pre-storm performance levels after completion of permanent repairs to bring the system back to the current standards [28; 29; 30; 31; 32; 33] (Appendix C.3.4).

The majority of increases in outage time of hurricane-affected areas are attributed to the significant damage Hurricanes Katrina and Wilma caused to overhead lines in Florida.

Rules approved by Florida Public Service Commission to strengthen State's Network

The Florida Public Service Commission (FPSC) has approved rules requiring Florida's investor-owned electric utilities to cost-effectively strengthen, or storm-harden, the state's electric infrastructure [29].

Each utility will be required to file storm-hardening plans, updated every three years. The plans must identify critical infrastructure and the utility's deployment strategy for strengthening electric service in their service areas, addressing measures to reduce outages and restoration time, including:

- accelerating tree trimming cycles;
- developing more detailed storm data;
- strengthening existing transmission structures;
- initiating collaborative university research on the effects of extreme winds and storm surges on electric facilities;
- increasing coordination with local governments to facilitate more effective communication on an ongoing basis;
- inspecting their wooden distribution poles once every eight years.

On February 21, 2007 the Florida Public Service Commission submitted a report to the Governor analyzing the reliability of the existing transmission system [30]. It also addresses the efforts to examine ways to strengthen the state's electric infrastructure in light of the 2004 and 2005 hurricane seasons. In 2006, the FPSC initiated a multifaceted approach for utilities to better prepare for storms, including:

- More frequent wood pole inspections;
- Vegetation management;
- Increased construction standards for electric facilities.

Each year, the Florida Public Service Commission (FPSC) requires electric utility companies in the state to report on the reliability of their service the previous year.

Storm Secure Plan

The last report of Florida Power and Light Company (FPL) submitted to FPSC indicates that absent any hurricanes, the company expects service reliability to be further enhanced in 2007 through its "Storm Secure" program and its reliability and maintenance program.

"Storm Secure" is a comprehensive plan, launched in 2006, aimed at providing customers with a more reliable and robust electrical infrastructure under future storm conditions. It is a long term commitment to make the system more resilient to future hurricanes.

The 2007 "Storm Secure" plans call for upgrading main lines that serve health facilities and major thoroughfares with community services [29; 32]. Overhead circuit highway crossings will be retrofitted to make them more storm-resilient. Other initiatives include:

- Vegetation Management – Clearing vegetation and trimming of "hot spots" where fast-growing trees threaten to intrude on conductors, especially for main distribution lines and also for their lateral lines;
- Concrete or steel structures – Upgrading program for transmission structures that will allow it to inspect nearly 17% of its transmission structures every year;
- Wood structures – Replacing wood structures with concrete poles;
- Poles – More frequent pole inspection. Based on the outcome of the inspection, poles may be treated, reinforced with a steel truss, or replaced if required;
- New technologies – Evaluating new products and technologies to efficiently make the infrastructure more resilient to hurricanes in the future;
- Thermovision – Investment in state of art technology, allowing the detection of potentially faulty equipment through an infrared inspection and replacement of equipment before it causes a power interruption.

FPL is engaged in collaborative research with other utilities to study the effects of hurricane winds and storm surge to better equip electrical infrastructure. A permanent post-storm forensic team has been established to analyze damage to the electrical system and improve grid design and equipment.

Dry-run exercise

On May 10, 2007, FPL tested emergency management processes, technologies and communication [32].

FPL uses a proven storm model to predict damage prior to the landfall of a hurricane. This allows FPL to customize the restoration.

Path, intensity and resources are three critical drivers of the restoration.

The utility follows a plan that allows first for the restoration of power generation plants, followed by repair activities to get electricity flowing through the high voltage lines. Concurrently, the company starts repairing poles and lines that serve critical infrastructure, such as hospitals, police, fire, communications, water, sanitary and transportation services deemed critical for the well-being of the community as a whole.

FPL's storm structure is divided into three distinct areas:

- The Storm Command Centre manages the restoration. It is where the restoration planning takes place and instruction is provided to staging sites;
- The Working Sites house the thousands of restoration crews and support personnel who are executing the restoration plan**.** These sites are pre-selected before the storm season and arrangements are made beforehand;
- The Logistics organization provides services such as materials, food, water and housing.

The exercise tested FPL emergency response personnel on pre- and post-hurricane readiness tactics and activities, including storm planning and tracking, damage assessment, customer communication and the company's restoration plan.

Preparedness

Tampa Electric prepared a comprehensive storm plan to help restore power as safely and quickly as possible in the event of a storm [33].

Safety is number one priority following a storm. The second objective in the event of widespread outages is to restore power to the largest number of customers in the shortest possible time. Electric service is restored in a pre-determined order of priority.

When a major storm's arrival is imminent, actions are coordinated with utilities and contractors across the nation to mobilize crews towards Florida. Those crews are placed on call so that they are available to repair any damage affecting lines and equipment, but only when they can do so safely.

A.12 USA – Ice storm on December 14-16, 2005

Ice storm

The ice storm of December 14-16, 2005 was triggered by a deep low pressure system formed over the Gulf of Mexico on December 14, which began moving northward. At the same time, cold arctic air from northern Canada penetrated deep into the central USA and lowered the temperatures at the surface while warm air from the Gulf Stream remained at the coast [34] (Appendix C.3.2).

Trees and power lines, along with numerous other lightweight structures, have come down in many areas from Georgia northward.

Outages – Power restoration

The ice storm has left over 700 000 people in the dark in and near the Appalachians, including 30 000 customers in Georgia, 358 000 in South Carolina, 328 000 in North Carolina and 13 000 in Virginia. It took over a week to restore power.

New policies

In response to the concerns expressed by the upstate customers the South Carolina Office of Regulatory Staff (ORS) has released a review of the performance regarding the service outage during the week immediately following the storm.

The ORS has gathered feedback on the reliability of the state's electric transmission and distribution systems by attending public hearings. The most frequent concern expressed was the length of time without power and not knowing when power was to be restored.

The focus of the review was to identify areas where there may be room for improvement in the infrastructure, operations, and response mechanisms. The report includes planned actions and provides a summary of policy and operational recommendations.

One of the most notable recommendations involves an underground conversion mechanism, since the vast majority of outages resulting from the storm were due to overhead distribution lines being affected by falling trees or limbs.

Other highlights recommend:

- Actively seek creative partnerships with municipalities and other entities to establish a financial support network for underground projects that would minimize the economic impact to customers and rate payers;

- Ensure it maintains current accurate contact information and adheres to its documented communication process to provide vital information to elected and public officials.

The ultimate goal in conducting this review was to ensure that customers and of all regulated utilities receive reliable and high quality service, even during times of extreme weather to better respond to major outages.

Other ice storm occurred recently in the USA

- November 30 and December 1, 2006, in Illinois – 220 000 customers out of power across 110 000 km^2; falling temperatures causing rain to freeze into heavy ice that toppled trees and downed power lines [35];

- The New Year's ice storm, 2007 in Nebraska – 1000 km of high voltage power lines remain out of service. Of this total, about 200 km of these lines were on the ground or severely damaged. Hundred substations were affected by the ice storm [36].

Service was restored to all customers by January 19, 2007. On February 13, 2007 nearly 60% of the damaged transmission system was reconstructed. Along with good weather and an ability to secure agreements with multiple contractors early in the reconstruction process, the utility also received timely access to materials and resources – all of which helped accelerate completion of the initial work scope. The use of helicopters also helped reduce costs and shorten reconstruction time. On May 11, 2007 the last of 37 transmission line segment damaged was placed into service. Some pole structures were replaced with custom-made laminated poles, designed to bend, but not break. In addition, the telecommunication lines that NPPD lost in several areas due to the initial storm were buried to eliminate future outages [37];

- January 11-24, 2007 – The North American ice storm was a severe ice storm that impacted a large swath of North America from the Rio Grande Valley to New England and southe-eastern Canada starting on January 11, 2007 through January 16, followed by a second wave in the southern United States from Texas to the Carolinas from January 16 through January 18 and a third one that hit the southern Plains and mid-Atlantic states as well as Newfoundland and Labrador from January 19 to January 24. Those winter storms across the nation have damaged electricity poles and lines, and at least 400 000 were without power on January 17. The storms affected 12 U.S. states and 3 Canadian provinces, killing dozens of people, mainly on roads, and coating telephone and electricity lines with ice. Missouri was one of the hardest-hit states [38];

- The Midwest winter storm, February 24, 2007 – Nearly 270 000 customers lost electric service as a mix of freezing rain, high winds, sleet and snow caused extensive damage to the electric distribution and transmission infrastructure of Interstate Power and Light Co [39]. IPL completed its initial restoration efforts on March 7, 2007. End of July, IPL concluded rebuild work and re-energized a 20-mile stretch of 345 kV transmission line in Poweshiek County, Iowa [40]. As part of the rebuild project, IPL rebuilt 82 steel H-Frame transmission structures. The redesign and rebuild of the transmission line was completed in less than five months. Rebuild projects of this magnitude typically require 18 to 30 months to design and construct.

Utilities must plan, prepare and respond to widespread and prolonged power outages. Mutual assistance is typical in the utility industry. Utilities have a proud tradition of mutual assistance, coming to each other's aid during power emergencies. Besides local crews, additional crews from across United States and Canada are trained to clear downed trees and debris, to repair or to replace poles, towers and crossarms and to string new wires.

A.13 USA – Wind storm on August, 2006

The wind storm, 2006

In August 2006, Midwest Energy (Hays, Kansas, US) experienced a windstorm that blew down a 3 km stretch of wood transmission and distribution poles in western Kansas. All poles broke at the ground line. Thousands of customers experienced outages (Engel, 2007).

Other wind storm events

Since 2004, the south-eastern United States has been hit with nine major hurricanes causing billions of dollars in damage to electrical and telecommunications infrastructure. And in December 2006, the Pacific Northwest experienced its worst windstorm in more than a decade, knocking out power to more than 1,5 million homes and businesses. Utilities are taking notice and are beginning to consider the possibility of exceeding minimum safety standards so that structures will be less likely to fail during extreme winds.

Current design parameters

Midwest Energy is a customer-owned electric and gas utility that serves about 80 000 customers in central and western Kansas. It is located in what the National Electrical Safety Code (NESC) designates as the Heavy Loading District. This requires all structures to comply with winter-storm loading criteria for combined heavy ice and wind loading conditions: 64 km/h with 13 mm of radial ice on the conductors. In addition, when this particular transmission line was designed, the NESC required structures more than 18 m tall to withstand extreme summer wind loading: 145 km/h wind speed on bare conductor.

The NESC requires that wood structures be replaced or rehabilitated when deterioration reduces the structure strength to two-thirds of that required when installed. Grade B construction requires that a wood pole withstand at least 4.0 times the loading. Field measurements of several failed poles indicate that the effective overload factor may have been reduced to 3,5.

In this case, it seems likely that the wind loadings simply exceeded structure design strength. An important lesson is that localized weather effects can result in winds much stronger than those recorded at nearby weather stations.

New developments

Upgrading infrastructure for high wind is an emerging but important topic. Ideally, a utility can compute the expected damage that will occur in future storms, compute the cost of various upgrading options and compute the expected damage reduction that will result from each of these options. This process allows for decisions to be made based on quantifiable costs and benefits, and goes far beyond the design of a structure for a specific wind speed. Possibilities for strengthening transmission and distribution lines include:

- Stronger poles;
- Upgraded poles;
- Shorter spans;
- Smaller conductors;
- Storm guying;
- Push braces;
- Less pole-mounted equipment;
- Fewer third-party attachments;
- Aggressive tree removal;

- A multitude of other options.

Conclusion

Achieving the proper level of infrastructure performance during high winds at the lowest possible cost is a daunting task, but will increasingly be demanded of utilities by their regulators and customers. Now is the time for utilities to question whether the use of existing design standards as the basis of structure strength will result in adequate performance, or whether hardened systems are in their future.

A.14 Major results of the Commission Nicolet in Canada

Scope of the Commission Nicolet

The Commission Nicolet "Commission scientifique et technique chargée d'analyser les évènements relatifs à la tempête de verglas survenue du 5 au 9 janvier 1998, ainsi que l'action des divers intervenants" ("Scientific and Technical Commission in Charge of the Analysis of the Events Relating to the Ice Storm of January 5 to 9, 1998, as well as the undertakings of the various intervening persons") [8; 9], set up after the January 1998 ice storm in Canada, was mandated to analyse the features of the 1998 ice storm and its consequences and impacts in order to draw as many lessons as possible for the future. This Commission was designated as a scientific and technical commission.

The following three types of observations were entrusted to the Commission:

- Based on the experience gained in January 1998, how can disaster management organisation and co-ordination be corrected, improved or reinforced?
- Would the scientific and technical instruments enable prediction of when and how often phenomena occurring from January 5 to 9, 1998 might occur?
- What are the additional means for ensuring increased security of the electrical power supply, reducing the length of outages and decreasing their impact on people?

The Commission held 44 public hearings and 20 citizens' forums. These public sessions enabled over 150 people and organisations to submit their analyses to the Commission.

The Report of the Commission was divided into three parts:

- Based on the analysis of the main features of the disaster and the impacts it triggered, questioning the possibility, in climatic terms, of a disaster of this type occurring again;
- A blueprint for a prospective emergency preparedness;
- The possibilities for upgrading the electricity network.

At no time during the storm were the centres where electricity was produced affected, as these centres are located hundreds of kilometres away. Except for a few minor elements, the transmission and distribution stations all resisted the freezing rain.

The January 1998 storm caused enormous damage to trees. It represents the most significant and the most visible environmental impact of the weather disaster.

The number of deaths directly attributable to the ice storm was relatively low. Nevertheless, several deaths and injuries could be probably have been avoided if the victims had given up the idea of venturing onto the roofs.

The distinction whether the impact on lines could be attributed directly to the weather disaster as such or to the events resulting from it, was not easy to make. It was not always possible to clearly attribute a given consequence to the weather or to the technological disaster.

Could such a disaster happen again?

There were two kinds of difficulties to be faced when attempting to specify whether and how often an ice storm similar to that of January 1998 might recur:

- Freezing rain is a weather phenomenon which is randomly triggered and therefore particularly difficult to predict;
- The meteorological services did not have at their disposal the appropriate tools to promote understanding.

It was already mentioned that, when freezing rain occurs, the temperatures of the air masses that cause it are close to the freezing point (Appendix A.1). A slight variation in temperature can modify the nature of the precipitation. Another degree of uncertainty is the local topography, such as the “valley effect” which plays an important role in forming of freezing rain. Moreover the phenomenon can affect a large part of Québec.

Environment Canada would then be able to improve its analysis tools and thus strengthen its knowledge of how freezing rain is formed and of the likelihood of its recurrence.

The Commission has attempted to establish a correlation between periods of freezing rain and El Niño, a link, it has been discovered, which simply does not exist. The various El Niño phenomena are far from having all been accompanied by major periods of freezing rain, and vice-versa. The El Niño phenomenon causes abundant precipitation, but the phenomenon is not, in itself enough to cause an ice storm. El Niño certainly explains to some degree the magnitude of the January 1998 ice storm; however El Niño cannot be linked to a cyclic recurrence of freezing rain.

Some experts put forward global warming, another worldwide phenomenon, to explain the January 1998 ice storm. It has led some to conclude that the risk of freezing rain increases as the planet heats up.

It will continue to be difficult to predict the occurrence of ice storms in Québec as long as there is no better understanding of the linkage between increased greenhouse gases in the atmosphere, global-scale disturbances in atmospheric and oceanic patterns (e.g. El Niño), and the simultaneous appearance of the two weather conditions necessary to the sustained production of freezing precipitation.

The most probable return period for this event is several hundred years, although return periods in excess of 100 years become quite unreliable due to a number of sources of uncertainty.

Upgrading the network system

The Commission Nicolet decided to proceed in three steps for the assessment of upgrading the network system:

- The main characteristics and design criteria;
- The behaviour of the network when subjected to the unpredictable event;
- The possible reinforcements.

HQ no longer accepts more than two lines in a same corridor.

Two characteristics had serious impact on the outages:

- A low mesh level;
- A limited number of interconnections.

According to the Commission, interconnections should play a larger role in helping difficulties encountered during disasters as the ice storm. The construction of strategic lines, meeting much more stringent standards than regular lines, is a convincing way of upgrading the network.

B. Specific regional aspects of some localized HIW

This Appendix B deals with specific regional aspects of localized High Intensity Events, such as downdrafts and tornadoes (Appendix C.3.3).

B.1 Canada – HIW storm on September 5, 1996

The microburst storm on September 1996

In the early hours of September 5, 1996 a severe thunderstorm moved through the rural area immediately northwest of Winnipeg. At 01h48 19 guyed steel towers of the HVDC transmission line collapsed (10 on Bipole 1 and 9 on Bipole 2) near Grosse Isle, causing total and complete failure of the Radisson – Dorsey Transmission System carrying 2020 MW. Another 3 steel towers on the HVDC transmission lines were destroyed. In addition 18 wood pole structures were damaged in total on both the east and west electrode lines [10].

Power restoration

In spite of the extensive loss of power and damage, customers were not affected. The lost power was immediately replaced by power imports, the duration of which was minimized by the quick restoration of the two transmission lines. Both the emergency procedure and the restoration scheme proved to be adequate.

Damages

All towers fell to the east. Some of the towers buckled at mid tower height. Others rotated off their bases with minimal damage to their foundations. The downed towers of Bipole 1 did not damage the adjacent Bipole 2. No guy-wires or anchor rods were broken. However, most of the windward anchor rods were bent. Most guy torque arms and connector cross arms were damaged. Electrode lines' poles snapped 2 to 3 m above ground.

A number of modes of failures were observed suggesting that the towers did not fail all at the same time. It was not possible to clearly establish what parts of each tower failed first. However, it could be concluded that no cascading action occurred. Towers outside the affected area withstood the high winds and the unbalanced conductor loadings, caused by failed towers and broken conductors.

Conductors were damaged at some locations but none were broken. Phase conductor clamp, spacer damper and insulator damage was observed at some tower locations with no consistent damage pattern. Broken insulator strings were not found. It is not mentioned whether these damages are initial failures or consequences of the tower collapses.

Microburst

The storm is believed to have been a microburst that produced extremely High Intensity down pressure and lateral Winds (HIW). The high winds moved through a narrow strip, approximately 2 km wide. This type of meteorological event, although reported in the past in Manitoba, had never caused any damage to Manitoba Hydro transmission lines.

Weather radar, located at Vivian, Manitoba, showed at 01h30 rapidly developing thunderstorms near Poplar Point, 35 km west of the site, and moving eastward. The radar recorded the thunderstorm moving trough Grosse Isle at 01h45.

Eyewitness accounts indicated the possibility of a tornado going through the area. Some witnesses claimed to have seen a funnel cloud while all noticed the presence of strong “groaning” and “whistling” winds that had lasted tens of minutes.

Likelihood of the event

An investigation conducted by the Environment Canada concluded that the event observed at Grosse Isle on September 5th, 1996 was a microburst rather than a tornado. Analysis of damage, supported by the radar data, suggested that a straight line wind associated with a microburst storm occurred. Based on the damage evidence, it was estimated that low end F1 winds (116-179 km/h) occurred in the area. The statistical microburst data are obtained by extrapolation from US data assuming the same intensity rates. This approach produced an indication of the likelihood of microburst occurrences on the HVDC transmission lines at any point between Radisson Station and Dorsey Station. According to this hypothesis, the probability of occurrence is estimated to 1 in 70 years.

Weather data

There was no accurate weather data available to thoroughly examine the wind storm events on September 5, 1996. The weather analysis was based on the following information:

- data from the Winnipeg International Airport located 20 km from the site;
- radar information;
- eyewitness observations of local residents.

Winnipeg Airport data indicates high wind gusts and variability in the wind direction. The strongest wind speed was recorded at 03h00 at NNE 54 gusting to 85 km/h.

Restoration and rebuilding

Emergency Response Procedures were in place based on a maximum of 3 towers down on each line, or 6 towers in total. The actual damage from September 5, 1996 was much greater than had previously been planned for. Therefore a decision was made to carry out the restoration in two stages.

As many as 230 people were on the site during the first few days of the restoration. It is worthy to note that there were no injuries during the entire restoration project. Due to the muddy fields caused by rain from the storm the transportation, assembling and erecting was difficult and time consuming.

A temporary wood pole bypass was constructed to bring Bipole 1 back to service as soon as possible. The design drawings for these wood structures had been prepared previously and were readily available. All efforts were directed towards the permanent restoration of Bipole 2. Due to a shortage of one spare tower, one 500 kV AC tower was used. By September 10, 1996, both Bipoles were operating in parallel mode using the wood pole bypass. This arrangement returned the Manitoba Hydro system to a near normal condition at 75% capacity. Bipole 2 was returned to normal operation on September 15, 1996 after all the steel towers were replaced. The final restoration of both HVDC lines included erecting of steel structures to replace the temporary wood pole bypass for Bipole 1 and re-conductoring of Bipole 1 and 2. This was done between October 11 and 27, 1996 (**Table B.1**).

Table B.1 – Scheduling the temporary and the permanent restoration

Date 1996	Bipole 1	Bipole 2	Electrode lines
Sept 5	10 towers collapsed	9 towers collapsed	18 poles damaged
Sept 6	Field survey	Field survey	18 poles replaced
Sept 10	Bypass (wood poles). Power restored at 00h45		
Sept 15		All steel towers, hardware and insulators replaced. Power restored at 02h15	
Oct 11-27	All steel towers replaced. Re-conductoring	Re-conductoring	
Nov 11	Debriefing		

Design review

A review of the design parameters and the ultimate capacities of various components of the HVDC transmission lines confirmed that the original design was adequate. Considering the low frequency of occurrences of microbursts, the very localized effects, the unpredictability of the magnitude of this type of wind storm, and the cost of strengthening the transmission lines, it was judged that for the existing Bipole 1 and 2 lines it was more economic and practical to develop an efficient emergency plan to minimize down time from extreme weather events such as this one, than to upgrade these transmission lines.

Recommendations

In spite of adequate restoration, the following was recommended:

- The emergency response plan should be updated to include both temporary and permanent restoration schemes;

- A future line should be located away from the existing HVDC lines to avoid loss of all lines at the same time;
- Weather patterns should be monitored to detect any climatic changes;
- Research should be carried out to study HIW and their impact on overhead lines.

It was decided not to upgrade the HVDC lines. They were designed to withstand steady wind speeds up to 140 km/h. The probability of occurrence of a storm similar to the one of September 5, 1996 on the HVDC lines was considered extremely low (once in 70 years). Restoration costs due to future wind storms could be significantly reduced by developing an improved Emergency Response Plan, in addition to storing sufficient spare towers and other spare material for immediate use. The cost of strengthening would far exceed the cost of repair, and strengthening would not preclude possible failure.

B.2 New Zealand – HIW storm on January 9, 2004 and March 25, 2005

The downdrafts on January 2004

On January 9, 2004, three towers of the BEN-HAY A 500 kV d.c. line collapsed under extreme winds exceeding 230 km/h. Nevertheless, this line was already upgraded after towers were blown over under severe wind gusts of 160 km/h on August 1, 1975 and October 15, 1988. Some towers were strengthened to new wind loading while others were re-spotted to reduce wind spans. Moreover additional strengthening was carried out in 1990 prior to upgrading to comply with the 1986 design criteria. However the failure of the 3 towers is attributed to extremely high winds with a return period of about 1300 years. The high localised wind gusts were generated by lee effect. The possibility of accelerations due to lee effect was not considered for strengthening [22].

The downdrafts on March 2005

Two towers of the EDG-TRK A 220 kV transmission line near Manawahe collapsed on March 25, 2005. After an aerial survey of some of the area, it seemed clear that much of the damage was due to many downdrafts from the thunderstorm clouds [21].

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During the events, especially cool air was measured at Rotorua Airport, consistent with evaporative cooling driving the descending air, and the many narrow, straight damage swaths were strongly indicative of microbursts. Based on the forest damage, the collapse was probably caused by a gust wind speed of about 43 m/s, corresponding to a return period of 900 years. The proportion of trees that suffer blowdown increases with the wind speed above this in a manner that depends on both the forest density and the height and type of tree.

Indications that a process of this type was present on March 25^{h}, 2005, are apparent in the surface readings at Rotorua Airport.

Original design

It is interesting to note that most failed towers (97,5%) had been originally designed to criteria adopted during the period 1957 to 1963. The design criteria adopted during this period had the lowest wind loading on the conductors and the lowest safety factors resulting in very light tower designs

Conclusion

One of the conclusions drawn from the investigation of the tower failures was the need to further increase the reliability for any upgraded towers with the adoption of site specific wind speeds and improved knowledge of localised High Intensity Wind behaviour, e.g. lee zone effects.

B.3 Ukraine – HIW storm on July 4-5, 2000

The July 2000 HIW

During a micro cyclone on July 4-5, 2000, several towers of the 330-750 kV network collapsed. The cyclone arose in the southern part of Lvov region (in western part of Ukraine) and moved to southeast (Black Sea coast). The maximum wind speeds were observed over a width of 10 to 20 km. From the Black Sea, the coast cyclone suddenly turned to northeast direction and was then observed in the northern part of Dnipropetrovsk region (in the eastern part of Ukraine). Along the edges of the cyclone some tornadoes were observed [26].

These tornadoes were the main reason of the overhead line damages. The maximal wind velocities measured on weather stations was 15 to 21 m/s, while the distance between the stations was 60 km, much larger than the width of the cyclone.

Damage

During the wind storm 67 towers and poles collapsed. All towers were suspension towers:

- 20 guyed steel towers for 750 kV lines;
- 7 steel towers for 330 kV lines;
- 40 reinforced concrete poles for 330 kV lines.

Analyses of the wind storm consequences showed that more than 80% of damage was due to cascades in open flat terrain.

The same climatic conditions with tornadoes were the main reason of other damages of overhead lines since 1992. Eleven events were mentioned with a mean value of 2 towers damaged per event. Two failures of towers in July, 2000 were on the same site just as previous failures.

The events on July 4-5, 2000 were followed by a very devastating ice storm on November 24-30, 2000, described in Appendix A.7.

Conclusions

The main conclusions of the Ukrainian study for the July 4-5, 2000 wind storm were:

- Climate change is probably the main cause of the wind storms with the appearance of tornadoes;
- Together with defined damages to overhead lines during the storm, there were a great number of indefinite implications of overhead line elements such as the relaxation in guys and conductors;
- The vertical wind profile during high intensity wind storms does not correspond with the current design methods for synoptic winds. During the July 4-5, 2000 storm practically in half of the cases a rotation wind was observed;
- Frequency and gust factor of high intensity wind storms must be defined on statistical data of observations.

B.4 Brazil – HIW storm on June 14, 2005

Various HIW events

A significant number of tower failures associated to a great variety of climatic phenomena occurred in the south and southeast areas of Brazil, rather than of a unique large scale storm event. Since 1982, eleven accidents have occurred in the AC and three in the DC lines of the 765 kV Itaipu Transmission System in the State of Paraná in Brazil caused by strong winds of short duration and restricted to small areas. The more recent accident of June 14, 2005 is described below.

The south of Brazil, as well as Argentine and Paraguay, is subjected to the formation of High Intensity Winds like downdrafts and tornadoes. Such phenomena, due to their narrow front, normally are not registered in meteorological stations, and there is no relevant statistic in Brazil.

In Brazil the following significations are used:

- TS or Thunderstorms for climatic phenomena such as downdrafts and tornadoes;
- EPS for Extended Pressure Systems or Synoptic Winds.

In two occurrences, the evidences have shown that the structures were struck by tornadoes. The transmission structures were analysed and reinforcements were defined for wind loading approximately 70% higher than the ones originally used by the utility. No other failures have been reported in the lines afterwards.

When the study of the 1st Brazil – Argentine 500 kV Interconnection has begun in the end of the last decade, the differences of wind loading criteria adopted in Argentine and Brazil have been clearly displayed. Loadings due to High Intensive Winds (with speed up to 240 km/h), including tornadoes, were already considered in the Argentine transmission lines, resulting in wind pressures much higher than the ones adopted in Brazil.

Finally in 2000, ANEEL, the Brazilian Electrical Energy Agency, responsible for the energy transmission concession market, launched a specification determining that the mechanical design of the transmission lines under concession should follow the International Standard IEC 60826 for synoptic winds. Also recommendations for the adoption of loadings due to High Intensive Winds will be stated in the new standard edition, which will result in wind loadings higher than the ones prescribed before, thus increasing the mechanical reliability and the availability of the Brazilian transmission lines.

The June 14, 2005 HIW

On June 14, 2005, 8 guyed towers and one self-supporting tower of the Itaipu transmission system failed after a supercell formation in the area. The Itaipu transmission system consists of 3 circuits 750 kV AC and 2 circuits 600 kV DC. In the Itaipu system there are 6778 guyed structures. The height varies from 37,5 m to 43,5 m. 64% of the towers have the maximum height of 43,5 m.

All towers failed practically in a direction normally to the transmission line axis. Due to the surrounding terrain, the possibility of debris carried by the wind has not to be considered.

Due to the number of failed towers, it seems that the wind front was extremely large, contrary to the usual assumption that strong winds have a narrow front. Unfortunately it was probably not possible to detect the track and the intensity of the tornadoes due to the absence of trees.

It has been observed that the guys become loose after some time, requiring frequent retensioning. Possible causes are:

- Settling of the guy wires;
- Slipping of guy wires from the hardware;
- Settling of foundations.

Ruy Carlos Ramos de Menezes (2006) stressed that records of wind speeds from synoptic winds and High Intensity Winds may not be mixed as well as the correction ratio between wind speeds measured during respectively 3 seconds and 10 minutes. The records of wind speeds during HIW should be removed from the data collection and processed independently. It is misleading to average the wind speed of HIW over 10 minutes as this event lasts only over a very short time. In Brazil it is recommended to follow IEC 60826 for synoptic winds. However it is suggested to introduce suitable loading cases to account for HIW events.

Ruy Carlos Ramos de Menezes (2006) also made a clear distinction regarding the characteristics of Synoptic Winds and High Intensity Winds (**Table B.2**).

Table B.2 – Comparison of Synoptic and High Intensity Winds in Brazil

	Synoptic winds	High Intensity Winds
Duration	Significant duration	Short duration (mostly less than 5 min)
Areas affected	Large areas as they have a huge dimension	Concentrated areas as they are associated with strokes
Constructions affected	Very important for small constructions	Barely may effect small constructions but long transmission lines
Wind speed	Records of mean values over long periods are able to characterize the storm event	Necessary to record gust wind speeds to characterize the storm event
Wind direction	Constant wind direction	Frequently varying wind direction

Tornadoes occur in the region, but their annual frequency too is low and their effects are too great to take them into consideration. There is a predominance of thunderstorm events between the equator and the latitude 17°S. At latitudes greater than 17°S, there is a mix of thunderstorms and extra-tropical storms.

C. Background information on Big Storms Events

C.1 Introduction

One of the most devastating storms of the 20th century for overhead transmission lines in Europe occurred in late 1999.

The destructive power of the windstorm on December 26, 1999, that swept in from the Atlantic Ocean, cut a devastating swath through France, Spain, Italy, Germany, Austria and Switzerland. Winds of up to 200 km/h were recorded and considerable damage was sustained by property and trees as well as transmission and distribution networks.

This so-called storm of the century was followed two days later by a second storm that ripped into southern France, slicing a path of destruction from Bordeaux to the Riviera.

Across Europe, this climatic event left nearly 150 people dead and deprived more than 2 million households of electricity.

France was by far the hardest-hit country, with more than 80 people killed and property damage running into billions of euros. Government officials deemed it the country's worst natural disaster in more than a decade. The landscaped park of the Versailles Castle lost around 10 000 of its trees, some of them centuries old. An estimated 10% of all trees in the Paris region were felled, including half of those in the famous Bois de Boulogne. In France, more than 4 million m^3 of wood was lost to this storm.

The 26 and 27-28 December 1999 storm was a natural phenomenon caused by a confluence between a warm air mass from the tropics and cold air from the North Atlantic. The resulting thermal shock off the northwest coast of France spawned the powerful storm system and sent it hurtling across the Continent.

Big Storm Events such as this should not be considered as isolated and local accidents limited to specified regions.

Records of global temperatures of the water in the oceans and the continental air have been kept since 1856. This may provide the possibility of a finding an answer to these phenomena, which is scientifically sound. The humidification of the air masses above the oceans, which depends on the difference between the temperatures of both parts, and the instability of those air masses increasing with the latent humidity they hold, justified the statistical analysis of the evolution of the differences between both temperatures.

Due to the continued divergence between the temperatures of the air masses and the water of the oceans, the influence of the increasing latent humidity of the air masses has to be considered as a possible factor of the catastrophic storm events.

The climatic warming up due to the permanent increase of the greenhouse effect linked to the increased concentration of CO_2 (carbon dioxide) in the atmosphere has been mentioned by the Fourth Assessment Report (AR4) of the IPCC (Intergovernmental Panel of Climate Change) (2007) as being the origin of the phenomena as confirmed by the predictions of the meteorological models. Only long observation series of the characteristics of the progress of the climate are able to give a definite answer to the enigma of the climate change.

In the following sub-clauses some background information is given to understand the causes of the Big Storm Events and their effects on overhead lines. The following items are considered:

- Origin or cause of wind storms: wind mechanism; wind speed and direction; wind shear; wind fronts; classification of wind storms (C.2);

- Different types of severe storm events: European windstorm; winter storm with freezing rain; tornadoes and downdrafts emanating from thunderstorms; tropical cyclones; coupled ocean-atmosphere phenomena (C.3);

- Effect of climate change on the magnitude, frequency and duration of Big Storm Events: climate change; global climate models; greenhouse effect; history of natural climate change; 4th Assessment Report of IPCC; projections of extreme storm events (C.4);

- Adaptation strategy to climate change (C.5).

This background information was requested by a majority of responders to the Questionnaire.

The various items have been considered from the viewpoint of the owners of overhead lines that may be confronted with more severe, widespread and frequent storm events.

C.2 Origin or cause of wind storms

C.2.1 Mechanism of the wind

Wind will arise between two air masses with different barometric pressure. Wind tends to flow from the area of high pressure to the area of low pressure until the two air masses are at the same pressure.

Global winds result from uneven solar heating of the Earth’s surface. Differential heating of the earth combined with the fact that:

- Warm air rises;
- Cool air falls,

leads to the following circulation patterns:

- An equator-to-pole flow in the upper atmosphere;
- A pole-to equator flow at lower levels.

This is the idealised model or process. However, there are three forces that cause the wind to move as it does. All three forces work together at the same time:

- The above mentioned **pressure gradient force** causes high pressure to push air toward low pressure;

- The **friction** force not only slows the wind down due to the roughness of the earth surface, but it also causes the diverging winds from high altitudes and converging winds near low altitudes;

- Because of the Earth's rotation, there is third force, the **Coriolis force** that affects the direction of wind flow.

Due to the Earth's rotation earth, the relative linear velocity compared to the rotation axis is maximum at the equator. This relative velocity decreases with higher latitudes so that winds blowing from the equator to the pole are deflected to the east. As a result of the corresponding Coriolis force, winds in the northern hemisphere always flow clockwise around a high pressure area and counter-clockwise around a low pressure area. The reverse occurs in the southern hemisphere.

In certain circumstances the Coriolis force acting on moving air may be almost or entirely overwhelmed by the centripetal force. Such a wind is characterized by rapid rotation. Tornadoes (C.3.3) and tropical cyclones (C.3.4) are typical examples of this type of wind.

The vertical component of the wind is typically very small (except in thunderstorm updrafts) compared to the horizontal component, but is very important for determining the day to day weather.

Rising air will cool, often to saturation (when air cools, it can hold less water vapour and condenses), and can lead to clouds and precipitation.

Sinking air warms causing evaporation of clouds and thus fair weather.

C.2.2 Wind speed and direction

Wind speed is affected by a number of factors, operating on various scales. These include pressure gradient, local weather conditions and the jet stream.

The greater the pressure difference, the faster the wind flows (from the high to low pressure). The pressure gradient, when combined with the Coriolis effect and friction, also influences wind direction.

C.2.3 Wind shear

Wind shear is the difference in wind speed and/or direction between two points in the atmosphere. Shear can be either vertical or horizontal.

Wind shear is a key factor governing the severity of thunderstorms (C.3.3). However wind shear generally inhibits tropical cyclone development (C.3.4).

C.2.4 Cold and warm fronts

A front is a boundary between two air masses of different density and temperature.

Fronts are the principal cause of significant weather. When a front passes over an area, it is marked by changes in:

- Temperature;
- Moisture;
- Wind speed and direction;
- Atmospheric pressure;
- Often a change in the precipitation pattern.

Cold front

A cold front is defined as the leading edge of a mass of air which is colder than the air in front of it. Cold fronts lift air the most abruptly. The colder air, being denser, wedges under the less dense mass of warmer air, that is lifted abruptly and condenses into clouds. The passage of a cold front usually results in velocity changes in winds and creates vertical movement of air.

If the temperature difference of the two air masses involved is large and if the turbulence is extreme due to wind shear, atmospheric disturbances may occur, such as thunderstorms (C.3.3), tornadoes and snowstorms ahead of and immediately behind the moving cold front.

Warm front

A warm front is defined as the leading edge of a mass of warm air. Warm fronts move more slowly than cold fronts and consist of generally stable air, with little vertical air movement.

Precipitation

Precipitation is the general term for rainfall, snowfall and other forms of frozen or liquid water falling from clouds.

Precipitation forms as water vapour condenses, usually in rising air that expands and hence cools. The upward motion comes from:

- Colder air pushing under warmer air (cold front);
- Warmer air riding over cooler air (warm front);
- Convection from local heating of the surface;
- Air rising over mountains;
- Other weather and cloud systems.

C.2.5 Classification of wind storms

A storm is any disturbed state of a planet's atmosphere, especially affecting its surface, and strongly implying severe weather. It may be marked by strong wind or by a wind storm with heavy precipitation, such as ice storm, or wind transporting some substance through the atmosphere, as in a storm of dust, snow, hail, etc. Ice storms are one of the most dangerous forms of winter weather.

Winds can be classified either by their scale, the kind of forces or the geographic region.

There is a need to define the limits of the concept of localized High Intensity Winds (HIW) as several definitions are found in the literature. For the purpose of the design of overhead lines, we further suggest designating the following categories of wind:

- **Synoptic wind** according to the boundary layer theory:
    - Wind only (C.3.1);
    - Ice with or without wind (C.3.2);
- **Localized High Intensity Winds** often associated with thunderstorms (C.3.3):
    - Tornadoes;
    - Downdrafts;
- **Tropical cyclones** (C.3.4):
    - Hurricanes (arising from North Atlantic Ocean, Northeast Pacific Ocean and South Pacific Ocean);
    - Typhoons (Northwest Pacific Ocean);
    - Cyclones (in the Indian Ocean and the South Pacific Ocean);
- **Jet stream** (See here under).

Synoptic winds are winds associated with large moving pressure systems such as warm and cold fronts. They usually cover hundreds or thousands of kilometres. Synoptic winds occupy the lower boundary of what is considered to be forecasted.

Most wind-resistant design codes, including the International Standard IEC 60826 (2003) for overhead power lines, are based on synoptic winds. Those are extreme winds recorded at weather stations that generally affect a large area and exhibit conventional characteristics. They are idealized as essentially horizontal winds with a velocity profile described by the boundary layer theory and its well known power law where the value of the exponent depends on terrain roughness.

Thunderstorms, characterized by the presence of lightning, occur throughout the world, with the highest frequency in tropical rainforest regions where there are conditions of high humidity and temperature along with atmospheric instability. They occur when high levels of condensation form in a volume of unstable air that generates deep, rapid, upward motion in the atmosphere.

Localized High Intensity Winds (HIW), such as downdrafts and tornadoes, take place over very short durations of time and spatially over only tens of hundreds of meters. Though small in scope, micro-scale winds can play a major role in human affairs. Downdrafts are often associated with thunderstorms.

There is growing awareness in the OH line design community that synoptic winds are not proper design parameters to predict, prevent or explain failures due to localized HIW (CIGRE WG06 HIW, 2008).

Tropical cyclones are warm-core, non-frontal synoptic-scale low pressure systems. They arise over the tropical and subtropical oceans, and tend to develop an organized circulation when they withdraw from the equatorial zone. Oceans absorb, store and release huge amounts of heat energy. Especially the air above oceans near the equator is warm and moist.

Extra-tropical cyclones are synoptic scale low pressure systems, that derive energy from horizontal temperature differences. They occur outside the tropics throughout the mid-latitudes of both hemispheres. Extra-tropical cyclones, along with anticyclones, drive the weather over much of the world. A tropical cyclone can become an extra-tropical cyclone as it moves towards higher latitudes and if its energy source changes from heat released by condensation to differences in temperature between air masses. The potential for causing damage, particularly as winter storms, is well documented. In contrast, tropical cyclones have little or no temperature differences across the storm (Holland, 1993) (AOML, 2007).

Subtropical cyclones have some characteristics of both a tropical cyclone and an extra-tropical cyclone.

Jet streams are fast flowing relatively narrow air currents flowing at high altitudes of around 11 km. They follow the boundaries between the hot and cold air masses. Jet streams blow from west to east, but the path of the jet typically has a meandering shape.

Jet streams can be explained as follows. If two air masses of different temperatures meet, the resulting pressure difference (which causes wind) is highest at the altitude of around 11 km. The wind will not flow directly from the hot to the cold area, but is rather deflected by the Coriolis force and flows along the boundary of the two air masses. In the northern hemisphere the jet streams are most commonly found between latitudes 20°N and 50°N for the subtropical jet stream and between latitudes 30°N and 70°N for the polar jet stream.

Meteorologists now understand that the path of the jet stream steers cyclonic storm systems at lower levels in the atmosphere, and so knowledge of their course has become an important part of weather forecasting. Jet streams also play an important part in the creation of super cells, the storm systems which create tornadoes.

Jet streams are often referred to as the storm track since they often steer atmospheric storms.

C.3 Different types of severe storm events

C.3.1 European windstorm

A European windstorm is a severe cyclonic storm that tracks across the North Atlantic towards north-western Europe in the winter months. These storms usually track over the north coast of Scotland towards Norway but can veer south to affect other countries including Ireland, Wales, England, France, Belgium, the Netherlands, Denmark, Sweden and Germany.

As these storms can generate hurricane-force winds (and sometimes even winds at the strength of major hurricanes), they are sometimes referred to as “hurricanes” or “orcans”, even though very few originate as tropical cyclones.

Severe European windstorms in recent history are:

- North Sea flood of 1953, January 31-February 1. Sea defences in eastern England and the Netherlands were overwhelmed. In the Netherlands, 1835 people died due to the dikes being flooded.

- Great Storm of 1987, October 15-16. This storm mainly affected south-eastern England and northern France. This storm received much media attention, not so much because of its severity, but because these storms do not usually track so far south, the trees and buildings are not used to such winds.

- Burns’ day Storm of 1990, January 25. The area affected by this winter storm was much greater than the October 1987 storm, as it tracked east into mainland Europe, where it caused severe damage, especially to forests (A.3).

- Lothar and Martin Storm of 1999, December 26 and 27-28. The first storm in the series rapidly developed just off of the French coast and swept inland. Each of these systems was associated with an intense jet stream aloft and benefited from latent heat release through atmosphere-ocean exchange processes. Both storms were extra-tropical cyclones and had a hurricane-like shape, with an eye at the centre (A.2).

- Gudrun Storm of 2005, January 8. The storm caused a lot of financial damage in Sweden, where the forest industry suffered greatly from damaged trees, as more than 75 000 000 m^3 of trees were blown down in southern Sweden. About 400 000 homes lost power in Sweden and several thousand of these were out of power for many days and even weeks in some cases (A.4).

C.3.2 Winter storm with freezing rain

Freezing rainstorms are one of the most dangerous types of winter storm for overhead lines. They typically occur when a warm air hovers over a region, but the ambient temperature is near 0°C, and the ground temperature is sub-freezing (A.1 and A.5 to A.8 and A.12).

Freezing rain begins as snow falling from a cloud towards earth. It melts completely on its way down through a layer of warm (above freezing) air and then super-cools in a small layer of cold air just before it impacts the surface. Due to being super-cooled the water freezes again upon impact. The ice can accumulate to thicknesses of several cm.

Usually freezing rain is associated with the approach of a warm front (C.2.4) when the circulation near the surface is channelled in such a way that cold air, below freezing temperature, is trapped in the lower levels of the atmosphere. This happens, for instance, when a low pressure system moves from the Mississippi River Valley toward the Appalachian mountains and the Saint Lawrence River Valley of North America, in the cold season, and there is a strong high pressure system sitting further East.

Ice storms often cause major power outages. Overhead lines coated with ice become extremely heavy, causing supports, insulators and lines to break, especially due to severe unbalanced ice loading or ice shedding. Tree limbs with branches heavily coated in ice also can break off under the enormous weight and fall onto overhead lines.

Notable ice storms include El Niño-related Ice Storm of January 1998, that affected much of eastern Canada, including Montreal and Ottawa, and upstate New York (A.1). In A.5 it is demonstrated how a strong wind can significantly increase ice accretion on conductors. Some other ice storms are described in A.6 to A.8 and A.12.

Unfortunately there are few statistical data available on combined wind and ice.

C.3.3 Tornadoes and downdrafts emanating from thunderstorms

Formation of a thunderstorm

Thunderstorms occur in an atmosphere that is unstable and supports deep, rapid upward motion. All thunderstorms require three ingredients for their formation:

- **Moisture** accumulated in the lower atmosphere. Typical sources of moisture are large bodies of water such as the Atlantic and Pacific oceans as well as the Gulf of Mexico.
- **Instability** through a significant fall in air temperature with increasing height. An unstable air mass is characterized by warm moist air near the surface and cold dry air aloft.
- A **lifting** mechanism. There are several processes: differential heating, mechanical

convergence along a cold front, etc.

Thunderstorms are usually accompanied by lightning and heavy rainfall.

The moisture rapidly cools into liquid drops of water, which appears as cumulus clouds. As the water vapour condenses into liquid, latent heat is released which warms the air, causing it to become less dense than the surrounding dry air, and so the air will tend to rise in an updraft due to the process of convection (convective precipitation).

Thunderstorms can also be accompanied by strong winds and hail. The total energy of a thunderstorm can be calculated if the quantity of water that is condensed in a cloud is known. Damaging wind from thunderstorms is much more common than damage from tornadoes. In fact, many confuse damage produced by "straight-line" winds and often erroneously attribute it to tornadoes.

Multi-cell storms

Multi-cell storms are groups of cells in different stages of development which have merged into a larger system. The cloud becomes divided into updraft and downdraft regions separated by a gust front.

As precipitation begins to fall, it drags some of the air with it. This "precipitation drag" initiates a **downdraft**. The downdraft is intensified by evaporative cooling as drier air from the edges of the storm mix with the cloudy air within the storm.

Super-cell storms

Most **tornadoes** are spawned from super-cell thunderstorms. Super-cell thunderstorms are characterized by a persistent rotating updraft and form in environments of strong vertical wind shear.

Downdraft

Downdrafts of all sizes originate from the upper regions of severe thunderstorms when initially cold dry air descends through very heavy rain. Strong evaporation of rain into this already cold air cools it further so that it falls even faster. When this rapid descending air strikes the ground, it can spread outward in all directions but because the thunderstorm is usually travelling the damage path typically indicates a surface wind in the direction of the thunderstorm’s motion (B.1and B.2).

The formation of a downdraft starts with hail or large raindrops falling through dryer air. Hailstones melt and raindrops evaporate - this is an endothermic process that demands a lot of energy (in form of latent heat) so the air is cooled.

Tornado

A tornado is a violently rotating column of air which is in contact with the surface of the earth and extending from thunderstorm base. Tornadoes can come in many shapes, but are typically in the form of visible condensation funnel, with the narrow end touching the earth. Often, a cloud of debris encircles the lower portion of the funnel.

They have been observed on every continent except Antarctica. However, a significant percentage of the world’s tornadoes occur in the USA. This is mostly due to the unique geography of the country, which allows the conditions which breed strong, long-lived storms to occur many times a year. In a typical year about 1000 tornadoes will strike the United States. The peak of the tornado season is April through June and more tornadoes strike the central United States than any other place in the world. This area has been nicknamed "tornado Alley."

Other areas which commonly experience tornadoes include Australia, south-central Canada, north-western Europe (B.3), south-central and eastern Asia, east-central South America (B.4) and Southern Africa.

Records of tornadoes are spotty and incomplete because of the vast amount of inhabited terrain and lack of monitoring. It is certain that tornadoes have gone unseen and unreported.

On February 1, 2007, the National Weather Service in the United States updated the Fujita Scale (F Scale) to the Enhanced Fujita Scale (EF Scale) (McDonald and Mehta, 2006). The different ranges of the original and the enhanced scale are given in **Table C.1**.

Table C.1 - The Enhanced Fujita scale for tornadoes (McDonald and Mehta, 2006)

Category		0	1	2	3	4	5
Description		Light	Moderate	Considerable	Severe	Devastating	Incredible
Wind speed (m/s)	F	< 33	≤ 50	≤ 70	≤ 92	≤ 116	≤ 142
	EF	< 38	≤ 49	≤ 60	≤ 74	≤ 89	≥ 90

Difference between a downdraft and a tornado

The physical properties of a downdraft are completely opposite that of a tornado. Downdraft damage will radiate from a central point as the descending column spreads out when impacting the surface, whereas tornado damage tends towards convergent damage consistent with rotating winds.

Simplified loading cases for localized High Intensity Winds

Localized High Intensity Winds striking overhead lines appear to be more frequent than previously anticipated and utilities are looking at simple ways of reducing the risk of catastrophic failures.

According to G. McClure (CIGRE WG06 HIW, 2008) it is feasible to increase significantly the survival of supports to localized High Intensity Wind storms with relatively simple improvements of the structures such as higher diagonal bracing capacity in self-supporting towers and higher flexural mast rigidity in guyed structures. Some simplified design loading cases are proposed to account for the effects of localized High Intensity Winds on overhead line supports. They require further validation through numerical simulations and/or physical observations.

C.3.4 Tropical Cyclones

Characteristics of a tropical cyclone

A tropical cyclone is a large, rotating system of clouds, wind and thunderstorms, fuelled by the moisture of warm ocean waters.

It can also be defined as a non-frontal synoptic scale low-pressure system over tropical or sub-tropical waters with organized convection (i.e. thunderstorm activity) and a definite cyclonic surface wind circulation (Holland, 1993) (AOML, 2005) (WMO-Statement, 2006) (A.11).

The primary energy source of the tropical cyclones is the heat released when warm moist air rises and the water vapour in it condenses at high altitudes. They are distinguished from other cyclonic windstorms such as European windstorms by the heat mechanism that fuels them (C.3.1).

The term describes the storm’s origin in the tropics and its cyclonic nature, which means that its circulation is counter-clockwise in the northern hemisphere and clockwise in the southern hemisphere.

Tropical cyclones are born and sustained over large bodies of warm ocean water, and lose their strength over land. They carry heat away from the tropics and help to maintain global heat balance by moving warm, moist tropical air to the mid-latitudes and polar regions. They bring much-needed precipitation to otherwise dry regions.

Nevertheless, they can produce extremely strong winds and tornadoes.

Scale

The Saffir-Simpson scale is a 1-5 rating commonly used to measure hurricane force wind in tropical cyclones (**Table C.2**). Wind speed is the determining factor in the scale.

Table C.2 – Saffir-Simpson scale for hurricanes

Category	1	2	3	4	5
Description	Minimal	Moderate	Extensive	Extreme	Catastrophic
Wind speed (km/h)	≥ 119	≥ 154	≥ 178	≥ 210	≥ 250

Formation of a tropical cyclone

The formation of tropical cyclones is the topic of extensive ongoing research and is still not fully understood. Six factors appear to be generally necessary to form a tropical cyclone:

- Warm ocean water temperatures of at least 27°C down to a depth of at least 50 m;
- An atmosphere which cools fast enough with height such that it is potentially unstable to moist convection. This allows the release of latent heat, which is the source of energy in a tropical cyclone;
- Relatively high humidity near the mid-level of the troposphere (5 000 m);
- Low vertical wind shear. When wind shear is high, the convection in the cyclone will be disrupted;
- Minimum distance from the equator, allowing the Coriolis force to deflect winds, causing a circulation around the low pressure centre;
- A pre-existing system of disturbed weather.

Visualisation of a tropical cyclone

A tropical cyclone can be visualized as a giant vertical heat engine supported by mechanics driven by physical forces such as the rotation and gravity of the Earth.

The Coriolis acceleration (C.2.1) initiates cyclonic rotation. The high speeds result from the conservation of angular momentum. This means that the air drawn in from an area much larger than the cyclone is magnified greatly as the air is drawn into the low pressure centre.

A tropical cyclone tends to develop an eye, an area of relative calm (and lowest atmospheric pressure) at the centre of circulation. The eye is often visible in satellite images as a small, circular, cloud-free spot. Surrounding the eye is the eye wall, an area in which the strongest thunderstorms and winds circulate around the storm's centre. Eyewall replacement cycles naturally occur in intense tropical cyclones. Rainbands spiral cyclonically toward the storm centre. Tornadoes often form in the rainbands.

Condensation leads to higher wind speeds. Much of the released energy drives updrafts that increase the height of the storm clouds, speeding up condensation. The evaporation of moisture is accelerated by high winds and reduced atmospheric pressure in the storm, resulting in a positive feedback loop.

Deep convection as a driving force is what primarily distinguishes tropical cyclones from other meteorological phenomena.

Scientists at the National Centre for Atmospheric Research (NOAA, 2000) estimate that a tropical cyclone releases heat energy per day equivalent to 200 times the world-wide electrical generating capacity per day.

To continue to drive its heat engine, a tropical cyclone must remain over warm water, which provides the needed atmospheric moisture. As a result, when a tropical cyclone passes over land, its strength diminishes rapidly.

The most devastating effects of a tropical cyclone occur when they cross coastlines, making landfall. Hurricane Katrina was the costliest tropical cyclone in the USA history (A.11). This can be attributed to a great degree, to the number of people living in susceptible coastal areas.

Weakening of a tropical cyclone

A tropical cyclone can weaken when:

- it moves over land;
- it remains in the same area;
- it moves over water significantly below 26°C;
- it experiences vertical wind shear;
- it merges with a nearby frontal zone.

Tracking of cyclones

There are 6 regional specialized meteorological centres worldwide responsible for tracking and issuing bulletins, warnings and advisories about tropical cyclones in their designated areas of responsibility (AOML, 2005).

Current location and intensity of tropical cyclones can be observed by land-based Doppler-radars. Although tropical cyclones are large moving systems generating enormous energy, their tracks are controlled by large-scale winds. Track predictions depend on determining the position and strength of high pressure and low pressure areas. The track of the tropical cyclone over the Earth's surface is controlled by large-scale winds. However, scientists say they are less skilful at predicting the intensity of tropical cyclones due to an incomplete understanding of factors that affect their development.

In 1960, the launch of TIROS-1, the first successful weather satellite marked the beginning of the age where weather information is available globally. Weather satellites have become an indispensable tool for studying a wide range of phenomena from forest fires to cyclones.

Tropical Season of 2004-2005

The tropical cyclone season of 2004-2005 (A.11) was highly unusual globally. It broke several records, including number of tropical cyclones, number of major hurricanes making landfall, and number of category 5 hurricanes.

The number of category 4 and 5 hurricanes increased by about 75% since 1970 (IPCC, 2007). Precipitation recorded in the US from hurricanes increased by 7% during the twentieth century.

Concurrent with these frequency changes, there have been periods with a strong mean intensity of the North Atlantic tropical cyclones, mid-1940s to the 1960s and 1995 to 1999, and a weak intensity, 1970s to early 1990s.

Only 11% of all tropical cyclones occur in the Atlantic, the rest in the Pacific and Indian Oceans. Chan and Shi (1996) found that the frequency of typhoons has been more variable since about 1980.

Destructiveness of a tropical cyclone

Work on the detection of trends in hurricane activity focus mostly on their frequency (Landsea, 1996; Chan, 1996) and shows no significant long-term trends. Nevertheless theory (Emanuel, 1987) and simulation (Knutson, 2004) predict that hurricane intensity should increase with increasing global mean temperatures.

Therefore, in an article in Nature, Kerry Emanuel (2005) defined the “Power Dissipation Index” as a measure for potential hurricane destructiveness. This PDI index combines:

- hurricane intensity;
- hurricane duration;
- hurricane frequency.

Kerry Emanuel (2005) showed that according to this definition the destructiveness of hurricanes increased markedly since the mid-1970s. This trend is due to both longer storm lifetimes and greater storm intensities.

The actual monetary loss in wind storms rises roughly as the cube of the wind speed, as does the total power dissipation, which integrated over the lifetime of the storm is given by:

$$\mathrm{PDI} = \int V^3_{\mathrm{max}}\,\mathrm{d}t \ ,$$

where V_{max} is the maximum sustained wind speed at the conventional measurement altitude of 10 m and $\mathrm{d}t$ is the infinitesimal time. Although not a perfect measure of net power dissipation, this index PDI is a better indicator of tropical cyclone threat than storm frequency or intensity alone.

Kerry Emanuel (2005) found that the record of net hurricane power dissipation is highly correlated with tropical sea surface temperature (SST), reflecting well-documented climate signals, such as:

- multi-decadal oscillations in the North Atlantic and North Pacific (Landsea, 1999) (C.3.5);
- climate change (C.4).

According to Hayden (2006), Kerry Emanuel was faced with the conclusion that during the past 3 decades, the storms have grown almost twice as destructive. Whatever the cause, the near doubling of power dissipation over the period of record should be a matter of concern as it is a measure of the destructive potential of tropical cyclones.

He also predicted “*My results lead to an upward trend in tropical cyclone destructive potential and – taking into account an increasing coastal population – a substantial* *increase in hurricane-related losses in the twenty-first century.*" There is a huge upward trend in hurricane damage in the US, but all or almost all of this is due to increasing coastal population and building in hurricane-prone areas (FAQ, 2006).

Peter Webster published in Science (2005) that during the past decade there has been a "*large increase in the number and proportion of hurricanes reaching categories 4 and 5*". While the number of cyclones has decreased overall, the number of very strong cyclones has increased.

Both Kerry Emanuel and Peter Webster consider sea surface temperatures to be very important in the development of cyclones. Peter Webster (2005) observed that over the past several decades the sea surface temperatures over most tropical ocean basins have increased in magnitude by between 0,25-0,50°C (WMO-Statement, 2006).

Possible future changes

Kerry Emanuel summarizes (FAQ, 2006): "*Neither basic theory nor numerical climate simulation is well enough advanced to predict how tropical cyclone frequency might change with changing climate.*"

According to the Sixth WMO International Workshop on Tropical Cyclones (November 2006), there is currently large overall uncertainty in future changes in tropical cyclone frequency as projected by climate models with future greenhouse gases (C.4.4). Most climate models (C.4.3) used for such global warming experiments have not been examined extensively concerning their ability to reproduce known historical (inter-decadal) variations in tropical cyclone activity in various areas.

According to the American Meteorological Society (AMS) (2007), there is evidence both for and against the existence of a detectable anthropogenic (man-made) signal in the tropical cyclone climate record to date. Hurricanes are projected to intensify with further warming of sea surface temperature. Midlatitude storm tracks are likely to shift pole-ward, with fewer but more intense storms.

The attribution of long-term trends in frequency and or intensity to global warming requires a longer global data record. Similarly, the attribution of a single event such as hurricane Katrina, regardless of how extreme, is fundamentally impossible. The WMO (2006) issued a press release declaring: "*No individual tropical cyclone can be directly attributed to climate change*."

A large body of research has been conducted on the potential impacts of climate change on tropical cyclones. Because of the rapid advances being made with this research, the findings in this statement may be soon superseded by new findings. Nevertheless the characteristics and the structure of tropical cyclones are difficult to estimate by satellite-based instruments.

Conclusion

Tropical cyclones (hurricanes and typhoons) exhibit:

- large variability from year to year;
- limitations in the quality of data compromise evaluations of trends.

Nonetheless, clear evidence exists for increases in category 4 and 5 storms globally since 1970 along with increases in the PDI (Power Dissipation Index) due to increases in intensity and duration of storms. The 2004-2005 season in the North Atlantic broke many records. The most active year was 1997, when a very strong El Niño began, suggesting that observed record high SSTs (Sea Surface Temperatures) played a key role (IPCC, 2007). The El Niño event is further discussed below in C.3.5.

C.3.5 Coupled ocean-atmosphere phenomena

Ocean currents transfer heat from the Equator to the Poles.

The temporal and spatial variations in regional sea level rise are influenced in part by patterns of coupled ocean-atmosphere variability, including the El Niño Southern Oscillation (ENSO) in the Pacific and the North Atlantic Oscillation (NAO) in the Atlantic.

Effect of the ocean conveyor belt on temperature

The ocean conveyor-belt is the density-driven thermohaline circulation.

Ocean currents are propelled mainly by prevailing winds and differences in water density, which changes with temperature and salinity.

Warm, saline seawater flows from the tropical Atlantic north toward the Pole in surface currents like the Gulf Stream. This water losses heat to the air as it is carried to the far reaches of the North Atlantic. When the coldness and the high salinity together make the seawater denser, it sinks deep into the ocean. Surface water moves in to replace it. The deep, cold water flows into the South Atlantic, Indian, and Pacific Oceans. After mixing again with warm water it rises back to the surface (D. Glick, 2004).

Changes in seawater temperature and salinity might have considerable effects on the ocean conveyor belt.

El Niño Southern Oscillation (ENSO)

An El Niño event involves extensive warming of the surface waters over the tropical central and eastern Pacific Ocean, with associated changes in ocean circulation.

It can be responsible for major climate fluctuations and sometimes unusual and severe weather events, not only in the immediate area, but also around the world. Changes in the trade winds, atmospheric circulation, precipitation and associated atmospheric heating set up extratropical responses.

Historically El Niño events occur about every 3 to 7 years and usually last 1 or 2 years. They alternate with La Niña events. During La Niña events the sea surface temperatures in these regions become colder than normal.

Hansen J. et al. (2006) stated that warming is larger in the Western Equatorial Pacific than in the Eastern Equatorial Pacific over the past century, and they suggested that the increased west-east temperature gradient may have increased the likelihood of strong El Niños, such as those of 1983 and 1997-1998.

The 1997-1998 El Niño event was the largest on record in terms of sea surface temperatures (SST) anomalies and the global mean temperature in 1998 was the highest on record. Tremberth et al (2002) estimated that global mean surface air temperature were 0,17 °C higher for the year centred on March 1998 owing to the El Niño. This El Niño event was followed by a prolonged La Niña phase that extended from mid-1998 to early 2001 (A.1 and A.2).

Whether observed changes in ENSO behaviour are physically linked to global climate change is a research question of great importance.

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation is a climatic fluctuation in the difference of pressure at sea-level between the Polar (Icelandic) Low Pressure and the Subtropical (Azores) High Pressure. This phenomenon controls the strength and direction of westerly winds and storms tracks across the North Atlantic in winter.

The relative strengths and positions of these systems vary from year to year, but also exhibit a tendency to remain in one phase for intervals lasting several years. This variation is known as the NAO index measured from December to March.

An increased pressure gradient (NAO+) results in more and stronger winter storms crossing the Atlantic Ocean on a more northerly track (with warm and wet winters in Europe and cold and dry winters in northern Canada).

In contrast, the reduced pressure gradient (NAO-) results in fewer and weaker winter storms crossing on a more west-east pathway (bringing moist air into the Mediterranean and cold air to Northern Europe). Nevertheless, the US coast experiences more snowy weather conditions.

C.4 Effect of climate change on storm events

C.4.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) issued on February, April and May 2007 the Summary and Technical Reports of Working Group I, II and III of the Fourth Assessment Report (AR4) (IPCC, 2007) on the current state of global warming.

“*Warming of the climate system is unequivocal*,” the AR4 report stated, as it is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average see level.

C.4.2 below gives the **definition** of weather, climate and climate change.

As the statements of the AR4 report are based on the results of global **climate models**, those models are discussed in C.4.3. The **greenhouse effect** is explained in C.4.4. All **natural causes** that contribute to climate change are analysed in C.4.5.

The most relevant **conclusions** of the above mentioned AR4 (Fourth Assessment Report, 2007) are summarized in C.4.6. The **effects** of climate change on storm events are assessed in C.4.7. Changes in extremes are summarized in Table C.3.

As global warming will get worse before it could get better in spite of mitigation policies, **adaptation** strategy (C.5) becomes necessary. It may include protection against more intense weather events.

C.4.2 Climate change

Weather is an atmospheric condition at any given time or place. Weather is characterized by temperature, atmospheric pressure, wind speed, precipitation, humidity, cloudiness, as well as sea surface temperature and thickness of sea ice.

Climate is the average state of weather on long time scales. More rigorously, climate is described statistically in terms of the mean value and variation of the weather characteristics over a long period of time – 30 years as defined by WMO. Climate is fairly stable and predictable.

Climate change in IPCC usage refers to any change in climate over time, due to natural variability or as a result of human activity.

Statistically significant variations of the mean state of the climate or of its variability, typically persisting for decades or longer, are referred to as “climate change” (IPCC-WGI, 2001).

C.4.3 Global climate models

Climate models use quantitative methods to simulate the interactions of the atmosphere, oceans, land surface, and ice. They are used for a variety of purposes from study of the dynamics of the weather and climate system to projections of future climate.

A global climate model or General Circulation Model (GCM) aims to describe air motion and climate behaviour by integrating a variety of fluid-dynamical, chemical, or even biological equations that are either derived directly from physical laws or constructed by more empirical means. They consider the energy transported horizontally and vertically (radiation, convection) in the atmosphere.

An Atmospheric GCM (AGCM) and an Ocean GCM (OGCM) can be coupled together into an Atmosphere-Ocean Coupled General Circulation Model (AOGCM). With the addition of other components (such as a sea ice model or a land model), the AOGCM becomes the basis for a full climate model.

Thousands of climate researchers around the world use climate models to understand the climate system. There are thousands of papers published about model-based studies in peer-reviewed journals - and a part of this research is work improving the models.

C.4.4 Greenhouse effect

The Earth's global mean climate is determined by incoming energy from the Sun and by the properties of the Earth and its atmosphere, namely the reflection, absorption and emission of energy within the atmosphere and at the surface.

Greenhouse gases have little effect on the incoming flow of sun energy, but they act as a blanket to reduce the outgoing infrared radiation emitted by Earth and its atmosphere. The surface, the atmosphere and the oceans therefore warm so as to increase the outgoing energy until outgoing and incoming energy are in balance (AMS, 2007).

Earth is hospitable to life because its atmosphere works like a greenhouse, retaining enough of the sun's heat to allow humans to exist. This natural climate-control system depends on the trace presence of certain atmospheric gases to trap the sun's radiation (B. McCibben, 2007).

Land and water absorb incoming sunlight and transform it into heat, which is released back into the air as infrared radiation. Atmospheric gases, principally carbon dioxide, methane, nitrous oxide, and water vapour, trap most of the ascending heat and keep it in the lower atmosphere. Without this natural process, commonly called the greenhouse effect, Earth's average temperature would hover at a frigid -18°C instead of the present 14,5°C.

About 99% of Earth's atmosphere is nitrogen (78%) and oxygen (21%). The crucial heat-retainers - carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) - make up only a fraction of the remaining 1%. Water vapour and ozone are also important greenhouse gases. Their amounts vary with local conditions.

Long-lived greenhouse gases (CO_2, CH_4, N_2O) are chemically stable and persist in the atmosphere over time scales of a decade to centuries or longer, so that their emission has a long-term influence on climate. CO_2 does not have a specific lifetime because it is continuously cycled between the atmosphere, oceans and land biosphere. About 45% of CO_2 will remain in the atmosphere; 30% is taken by the oceans; and 25% by the terrestrial biosphere. About 50% of a CO_2 pulse to the atmosphere is removed over a time scale of 30 years; a further 30% is removed within a few centuries; and the remaining 20% will typically stay in the atmosphere for many thousands of years. Short-lived gases (SO_2, CO) are chemically reactive and generally removed by natural oxidation processes in the atmosphere, by removal at the surface or by washout in precipitation (B. McCibben, 2007).

Aerosols arise from dust, sea salt, and air pollution. They absorb and redirect radiation emitted by the sun and Earth.

C.4.5 History of natural climate change

The National Research Council placed the Earth's current warming in a historical context by completing a study to assess the efforts to reconstruct temperatures since the Industrial Revolution around 1750 (NRC, 2001) and of the past one to two millennia (NRC, 2006).

The most important **natural climate processes** of the last several million years are the glacial and interglacial cycles of the present ice age involving large continental ice sheets and 130 m sea-level change.

Global average sea level in the last interglacial period (about 125 000 years ago) was likely 4 to 6 m higher than during the 20th century.

Over the past 400 000 years the warm spells, or interglacials, occur nearly every 100 000 years and last about 10 000 years, driven by changes in Earth’s orbit (around the sun) and orientation. Last Ice Age ended 11 500 years ago. Historically, temperature rose first, then carbon dioxide (CO_2) increased, accelerating temperature rise. Sea levels followed in turn. Carbon dioxide levels, as measured in Antarctic ice cores, have risen and fallen in step with global temperatures and sea level over the past 400 000 years. The following variations have been noticed:

- See level varied between +4 m to +6 m and -120 m;
- Temperature varied between +2°C and -8°C with reference to the present temperature;
- Finally greenhouse gas concentrations varied: carbon dioxide (CO_2) between minimum 180 ppm and maximum 300 ppm (parts per million) (low concentrations during cool glacial periods; high concentrations during warm interglacial periods).

Causes of the glacial and interglacial cycles are low orbital changes of the Earth around the sun affecting the amount of sunlight received on the Earth's surface such as:

- Changes in the shape of the Earth's orbit expanding and contracting between more circular and more elliptical paths (period: 100 000 years);
- Changes in the tilt (obliquity) of the spin axis of the Earth (period: 20 000 years);
- Changes in the precession: the spin axis wobbles like an unsteady top, gradually making nearly a full circle in space (period: 40 000 years).

Other known **natural causes** or “drivers” of past climate change include:

- Changes in sun’s intensity: reduced solar activity from the 1400s to the 1700s being likely a key factor in the “Little Ice Age” which resulted in a slight cooling of North America, Europe and probably other areas around the globe (NRC, 2006);
- Volcanic eruptions affecting the climate because they can emit aerosols and carbon dioxide into the atmosphere;
- Changes in ocean circulation.

Climate models show that those drivers alone cannot explain the current global warming.

There is now little doubt (C.4.6) that pouring carbon dioxide and other heat-trapping gases into the atmosphere faster than plants and oceans can soak them up, by clearing forests and burning coal, oil, and gas, is a key-factor in changing Earth’s climate. Climate models show that natural processes discussed above cannot explain all that warming.

On the scale of several decades, climate changes can also result from changes within the ocean/atmosphere systems. Most obviously El Niño Southern Oscillation (C.3.5) has been recognized as a mode within the climate system, owing their existence at least in part to different ways that heat can be stored in the oceans and move between different reservoirs.

C.4.6 Fourth Assessment Report of IPCC

Assessment Reports of IPCC

Recognizing the problem of potential global climate change, the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) established in 1988 the Intergovernmental Panel on Climate Change (IPCC). The role of the IPCC is to provide scientific, technical and socio-economic advice relevant to understanding the scientific basis of the risk of the natural and human drivers of climate change, observed changes in climate, their potential impacts and options for adaptation and mitigation, and projections for future climate change.

The main activity of IPCC is to provide in regular intervals of 5 to 6 years Assessment Reports of the state of knowledge on climate change. IPCC does not carry out research nor does it monitor. Its assessment reports are mainly based on published and reviewed scientific and technical literature.

The excerpts given in C.4.6 and C.4.7 are taken from the Summary Report for Policymakers and the Technical Summary of the Contribution of Working Group I of the Fourth Assessment Report (AR4) of IPCC, issued on February 2nd, 2007, corrections made as of February 5th, 2007 to highlight the possible impact on severe Big Storm Events.

The IPCC Assessment Reports are considered by most scientists as a consensus document. Other scientific assessments reach similar conclusions.

According to the National Academy of Sciences (NAS) (2001), the full report of IPCC Working Group I (2001) is “an admirable summary of research activities in climate science, adequately summarized in the Technical Summary”. For NAS it is critical that the IPCC process remain truly representative of the scientific community.

Warming trend of atmosphere

Instrumental observations over the past 157 years, from 1850 to present, show that temperatures at the surface have risen globally, with important regional variations. Coverage is much better after about 1980, when satellite measurements began.

The global average surface temperature has increased, especially since about 1950. The warming trend over the last 50 years is 0,13°C ± 0,03°C per decade. It is nearly twice that for the last 100 years. The total temperature increase during the last 100 years (from 1906 to 2005) is 0,74°C ± 0,18°C. The tolerance values show the 5%-95% confidence range. It means that the uncertainty ranges are 90% confidence intervals (i.e., there is an estimated 5% likelihood of the value being below the lower end of the range or above the upper end of the range).

An increasing rate of warming has taken place over the last 25 years, and 11 of the 12 warmest years on record have occurred in the past 12 years (1995 to 2006), with 1998 and 2005 being the two warmest years on record. Surface temperatures in 1998 were enhanced by the major 1997-1998 El Niño (C.3.5) but no such strong anomaly was present in 2005.

Records now available show significantly faster rates of warming over land than ocean in the past two decades (about 0,27°C versus 0,13°C per decade). The warming in the last 30 years is widespread over the globe, and is greatest at higher northern latitudes. There is evidence for long-term changes in the large-scale atmospheric circulation, such as a poleward shift and strengthening of the westerly winds. Average arctic temperatures increased at almost twice the global average rate in the past 100 years.

Widespread increases in heavy precipitation events have been observed. These changes are associated with increased water vapour in the atmosphere arising from the warming of the world’s oceans, especially at lower latitudes.

More precipitation now falls as rain rather than snow in northern regions, and in areas where temperatures are near freezing.

Local and regional changes in the character of precipitation also depend a great deal on atmospheric circulation patterns determined by El Niño and the North Atlantic Oscillation.

Confirmation of global warming comes from warming of the oceans, rising sea levels, glaciers melting, shorter freezing seasons, sea ice retreating in the Arctic, diminished snow cover and decreases in permafrost extent in the northern hemisphere. Glaciers are recognized as one of the most sensitive indicators of possible climate change.

Warming trend of oceans

The heat capacity of the oceans is about 1000 times larger than that of the atmosphere.

Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3 000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes sea water to expand, contributing to sea level rise. The total 20th century rise is estimated to be 0,17 m ± 0,05 m. Global average sea level rose at an average rate of 1,8 mm ± 0,5 mm per year over 1961 to 2003, but was faster over 1993 to 2003: 3,1 mm ± 0,7 mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear.

Sea level changes show geographical variation because of several factors, including the distributions of changes in ocean temperature, salinity, winds and ocean circulation.

Evaporation

A consequence of global warming is increased evaporation, provided that adequate surface moisture is available as it always is over the oceans and other wet surfaces.

Heat used for evaporation act to moisten the air than warm it.

An observed consequence is that summers often tend to be either warm and dry or cool and wet. The warmer climate therefore increases risks of both drought where it is not raining, and floods where it is raining, but at different times and/or places.

Changes in snow/ice cover

An important property of snow and ice is its high surface albedo. Because up to 90% of the incident solar radiation is reflected by snow and ice surfaces, while only about 10% is reflected by the open ocean or forested lands, changes in snow and ice cover are important feedback mechanisms in climate change. In addition snow and ice are effective heat insulators.

Permafrost

Permafrost and seasonally frozen ground in most regions display large changes in recent decades. Changes in permafrost can affect landscape stability and can cause damage to infrastructure. Temperature increases at the top of the permafrost layer of up to 3°C since the 1980s have been reported. The maximum area covered by seasonally frozen ground decreased by about 7% in the northern hemisphere over the latter half of the 20th century, with a decrease in spring of up to 15%. However, considerable spatial variability has also been observed, with some regions showing trends of opposite sign.

Greenhouse gases

Most of the observed increase in globally averaged temperatures since the mid-20th century is with more than 66% confidence due to observed increase in anthropogenic (man-made) greenhouse gas concentrations. This is an advance since the conclusions of the Third Assessment Report (IPCC, 2001) that "*most of the observed warming over the last 50 years is with more than 50% confidence due to the increase in greenhouse gas concentrations*".

Global atmospheric concentrations (C.4.4) of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The global increases in CO_2 concentration are due to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.

Before the industrial revolution, the Earth's atmosphere contained about 280 ppm (parts per million) of carbon dioxide. When measuring started in the late 1950s, it had already reached the 315 ppm level. Now it is at 380 ppm.

The atmospheric concentration of CO_2 in 2005 exceeds by far the natural range over the last 650 000 years (180 to 300 ppm) as determined from ice cores (C.4.5). The annual CO_2 concentration grow-rate was larger during the last 10 years (1995-2005: 1,9 ppm per year) than it has been since the beginning (1960) of continuous direct atmospheric measurements although there is a year-to-year variability in growth rates. The past couple of years have seen a series of reports indicating that 450 ppm CO_2 is a threshold we'd be wise to respect.

Limitations and gaps prevent more complete attribution of the causes of observed system responses to anthropogenic warming. First, the available analyses are limited in the number of systems and locations considered. Second, natural temperature variability is larger at the regional than the global scale.

C.4.7 Projections of extreme storm events

Projections of global warming

For the next two decades a warming of about 0,2°C per decade is projected for a range of emission scenarios described by IPCC (2007). Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0,1°C per decade would be expected. Once introduced in the atmosphere, CO_2 remains for at least a few hundred years and implies a lengthy guarantee of sustained future warming.

Moreover, the effect of constant concentrations is delayed several decades due to the thermal inertia of the oceans. With their large mass and high capacity for heat storage, oceans will continue to slowly warm to great depths and thus expand for several centuries (AMS, 2007).

Clouds and humidity remain sources of significant uncertainty in the climate models. If CO_2 changes the amount or distribution of clouds, it could have serious complex effects on the climate. Among the most important uncertainties are changes in clouds, which can either cool or warm the climate.

Projections of extreme events

The assessment of extreme events is based on long-term observational series of weather events. Extremes refer to rare events based on statistical model of particular weather elements.

Changes in extremes may relate to changes in the:

- Mean;
- Variance.

They are assessed at a range of temporal and spatial scales. The rarer the event, the more difficult it is to identify long-term changes. Most studies of extremes consider the period since about 1950 with even greater emphasis on the last few decades since 1979.

Projections of tropical cyclones

According to IPCC-WG I (2007) there is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures (SST). There are also suggestions of increased intense cyclone activity in some other regions where concerns over data quality are greater.

However, there is no clear trend in the total annual numbers of the tropical cyclones. The detection of those long-term trends are complicated by:

- Multi-decadal variability;
- The quality of the tropical cyclone records prior to routine satellite observations in about 1970.

Analysed decreases in cyclone numbers over the southern extra-tropics and increases in mean cyclone radius and depth over much of the southern hemisphere over the last two decades are subject to even larger uncertainties.

Based on a range of various climate models (C.4.3), it is likely (confidence level higher than 66%) that future tropical cyclones will become more intense, with larger gust wind speeds and heavier precipitation.

There is less confidence in projections of a global decrease in total number of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models.

There is more than 50% confidence that there is a human contribution to the observed trend of intense tropical cyclone activity increase. The magnitude of the anthropogenic contributions is not assessed. Attribution for these phenomena is based on expert judgement rather than formal attribution studies.

Changes in tropical storm and hurricane frequency and intensity are masked by large natural variability. The El Niño-Southern Oscillation greatly affects the location and activity of tropical storms around the world, so that increases in one basin are often compensated by decreases over other oceans.

Projections of extra-tropical cyclones

Based on a variety of measures at the surface and in the upper troposphere, it is likely that there has been:

- a pole-ward shift as well as
- an increase in the winter storm activity,

in the northern hemisphere over the second half of the 20th century.

Observations from 1979 to the mid-1990s reveal a tendency towards a stronger December to February circumpolar westerly atmospheric circulation, together with pole-ward displacements of jet streams and increased storm track activity.

These changes are part of variations in wind, precipitation, and temperature patterns, that have occurred related to the North Atlantic Oscillation (C.3.6).

Projections of small-scale weather phenomena

Due to the very strong spatial variability of small-scale severe weather phenomena, such as tornadoes, hail, thunderstorms, dust storms and other severe local weather, there is insufficient evidence to determine whether trends exist.

The density of surface meteorological observing stations is too coarse to measure all such events. Moreover, homogeneity of existing station series is questionable.

The changes in extremes over the specified region and period are summarized in **Table C.3**.

Table C.3 – Changes in extremes over the specified region and period				
Phenomenon	Change	Region	Period	Confidence
Tropical cyclones	Trends towards longer life times and greater storm intensity, but no trend in frequency	Tropics	Since 1970s	Likelihood ≥ 66%; more confidence in frequency and intensity
Extra-tropical storms	Net increase in frequency/intensity and pole-ward shift in track	Northern hemi-sphere	Since about 1950	Likelihood ≥ 66%
Small-scale severe weather phenomena	Insufficient studies for assessment			

Conclusion

The predicted effects of global warming for the environment and for human life are numerous and varied. The main effect is an increasing global average temperature. From this flow a variety of resulting effects, namely, ice melting, rising sea levels, coastal flooding, changes in rainfall patterns, increased extreme weather events.

Changes in extremes are often most sensitive to inhomogeneous climate monitoring processes making assessment of change more difficult than assessing the change in the mean. Changes in the frequency of many extremes can be surprisingly large for seemingly modest mean changes in climate (Katz, 1999).

The threat of climate change is now more widely understood. Nevertheless, more research and knowledge is necessary regarding the structure, the probability, the intensity, the duration, the extent, the location and the track of severe weather events. Moreover, the extent and likelihood of the causes, consequences and policies of mitigation and adaptation are a matter of considerable political controversial.

C.5 Adaptation to climate change

Benefits of adaptation

The “Stern Review on the Economics of Climate Change” (October 30, 2006) has been prepared for the British Government by Sir Nicholas Stern, a former Vice-President of the World Bank. Stern’s report discusses the effect of climate change on the world economy. It is significant as the largest and most widely known and discussed report of its kind.

Using the results of formal economic models, the Stern Review estimates that if we do not act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year. The estimate could rise to 20% if a wider range of risks and impacts is taken into account. In contrast, the costs of mitigation can be limited to around 1% of global GDP each year.

The benefits of strong, early action on climate change considerably outweigh the costs. What we do in the next 10 to 20 years can have a profound effect on the climate in the second half of this century and in the next.

Climate change is the greatest market failure the world has ever seen. It demands an international response. Climate change will affect the basic elements of life for people around the world. People could suffer hunger, water shortages and coastal flooding. The UN and the Kyoto Protocol provide a basis for international co-operation.

Risks of climate change would be lowered much more effectively and economically by reducing current and future vulnerability to climate change rather than through its mitigation. There is a potential for developed and developing countries to enhance and acquire adaptive capabilities.

Key elements for future frameworks should include:

- Emissions trading;
- Technology cooperation for the deployment of new low-carbon technologies;
- Action to reduce deforestation;
- Adaptation.

Emissions from deforestation around the world are very significant – they are estimated to represent more than 18% of global emissions, a share greater than is produced by the global transport sector.

Adaptation to climate change is essential. It is taking steps to build resilience and minimise costs. It is no longer possible to prevent the climate change that will take place over the next two to three decades, but it is still possible to protect our societies and economies from its impacts to some extent.

Adaptation policy is crucial for dealing with the unavoidable impacts of climate change. According to the Stern report, the additional costs of making new infrastructure and buildings resilient to climate change could be 0,05-0,5% of GDP each year.

Definition of adaptation

Adaptation to the variability and extremes of global warming covers all actions aimed at reducing the adverse impacts of global warming.

This in contrast to **mitigation** of global warming which involves actions meant to avoid or delay the occurrence of climate change due to global warming.

Wind, solar and nuclear energy are mitigation strategies for generating power in order to prevent excess greenhouse gases from being released in the atmosphere (J. Kluger, 2007).

On the contrary to mitigation activities, preparedness measures are targeted at preparing activities to be taken when a disaster occurs, i.e. planning. Most of the consequences of global warming would result from one of three physical changes: higher local temperatures, sea level rise, and changes in rainfall patterns.

Adaptation strategy

Adaptation is a necessary strategy at all scales to complement climate change mitigation efforts because we cannot be sure that all climate change can be mitigated (IPCC-WG II, 2001).

The argument for adaptation is that even if we stop all emissions today, the greenhouse gases which are already in the air would be enough to cause some climate change:

- CO_2 in particular is long-lived atmospheric gas, and it would take a long time for CO_2 levels to stabilize to pre-industrial levels;
- Total CO_2 emissions are likely to rise in the coming decades. Climate change is already happening: glaciers are melting, sea levels have risen, and hurricanes are getting more intense.

With rising CO_2 levels, climate change is likely to get worse before it gets better. For these reasons, the world must prepare and adapt to the effects of global warming.

Human-induced climate change represents a new challenge, and may require adaptation approaches to changes that are potentially larger and faster than past experiences with recorded natural climatic variability.

Adaptation to environmental change is not a new concept. Human societies have shown throughout history a strong capacity for adapting to different climates and environmental changes. In human society, much of adaptation may be planned and undertaken by private decision makers and by public agencies or governments.

For humans, adaptation is a risk-management strategy that has costs and is not foolproof. The effectiveness of any specific adaptation requires consideration of the expected value of the avoided damages against the costs of implementing the adaptation strategy (NRC, 2001) (Easterling et al., 2004).

It is uncertain how much of an increase in:

- Intensity;
- Duration;
- Frequency;
- Persistence,

of extreme weather events the Owners of Overhead Lines can tolerate.

D. Statistical tables per question

Table D.1 – List of Answers

Table D.1 - One page Questionnaire on “Lessons to be Drawn from Big Storm Events”
List of Answers

	Country	ISO code (1)	Responders	Date of answer	Questions responded				Big Storm Event	Re-port (2)
					1	2	3	4	Date	
1	Algeria	DZ	Farid Khadri	06.12.06	1	2	-	-	-	-
2	Australia	AU	Angus Ketley	03.04.06	1	2	-	-	-	-
3	Austria	AT	Herbert Lugschitz	14.02.06	1	2	-	-	No event	-
4	Belgium	BE	Eric Cloet Jan Rogier	31.07.06	1	2	3	4	25.01 + 26.02.90	1P
5	Bosnia & Herzegovina	BA	Ibrahim Musabasic	28.03.06	1	2	-	-	-	-
6	Brazil	BR	João Batista G. F. da Silva	19.04.06	1	2	3	-	9 events in 20 years	-
7	Canada 1	CA1	Zibby Kieloch	01.02.06	1	2	3	4	05.09.96	1P
8	Canada 2	CA2	André Vallée	05.05.06	1	2	3	4	05-09.01.98	1E + 2P
9	China 1	CN1	Liang Xidong	05.11.06	1	2	3	4	12.04	-
10	China 2	CN2	Liu Wancai	05.11.06	1	2	3	4	04-05.10.92	-
11	China 3	CN3	Lin Jiang	05.11.06	1	2	3	4	14.06.05 + 10.08.06	-
12	China 4	CN4	Ye Hongsheng	05.11.06	1	2	3	4	01.05	-
13	Czech Republic	CZ	Jiří Hrabánek Pavel Froněk	26.04.06	1	2	3	-	15-20.01.74	2E
14	Denmark	DK	Henning Öbro	31.01.06	1	2	3	-	01.06	-
15	Estonia	EE	Väino Milt	17.11.06	1	2	-	-	-	-
16	Finland	FI	Yrjö Ojala Pekka Rissiö	01.03.06	1	2	-	-	No event	-
17	France	FR	Fabien Rancoule	26.04.06	1	2	3	4	26+28.12.99	2E + 2P
18	Germany 1	DE1	Hubert Brüninghoff	26.04.06	1	2	3	4	24-25.11.05	web
19	Germany 2	DE2	Detlef Hussels		1	2	3	-	19.01.96	-
20	Germany 3	DE3	Friedrich Kiessling		1	2	3	-	12-13.04.94	-
21	Ireland	IE	Cathal O’Luain Cathal Boylan	23.02.06	1	2	-	-	No event	-
22	Italy 1	IT1	Maurizio Leva	04.05.06	1	2	3	-	4 ev. 04 +05	-
23	Italy 2	IT2					3	-	3 events	-

24	Japan	JP	Koji Fukami	06.02.06	1	2	3	4	24.12.80	3E
25	Netherlands	NL	Rob Meijers	27.11.06	1	2	-	-	-	-
26	New Zealand	NZ	Robert Lake	02.04.06	1	2	3	4	09.01.04	2E
27	Norway	NO	Lars Rolfseng	06.10.06	1	2	3	4	01.01.92	-
28	Poland	PL	Irena Kuczkowska Krzysztof Put	28.04.06	1	2	3	4	20.02.03	-
29	Portugal	PT	José Peralta	07.12.06	1	2	-	-	-	-
30	Russian Federation	RU	Vladimir Skhaptsov	02.02.06	1	2	3	4	16.07.04	1E
31	Serbia	RS	Ljiljana Samardzic Sava Skrobonja	17.11.06	1	2	-	-	-	-
32	South Africa	ZA	Rob Stephen	29.08.06	1	2	3	4	12.05-01.06	1E
33	Spain	ES	Rafael Garcia Fernandez	03.02.06	1	2	3	4	-	-
34	Sweden 1	SE1	Leif Söderberg (†)	21.04.06	1	2	3	4	08.01.05	1E
35	Sweden 2	SE2					3	4	30.03.91	-
36	Sweden 3	SE3					3	4	01.02.90	-
37	Ukraine1	UA1	Sergey Turbin	21.08.06	1	2	3	4	24-30.11.00	1E
38	Ukraine1	UA2					3	4	04-05.07.00	1E
39	United Kingdom	GB	Sven Hoffmann	13.11.06	1	2	-	-	-	-
40	USA 1	US1	Leon Kempner	03.02.06	1	2	-	-	-	-
41	USA 2	US2	Peter Catchpole	07.02.06	1	2	-	4	-	-
42	USA 3	US3	Robert Kluge	08.02.06	1	2	-	4	-	-
43	USA 4	US4	Tip Goodwin	16.11.06	1	2	-	-	-	-
44	Venezuela	VE	Carlos Garcia Alamo José Pardiñas	08.02.06	1	2	-	-	No event	-

(1) Country Code according to ISO 3166-1
(2) E = Electronic report; P = Paper report

Table D.2 – List of all answers to Questions 1 & 2

Table D.2 – List of all answers to Questions 1 & 2																
		1. Definition										**2. Scope**				
	Question	Climatic load in excess	Widespread load	Major system damage	Major outages	Impact on population	Use of ERS	Decreasing load impact	Increasing strength	Design rules reviewed	Other	Mitigation actions > event	To compare experience	To assess actions/review	To share lessons	Other
	Item	1.1	1.2	1.3	1.4	1.5	1.6	1.7.1	1.7.2	1.8	1.9	2.1	2.2	2.3	2.4	2.5
1	DZ	Y	N	N	N	N	N	N	Y	Y	N	N	Y	Y	Y	-
2	AU	1	N	2	4	3	5	Y	N	Y	N	1	5	4	3	2
3	AT	N	Y	Y	Y	Y	N	N	Y	N	-	Y	Y	Y	Y	Y
4	BE	2	1	4	3	5	6	9	8	7	-	1	2	3	4	-
5	BA	Y	N	Y	N	Y	Y	N	N	Y	N	Y	Y	N	Y	-
6	BR	Y	N	Y	Y	Y	N	Y	Y	Y	-	Y	Y	Y	Y	N
7	CA1	-	4	1	2	3	5	-	-	-	-	-	Y	Y	Y	-
8	CA2	1	2	3	5	4	9	7	8	6	-	Y	Y	Y	Y	Y
9	CN1	1	5	2	4	3	Y	N	Y	Y	N	2	1	3	4	-
10	CN2	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	-
11	CN3	1	8	2	7	9	3	4	5	6	Y	1	2	3	4	Y
12	CN4	Y	Y	Y	Y	Y	Y	-	Y	Y	-	Y	Y	Y	-	-
13	CZ	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	-
14	DK	1	Y	3	Y	Y	-	-	-	2	N	Y	Y	Y	N	-
15	EE	Y	Y	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y
16	FI	5	1	2	3	4	N	N	N	6	N	Y	Y	Y	Y	N
17	FR	1	2	Y	Y	Y	N	N	N	N	-	Y	Y	Y	Y	-
18	DE1	Y	Y	Y	Y	N	Y	N	Y	Y	N	N	Y	Y	Y	Y
19	DE2	Y	N	Y	N	N	N	N	Y	Y	N	N	Y	Y	Y	Y
20	DE3	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y
21	IE	Y	N	Y	Y	Y	N	Y	Y	Y	-	N	Y	Y	Y	-
22	IT	4	5	3	2	1	-	-	-	Y	Y	Y	Y	N	Y	-
24	JP	2	-	1	Y	-	-	-	-	Y	-	-	-	Y	Y	-
25	NL	1	N	2	3	5	6	N	7	4	N	2	1	3	N	-
26	NZ	Y	Y	Y	Y	N	N	N	N	Y	N	N	Y	Y	Y	-
27	NO	4	5	3	2	1	6	N	N	Y	N	N	1	2	3	-
28	PL	1	-	2	3	-	N	-	-	-	-	-	Y	Y	Y	-

29	PT	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	-
30	RU	Y	-	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y
31	RS	2	4	1	3	5	8	N	7	6	-	Y	Y	Y	Y	-
32	ZA	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y
33	ES	2	4	1	-	-	-	-	3	-	-	Y	Y	-	Y	-
34	SE	4	5	1	2	3	-	N	N	7	6	N	Y	Y	Y	-
37	UA	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	-
39	GB	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	Y
40	US1	4	1	2	3	5	6	Y	Y	Y	-	1	3	2	4	-
41	US2	N	N	N	N	N	N	Y	Y	Y	N	N	Y	Y	Y	-
42	US3	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	Y	YN	Y	Y
43	US4	Y	N	Y	Y	N	N	N	N	N	-	Y	Y	Y	N	-
44	VE	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	Y	Y	Y	-
Question		Climatic load in excess	Widespread load	Major system damage	Major outages	Impact on population	Use of ERS	Decreasing load impact	Increasing strength	Design rules reviewed	Other	Mitigation actions > event	To compare experience	To assess actions/review	To share lessons	Other
Item		1.1	1.2	1.3	1.4	1.5	1.6	1.7.1	1.7.2	1.8	1.9	2.1	2.2	2.3	2.4	2.5
Tot	Y	36	27	37	34	29	19	17	25	32	5	27	39	37	36	12
	N	3	10	3	5	8	16	16	10	5	19	10	0	2	3	2
	-	1	3	0	1	3	5	7	5	3	16	3	1	1	1	26
Tot	1	8	3	5	-	1	1	-	-	-	-	4	3	-	-	-
	2	4	2	7	4	-	-	-	-	1	-	2	2	2	-	1
	3	-	-	4	6	3	1	-	1	-	-	-	1	4	2	-
	4	4	3	1	2	2	-	1	-	1	-	-	-	1	4	-
	5	1	4	-	1	2	4	-	1	-	-	-	1	-	-	-
	6	-	-	-	-	-	2	-	-	4	1	-	-	-	-	-
	7	-	-	-	1	-	-	1	2	2	-	-	-	-	-	-
	8	-	1	-	-	-	-	-	2	-	-	-	-	-	-	-
	9	-	-	-	-	-	2	1	-	-	-	-	-	-	-	-

Table D.3 – List of the answers to Questions 1 & 2 only for widespread BSE

Table D.3 – List of the answers to Questions 1 & 2 only for widespread BSE

		1. Definition										**2. Scope**				
	Question	Climatic load in excess	Widespread load	Major system damage	Major outages	Impact on population	Use of ERS	Decreasing load impact	Increasing strength	Design rules reviewed	Other	Mitigation actions > event	To compare experience	To assess actions/review	To share lessons	Other
	Item	1.1	1.2	1.3	1.4	1.5	1.6	1.7.1	1.7.2	1.8	1.9	2.1	2.2	2.3	2.4	2.5
4	BE	2	1	4	3	5	6	9	8	7	-	1	2	3	4	-
7	CA1	-	4	1	2	3	5	-	-	-	-	-	Y	Y	Y	-
8	CA2	1	2	3	5	4	9	7	8	6	-	Y	Y	Y	Y	Y
9	CN1	1	5	2	4	3	Y	N	Y	Y	N	2	1	3	4	-
10	CN2	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	-
11	CN3	1	8	2	7	9	3	4	5	6	Y	1	2	3	4	Y
12	CN4	Y	Y	Y	Y	Y	Y	-	Y	Y	-	Y	Y	Y	-	-
13	CZ	Y	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	-
17	FR	1	2	Y	Y	Y	N	N	N	N	-	Y	Y	Y	Y	-
18	DE1	Y	Y	Y	Y	N	Y	N	Y	Y	N	N	Y	Y	Y	Y
20	DE3	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y
22	IT1	4	5	3	2	1	-	-	-	Y	Y	Y	Y	N	Y	-
24	JP	2	-	1	Y	-	-	-	-	Y	-	-	-	Y	Y	-
26	NZ	Y	Y	Y	Y	N	N	N	N	Y	N	N	Y	Y	Y	-
27	NO	4	5	3	2	1	6	N	N	Y	N	N	1	2	3	-
30	RU	Y	-	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y
32	ZA	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y
34	SE	4	5	1	2	3	-	N	N	7	6	N	Y	Y	Y	-
37	UA	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	Y	Y	Y	Y	-

Question	Climatic load in excess	Widespread load	Major system damage	Major outages	Impact on population	Use of ERS	Decreasing load impact	Increasing strength	Design rules reviewed	Other	Mitigation actions > event	To compare experience	To assess actions/review	To share lessons	Other
Item	1.1	1.2	1.3	1.4	1.5	1.6	1.7.1	1.7.2	1.8	1.9	2.1	2.2	2.3	2.4	2.5
Y	18	16	18	18	14	10	9	12	17	5	11	18	18	18	6
N	0	1	1	1	4	6	6	4	1	7	6	0	1	0	0
-	1	2	0	0	1	3	4	3	1	7	2	1	0	1	13
1	4	1	3	-	2	-	-	-	-	-	2	2	-	-	-
2	2	2	2	4	-	-	-	-	-	-	1	2	1	-	-
3	-	-	3	1	3	1	-	-	-	-	-	-	3	1	-
4	3	1	1	1	1	-	1	-	-	-	-	-	-	3	-
5	-	4	-	1	1	1	-	1	-	-	-	-	-	-	-
6	-	-	-	-	-	2	-	-	2	1	-	-	-	-	-
7	-	-	-	1	-	-	1	-	2	-	-	-	-	-	-
8	-	1	-	-	-	-	-	2	-	-	-	-	-	-	-
9	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-

Table D.4 – List of all answers to Questions 3 & 4

Table D.4 – List of all answers to Questions 3 & 4																				
		3. Questions on the event																4. Reports		
Question		Wind load only	Ice load only	Combined wind and ice	Date	Location	Gust wind speed	Ice thickness	Extent of event	Number towers failed	Original design criteria	Re-calculation use factor	Solution incr. reliability	Strength coordination	New design rules	Ice observation sheets	Other	Reports available	Updated and accessible	Reports forwarded
Item		3.1.1	3.1.2	3.1.3	3.2	3.3	3.4.1	3.4.2	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	3.13	4.1	4.2	4.3
1	DZ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	AU	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	AT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	BE	Y	-	-	X	X	X	-	X	X	X	Y	Y	Y	Y	N	-	Y	Y	Y
5	BA	N	N	Y	-	-	-	-	-	-	-	N	Y	Y	Y	N	-	N	Y	-
6	BR	Y	N	N	X	X	-	-	X	X	X	Y	Y	Y	Y	N	-	Y	Y	-
7	CA1	Y	-	-	X	X	X	-	X	X	X	N	N	N	N	N	Y	Y	Y	Y
8	CA2	N	N	Y	X	X	X	X	X	X	X	Y	Y	Y	Y	N	_	Y	Y	Y
9	CN1	N	N	Y	X	X	-	-	-	-	-	Y	Y	Y	N	N	-	N	N	-
10	CN2	N	N	Y	X	X	-	X	X	X	-	Y	Y	Y	Y	N	Y	Y	N	-
11	CN3	Y	N	N	X	X	X	-	X	X	X	Y	Y	Y	Y	N	N	N	N	-
12	CN4	N	N	Y	X	X	-	-	-	-	X	Y	Y	Y	Y	N	Y	Y	-	-
13	CZ	N	N	Y	X	X	X	X	X	X	X	N	Y	Y	Y	N	N	Y	Y	Y
14	DK	-	Y	-	X	X	-	X	X	X	-	-	-	Y	N	N	-	N	N	-
15	EE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	FI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	FR	Y	N	N	X	X	X	-	X	X	X	Y	N	Y	Y	N	-	Y	Y	Y
18	DE1	N	N	Y	X	X	X	X	X	X	X	F	N	F	Y	N	Y	N	Y	Y
19	DE2	N	Y	N	X	X	X	X	X	X	X	N	N	N	Y	N	-	N	N	-
20	DE3	N	N	Y	X	X	X	X	X	X	X	N	N	Y	Y	N	Y	N	N	-
21	IE	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	IT1	-	-	Y	X	X	X	X	X	X?	X	N	N	N	Y	N	-	N	N	-
23	IT2	Y	-	-	X	X	X	-	-	X	X	N	N	N	Y	-	-	N	N	-
24	JP	N	N	Y	X	X	X	X	X	X	X	Y	Y	N	Y	N	-	N	N	Y
25	NL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	NZ	Y	N	N	X	X	X	-	X	X	X	Y	Y	Y	N	N	Y	Y	N	Y
27	NO	N	N	Y	X	X	X	-	X	X	X	N	Y	Y	Y	N	Y	Y	N	-

28	PL	N	N	Y	X	X	-	X	-	X	X	Y	Y	Y	Y	N	Y	N	Y	-
29	PT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	RU	Y	-	-	X	X	X	-	X	X	X	-	-	-	Y	-	-	Y	Y	Y
31	RS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
32	ZA	N	N	N	X	X	-	-	X	-	-	-	-	-	-	-	Y	Y	-	-
33	ES	-	Y	Y	-	-	-	-	-	X	-	-	Y	-	-	N	-	Y	N	-
34	SE1	Y	N	N	X	X	X	X	X	X	X	N	Y	N	N	N	N	Y	Y	Y
35	SE2	Y	N	N	X	X	X	X	-	X	X	N	N	N	N	N	-	N	N	-
36	SE3	N	Y	N	X	X	X	X	-	X	X	N	N	N	N	N	Y	N	N	-
37	GB	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	UA1	N	N	Y	X	X	X	X	X	X	-	-	-	-	Y	-	-	Y	Y	Y
39	UA2	Y	N	N	X	X	X	-	-	-	-	-	-	-	-	-	-	Y	Y	Y
40	US1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
41	US2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Y	N	-
42	US3	Y	-	Y	-	-	-	-	-	-	-	Y	Y	-	Y	-	-	Y	N	-
43	US4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
44	VE	Y	N	N	-	-	-	-	-	-	X	N	Y	N	N	N	N	N	-	-
	Question	Wind load only	Ice load only	Combined wind and ice	Date	Location	Gust wind speed	Ice thickness	Extent of event	Number towers failed	Original design criteria	Re-calculation use factor	Solution incr. reliability	Strength coordination	New design rules	Ice observation sheets	Other	Reports available	Updated and accessible	Reports forwarded
	Item	3.1.1	3.1.2	3.1.3	3.2	3.3	3.4.1	3.4.2	3.5	3.6	3.7	3.8	3.9	3.10	3.11	3.12	3.13	4.1	4.2	4.3
Tot	X	-	-	-	27	27	20	14	20	23	22	-	-	-	-	-	-	-	-	-
	Y(F)	13	4	15	-	-	-	-	-	-	-	13	15	16	20	0	10	18	13	12
	N	15	21	11	-	-	-	-	-	-	-	12	11	9	8	25	4	14	16	0
	-	16	19	18	17	17	24	30	24	21	22	19	18	19	16	19	30	12	15	32

Table D.4 – List of all answers to Questions 3 & 4

Table D.5: List of the answers to Questions 3 & 4 if BSE is reported (1/2)

Table D.5 – List of the answers to Questions 3 & 4 if a BSE is reported (1/2)

		3. Questions on the event							
Question		Wind (W) and/or ice (I)	Date	Location	Gust wind speed (m/s)	Ice thickness (mm) /density (kg/m^3) / mass per length (kg/m)	Extent of event (1000 km^2)	Number towers/poles/ lines failed	Original design criteria
Item		3. 1.1	3. 2	3. 3	3. 4.1	3. 4.2	3. 5	3. 6	3. 7
4	BE	W	25.01.90 + 26.02.90	west	47	-	1/3 BE	69/-/x	Reg /Spec
6	BR	W	9events/20y	southeast	-	-	big	39/-/-	Code
7	CA1	W	05.09.96	S Manitoba	50	-	a few	19/-/-	CSA
8	CA2	W+I	05-09.01.98	Québec	15	65/900/-	150	500/2500	CSA
9	CN1	W+I	12.04	Hunan	-	-	large	many	DL/T
10	CN2	W+I	04-05.10.92	Qinghai	-	25/900	small	5/-/-	-
11	CN3	W	14.06.05 + 10.08.06	Ningde Siyang	60 33	-	13.4 0.4	3000/-/- 10/-/-	SDJ3, DL/T
12	CN4	W+I	01.04	Hunan	-	-	-	-	DL/T
13	CZ	W+I	15-20.01.74	Bohemian	28	50-20/600/12-15	2.5	37/x/-	CSN
14	DK	I	01.05	north	0	40/-/-	-	2/-/-	-
17	FR	W	26+28.12.99	Except S+SE	42	-	2/3 FR	1047/-/556	Reg.
18	DE1	W+I	24-25.11.05	northwest	20	40/-/6-10	1	83/-/-	VDE
19	DE2	I	19.01.96	Central	8	(ø200)/-/6	0.5	13/-/-	VDE
20	DE3	W+I	12-13.04.94	S Bavaria	20	(ø150)/-/6	5	100/-/-	VDE
22	IT1	W+I	4 ev. 04+05	NE+ S+C	22	12-15/500/-	50	-	Reg
23	IT2	W	3 ev. 94-04	C+SE	-	-	-	2 +adj	Reg
24	JP	W+I	24.12.80	Tohoku	20	(ø80-150)/400/-	2	62/-/-	Reg
26	NZ	W	09.01.04	N Island	60	-	a few	3/-/-	Int req
27	NO	W+I	01.01.92	NW & C	62	-	53 Util	3,2%/-/-	NEN
28	PL	W+I	20.02.03	southeast	-	-/-/4,8	-	5/-/-	PN
30	RU	W	16.07.04	Irkutsk	33	-	90	-/-/4	PUE
32	ZA	-	12.05-01.06	W Cape	-	-	-	-	-
34	SE1	W	08.01.05	south	42	-	40	-/x/-	SS
35	SE2	W	30.03.91	Östersund	46	-	-	2/-/-	SS
36	SE3	I	01.02.90	north	0	-	-	8/-/-	SS
37	UA1	W+I	24-30.11.00	SE	17	-/800/-	226	239/268/507	-
38	UA2	W	04-05.07.00	Lvov (W)	21	-	-	27/40/-	-

Table D.6 – List of the answers to Questions 3 & 4 if BSE is reported (2/2)

Table D.6 – List of the answers to Questions 3 & 4 if a BSE is reported (2/2)														
		3. Questions on the event										**4. Reports**		
	Question	Wind load only	Ice load only	Combined wind and ice	Date	Re-calculation use factor	Solution incr. reliability	Strength coordination	New design rules	Ice observation sheets	Other	Reports available	Updated and accessible	Reports forwarded
	Item	3.1.1	3.1.2	3.1.3	3.2	3.8	3.9	3.10	3.11	3.12	3.13	4.1	4.2	4.3
4	BE	Y	-	-	25.01+26.02.90	Y	Y	Y	Y	N	-	Y	Y	Y
6	BR	Y	N	N	9events/20y	Y	Y	Y	Y	N	-	Y	Y	-
7	CA1	Y	-	-	05.09.96	N	N	N	N	N	Y	Y	Y	Y
8	CA2	N	N	Y	05-09.01.98	Y	Y	Y	Y	N	-	Y	Y	Y
9	CN1	N	N	Y	12.04	Y	Y	Y	N	N	-	N	N	-
10	CN2	N	N	Y	04-05.10.92	Y	Y	Y	Y	N	Y	Y	N	-
11	CN3	Y	N	N	14.6.05+10.8.06	Y	Y	Y	Y	N	N	N	N	-
12	CN4	N	N	Y	01.04	Y	Y	Y	Y	N	Y	Y	-	-
13	CZ	N	N	Y	15-20.01.74	N	Y	Y	Y	N	N	Y	Y	Y
14	DK	-	Y	-	01.05	-	-	Y	N	N	-	N	N	-
17	FR	Y	N	N	26+28.12.99	Y	N	Y	Y	N	-	Y	Y	Y
18	DE1	N	N	Y	24-25.11.05	F	N	F	Y	N	Y	N	Y	Y
19	DE2	N	Y	N	19.01.96	N	N	N	Y	N	-	N	N	-
20	DE3	N	N	Y	12-13.04.94	N	N	Y	Y	N	Y	N	N	-
22	IT1	-	-	Y	4 ev. 04 + 05	N	N	N	Y	N	-	N	N	-
23	IT2	Y	-	-	3 ev. 94-04	N	N	N	Y	-	-	N	N	-
24	JP	N	N	Y	24.12.80	Y	Y	N	Y	N	-	N	N	Y
26	NZ	Y	N	N	09.01.04	Y	Y	Y	N	N	Y	Y	N	Y
27	NO	N	N	Y	01.01.92	N	Y	Y	Y	N	Y	Y	N	-
28	PL	N	N	Y	20.02.03	Y	Y	Y	Y	N	Y	N	Y	-
30	RU	Y	-	-	16.07.04	-	-	-	Y	-	-	Y	Y	Y
32	ZA	N	N	N	12.05-01.06	-	-	-	-	-	Y	Y	Y	Y
34	SE1	Y	N	N	08.01.05	N	Y	N	N	N	N	Y	Y	Y
35	SE2	Y	N	N	30.03.91	N	N	N	N	N	-	N	N	-
36	SE3	N	Y	N	01.02.90	N	N	N	N	N	Y	N	N	-
37	UA1	N	N	Y	24-30.11.00	-	-	-	Y	-	-	Y	Y	Y
38	UA2	Y	N	N	04-05.07.00	-	-	-	-	-	-	Y	Y	Y
	Tot	11	3	12	27	11	13	14	18	0	10			13

Table D.7 – List of the additional comments clausewise

Table D.7 – List of the additional comments clausewise **(Ranked according the country codes – See Table D.1)**	
1.	**How would you define a "Big Storm Event" (please rank all criteria that apply)?**
1.1	Climatic load **in excess** of normal design load? 1. AU – Are large tornadoes in known tornado hot spots classed as big storm events even if loads are in excess of normal design? 2. CA2 – Absolutely required 3. CN4 – Rare ice load and rare wind load 4. CZ – Ice load 5. DE1 – Ice loads approx. 60 to 100 N/m 6. DE2 – 55 N/m 7. DE3 – Ice load approx. 60 N/m 8. FR – 1.1 & 1.2 are the most important criteria 9. GB – The first two criteria are probably the most important ones. In my opinion a "big storm" event needs both of these criteria. 10. NZ – TP has gone through a progressive review of the design loads, and consider that what we have now are reasonable and defendable 11. US2 – Near or in excess
1.2	**Widespread** climatic load? 1. AU – Could be narrow event in system critical location 2. BR – Can be in a restricted area 3. CA2 – Absolutely required 4. CN1 – I would like to distinguish "big storm event" and "high intensity wind" as follows: HIW is very strong wind only, so it is normally in small area. And heavy ice or snow or sand or salt is the main feature of BSE. Wind is necessary but wind speed here is not very important. Hence BSE is widespread. It will cover much larger area than HIW. 5. CN4 – Normal ice load and rare wind load 6. CZ – Area affected 7. DE1 – Event observed in Belgium, the Netherlands and north-west Germany 8. DE2 – Local ice event 9. DE3 – Wide spread low pressure system "Pallas" 10. FR – 1.1 & 1.2 are the most important criteria 11. GB – The first two criteria are probably the most important ones. In my opinion a "big storm" event needs both of these criteria. 12. NZ – Covering more than one asset over a widespread area. 13. UA – Observations and data relating to the events themselves should not be forgotten! This helps put other issues above into context. For example, was widespread failure caused by loads in excess of design, or by widespread occurrences of poor asset condition? 14. US4 – Does not define BSE
1.3	Major damage to the system? 1. CA2 – Absolutely required 2. CN4 – Transmission lines collapsed and towers damaged 3. CZ – In the area 4. DE1 – 83 110 kV towers and many 20 kV lines collapsed 5. DE3 – Several 110 kV lines damaged 6. FR – This criterion can define a Big Storm Event. However it is rather a consequence of climatic load in excess of widespread load 7. GB – As per comment above, a widespread occurrence of loads in excess of the normal design loads would be highly likely to cause major damage, resulting in major outages and a significant impact on population. However, other events may lead to the same or similar outcomes.

	8. UA – See 1.2 9. US2 – Any damage 10. ZA – Could be major damage to large part but not all system
1.4	Major outages? 1. CN4 – Out of electrical supply 2. CZ – In the area 3. DE1 – Some consumers were out of supply for two days 4. DE3 – Some clients not supplied 5. FR – This criterion can define a Big Storm Event. However it is rather a consequence of climatic load in excess of widespread load 6. GB – See 1.3 7. US2 – Any damage
1.5	Impact on population? 1. CN4 – Out of electrical supply 2. CZ – In the area 3. CN1 – Most BSE will result outages in large area. But sometimes BSE only results limited outages. 4. DE1 – No direct injuries 5. DE3 – No injuries 6. FR – This criterion can define a Big Storm Event. However it is rather a consequence of climatic load in excess of widespread load 7. GB – See 1.3 8. NZ – They would not necessarily have a large impact on the population depending on the location. 9. US4 – May or may not
1.6	Use of emergency restoration systems? 1. BR – Can be a consequence 2. CA2 – Important but generally not available in enough quantity for a big storm as defined above 3. CN1 – Sometimes no 4. CN4 – Additional electrical source 5. CZ – Not available 6. DE1 – Some lines were replaced by emergency systems 7. GB – Not necessarily – in fact I would imagine an ERS being used to deal with more localized damage. It is not envisaged that any utility in the UK would carry sufficient quantities of ERS materials to enable widespread damage to be dealt with. It is much more likely that an ERS would be able to deal with a loss of two or three structures at most. In a major event, however, this might be all that is needed to get a critical circuit back into service. 8. IT – Not at the moment 9. NZ – We have had to use these for where we have had a single tower collapse due to flooding undermining the foundations. So not wide spread or involving multi lines, but still necessary to reinstate quickly. 10. US4 – Does not define BSE 11. ZA – We had large pollution events which did not result in need for ERS
1.7	Involved innovative solutions for increasing structural reliability (upgrading)
1.7.1	- By decreasing impact of climatic limit loads? 1. AU – Depends on line reliability required 2. BR – More difficult to achieve 3. CN4 – Keep away from strict area 4. CZ – E.g. additional towers

	5. DE3 – Doubling of ice assumptions 6. FR – It is a lesson of an event 7. GB – Again, I do not see these criteria as necessarily defining a big storm event. In the case of ANY failure of an OHL component I would expect the cause of that failure to be reviewed and appropriate actions taken in light of the results of the findings, including a review of design criteria following significant climatic events. 8. NZ – Would depend on whether the extreme event was seen as something necessary to consider for future line designs. However it may flow out of a big storm event, that minor changes to designs could limit any damage. 9. PT – I sense that both 1.7.1 and 1.7.2 are necessary 10. UA – First of all big storm events must be analyzed. In this we may face on two most frequent reasons. 1. The BSE is an overload with return period bigger then declared in norms. 2. The norms used wrong assumptions, or little time of observations of climatic loads etc. This case were confirmed when we face some of damages in few years. In first case we cannot use corrections of the norms because in some cases we observed very big overloading particularly with icing deposits (for example in 2000 on Ukrainian weather station Zatish`e were observed icing with the thickness near 200 mm). In the second case we must revised the norms and after this revised possibilities of structural reliability increasing. First of all the increasing of structural reliability with decreasing of climatic limit loads impact must be used (especially if we have big icing storm) and increasing strength of line components must be used also but as second step.
1.7.2	- By increasing strength of line components? 1. AU – Depends on line reliability required 2. BR – More common practice 3. CN4 – Increase of load assumptions 4. CZ – Reinforcement of towers 5. DE1 – Adjusted design criteria for replacement of lines 6. DE2 – Increase of load assumptions 7. DE3 – Strength increased by higher ice loads 8. FR – It is a lesson of an event 9. GB – See 1.7.1 10. NZ – Would depend on whether the extreme event was seen as something necessary to consider for future line designs 11. UA – See 1.7.1
1.8	Required a review of design rules for new lines? 1. BR – Lessons learned 2. CN4 – Adjusted design criteria 3. CZ – Ice regions 4. DE1 – Increase of ice load assumptions under consideration 5. DE3 – Loading assumptions adjusted 6. FR – It is a lesson of an event 7. GB – See 1.7.1 8. IT – Yes according to new national standards 9. NO – New Wind Code 10. NZ – Although this may only be to confirm that the existing levels are reasonable and practical. 11. PT – Yes, but this must be put in context. In some cases review will not necessarily mean change. 12. SE – New components “weak links” 13. UA – See 1.7.1
1.9	Other (e.g. salt sea or man made pollution with ice/wind)? 1. AU – Should be investigated as part of design as a normal event 2. CN3 – Man made pollution with wind

	3. CN4 – Pollution design should be reinforced 4. IT – Salt sea with wind (extensive use of composite or glass coated insulators) 5. PT – We do have some of these, but I don’t agree this qualifies as storm events 6. SE – Falling trees of distribution lines
2.	**What would you like to see discussed in an Electra Report on “Big Storm Events”?**
2.1	To observe mitigation actions rather than the storm event? 1. CA2 – Causes of events vary greatly from country to country 2. CN4 – Need to have causes of events 3. FR – We need to have main characteristics of the event (see § 3) 4. GB – Sharing lessons learned from real events and experiences is always useful! 5. IE – Both 6. IT – Item of international interest 7. NO – Both are of interest 8. NZ – It is always good to put the reaction into context. 9. PT – This means focus. Of course weather specialists must analyze the full cycle of storm events and validate models from which mechanical actions can be inferred. However big means big and that certainly places technical challenges on the design of mitigation actions. 10. SE – Both 11. UA – All information about BSE is important. I may range the importance of this information as p. 2.2 than p. 2.1 than 2.4 and 2.3 this range is showed the importance of the knowledge under provision of trouble-free operation of the system. The BSE may be as only wind as well as only ice. For Ukrainian conditions most important case is wind with ice combinations after this only icing and than only wind. 12. US1 – Storm Event would be interesting 13. ZA – Need both
2.2	To compare worldwide experience on mitigation actions? 1. CA2 – Causes of events vary greatly from country to country 2. GB – See 2.1 3. IT – Item of international interest 4. NZ – This would compare the level of preparedness and ability to respond.
2.3	To identify and assess pro-active and re-active actions, including design code changes for new lines? 1. CA2 – IEC has new loading criteria not very well known 2. CN4 – Designed by new criteria and old criteria 3. GB – See 2.1 4. IT – Item of international interest 5. NZ – Especially any design code changes. 6. US3 – Maybe
2.4	To share lessons in preparedness? 1. CN4 – Attach importance to response 2. DK – See CIGRE report WG B2.13 3. GB – See 2.1 4. IT – Item of international interest 5. NZ – Will definitely help others to gauge their needs in the context of possible events in their area. 6. PT – This is quite important, because this kind of benchmarking is very helpful for decision makers.
2.5	Other? 1. CA2 – Experience on remedial actions (or not) undertaken with existing lines and codes scope regarding this subject 2. CN3 – To compare design strategies

	3. DE – To compare design strategies EE - Measured climatic characteristics (wind, frost etc) + did they exceed thestandards + what exactly happened as a result (damage to the elements of power-lines etc) 4. GB – Observations and data relating to the events themselves should not be forgotten! This helps put other issues above into context. For example, was widespread failure caused by loads in excess of design, or by widespread occurrences of poor asset condition? 5. RU – To discuss efficiency of anti-cascading measures 6. ZA – We had to undergo urgent reinsulation
3.	**Questions on Big Storm Events (please repeat Item 3 as necessary)**
3.1	Type of loading exceeded (see IEC 60826 or TB 178)
3.1.1	- Wind load only? 1. BR – No ice in Brazil 2. CN1– Climate condition about bad weather in China is classified as wind and ice. Wind speed and ice thickness are the two main climate parameters. There is no definition of storm from the point of view of transmission line design. Therefore different persons may give different answers for this questionnaire 3. CN2 –- Ice load should be considered at the same time 4. IT2 – 3 cases (tornadoes) 5. SE1 – Refers to “Gudrun” 2005
3.1.2	- Ice load only? Type of ice? 1. BR – For countries with ice 2. CN2 – Wind load should be considered at the same time 3. DE1 – Wet snow 4. DE2 – Unsymmetrical ice load 5. SE3 – Glaze ice 6. VE – No ice in Venezuela
3.1.3	- Combined wind and ice loads? Type of ice? 1. BR – For countries with ice 2. CN1 – Yes, but BSE should cover ice storm, snow storm, salt storm and sand storm etc. Ice storm is normally much more severe than others. 3. DE1 – Wind increased ice accretion and contributed to the total load 4. DE3 – Wet snow 5. IT1 – 4 cases 6. JP – Wet snow 7. NO – Very low occurrence
3.2	Date (day, month, year)? See Table 3B 1. BR – 9 events in about 20 years; from April to November 2. CA2 – Few events, all during winter period; from November to April 3. CN1 – Dec. 2004 and Jan. 2005, two big ice storms happened in Hunan province, central of China. Many towers collapsed, resulting big outages in large area. 4. IT1 – 150 kV only: February 2004 (north east), December 2004 (south), January 2005 (center), November 2005 (center) 5. IT2 – Augustus 1994 (center), October 1999 (south east), November 2004 (center) 6. NO – 1992-01-01 (worst wind loads)
3.3	Location (country, region)? 1. BE – Western part of Belgium 2. BR – Southeast of Brazil 3. CA1 – Canada, Southern Manitoba

	4. CA2 – Canada, Québec 5. CN2 – Qinghai province, Northwest of China (330kV line) 6. CN3 – Ningde region, Fujian province; Wenzhou region, Zhejiang province; China (typhoon) and Siyang county, Jiangshu province, China (downburst) 7. CN4 – Hunan province, China 8. CZ – Mainly East-Bohemian and South-Moravian (Czecho-Moravian Highlands) 9. DE1 – North-west Germany (Muensterland) 10. DE2 – Line Twistetal – Elsen, Germany, central area 11. DE3 – Germany, southern Bavaria 12. DK – North of Denmark 13. FR – All France except south and southeast 14. IT1 – 150 kV only: February 2004 (north east), December 2004 (south), January 2005 (center), November 2005 (center) 15. IT2 – Augustus 1994 (center), October 1999 (south east), November 2004 (center) 16. JP – Tohoku 17. NO – Norway, North west and middle part 18. NZ – Northern North Island, Molesworth 19. PL – South-east mountain area 20. RU – Irkutsk region 21. SE1 – South of Sweden 22. SE2 – Middle part of Sweden, Östersund 23. SE3 – North part of Sweden 24. ZA – South Africa
3.4	**Magnitude** of event (see IEC 60826 or TB 178)
3.4.1	- Gust wind speed (3 sec; 10 m height; terrain category)? See Table E, column 3.4.1 1. BE – 115 to 168 km/h – Terrain category B – Wind storm WSW 2. BR – Terrain category B 3. CA1 – 180 km/h (estimated), flat terrain 4. CA2 – 55 km/h, terrain type B 5. CN3 – 60 m/s (typhoon) and 32,9 m/s (downburst) 6. CZ – up to 100 km/ hour (without specification) 7. DE1 – Up to 20 m/s 8. DE2 – Up to 8 m/s 9. DE3 – 20 m/s, rolling terrain, Terrain category B 10. FR – 150 km/h (2 s, 10m height, terrain type II (EN 50341)) 11. IT1 – 80 km/h 12. IT2 – High Intensity Wind 13. JP – 19,6 m/s, h=15,9 m, roughness D. Instantaneous max value measured by vane velocity meter. See clause 9.8. Wind velocity specified was measured as an instantaneous maximum value. The value is affected by what measuring instrument (in this case, vane velocity meter was used instead of Cup-type velocity meter) you use. Vane type velocity meter has shorter response time (about 0,25 second) than 3 seconds specified in Question 3.4.1. Therefore the value of wind speed also has 0,25-sec response time. For power transmission towers, load applied for longer time (such as 3 seconds) seems more critical than the shorter one, however we usually adopt wind velocity value as a observed instantaneous maximum value, which seems to lead to conservative tower design. 14. NO – 62 m/s, Lighthouse 15. NZ – >60 m/s, 3 sec gust, 10m. Considered to be a 1300 yr RP event. 16. PL – Unknown 17. RU – Gust wind up to 33 m/s hilly and flat terrain 18. SE1 – 42 m/s 19. SE2 – 46 m/s 20. VE – Terrain C - No big storm event in Venezuela.

3.4.2	- Ice thickness (& density) or ice mass per unit length? 1. CA2 – Up to 65 mm 0,9 kg/m^3 density 2. CN2 – Ice thickness above 25mm, ice density about 0,9 kg/m^3 3. CN3 – 0 mm 4. CZ – 50-120 mm (600 kg/m^3) 12-15 kg/m 5. DE1 – Radial ice 40 mm; approx. 60 to 100 N/m 6. DE2 – 60 N/m, diameter of ice accretion 200 mm 7. DE3 – Diameter of ice accretion 150 mm, weight 60 N/m 8. DK – Thickness: 4 cm 9. IT1 – 12-15 mm (500 kg/m^3) 10. JP – Diameter around 8-15 cm. Density around 400 kg/m^3 (wet snow) 11. NO – No exact observations 12. PL – ≈ 4,8 kg/m earth wire 13. SE3 – 100 N/m, design limit 28,6 N/m
3.5	**Extent** of event (km^2)? See Table E – column 3.5 1. BE – 1/3 of the Belgian territory 2. BR – Very big area 3. CA1 – Very localized, few km^2 4. CN2 – Limited region, across mountain valley 5. CN3 – 13 400 km^2 and 400 km^2 6. CZ – 2 500 km^2 7. FR – 2/3 of France 8. DE1 – 1000 km^2 (in Germany) 9. DE2 – 500 km^2 10. DE3 – 5 000 km^2 11. FR – 2/3 of France 12. IT1 – More than 50 000 km^2 13. JP – About 2 000 km^2 14. NO – 53 utilities involved 15. NZ – A few 16. RU – 50 000-90 000 km^2 17. SE1 – 40 000 km^2 - 250 million trees 18. ZA – Western Cape
3.6	Number and type of supports (or lines) failed/damaged? 1. BR – 9 events / 39 supports collapsed guyed and self supported towers 2. CA1 – 19 guyed steel towers 3. CA2 – About 3 000 transmission line structures (± 2 500 wood structures and ± 500 steel lattice structures) in Québec 4. CN2 – 5 towers collapsed 5. CN3 – 3 000 poles or towers (10kV-220 kV) and 10 towers (500 kV) 6. CZ – 37 lattice towers - many wooden and concrete poles 7. DK – 2 towers 150 kV, 1 OPGW 400 kV after lightning stroke 8. DE1 – 83 supports 9. DE2 – 13 towers of a 4 circuit 380 kV line 10. DE3 – Approximately 100 supports 11. FR – 1047 supports damaged (556 lines) 12. IT2 – Typically 2 towers collapsed + adjacent towers 13. JP – 62 towers (collapsed) 14. NO – 3,2% of 42 196 km OH lines (0,23-132 kV) 15. NZ – 3 lattice towers failed 16. PL – 1 tension, 3 suspension supports 17. RU – 2 lines 500 kV; 1 line 220 kV and 1 line 110 kV 18. SE1 – Distribution lines, mainly 0,4 – 10 kV (numberless amount of wooden poles) -

	Southern Sweden - 500 000 households without electricity - 250 000 households without tele connection 19. SE2 – 2 guyed towers 400 kV 20. SE3 – 8 guyed towers 400 kV
3.7	Reference to original design criteria (code or regulation)? 1. BE – National Regulation and Technical Specifications 2. BR – Codes 3. CA1 – CSA C22.3 No. 1 4. CA2 – CSA C22.3 5. CN3 – SDJ3-1979, DL/T5092-1999 6. CN4 – DL/T 5092-1999 7. CZ – ČSN ESČ 178, ČSN 341100 8. DE1 – VDE 0210, different issues 9. DE2 – DIN VDE 0210/5.69 10. DE3 – DIN VDE 0210 different issues, partly increased ice load 11. DK – Approximately 2 times design load 12. FR – French technical Regulation and NNA 50341-3-8 13. IT1 – National Regulation 14. IT2 – National Regulation 15. JP – National Regulation 16. NO – NEN 11.2.65 and FEF 17. NZ – Internal requirements, approx 350yr RP capacity 18. PL – PN-75/E-05100 19. RU – 30 m/s (code PUE 6) 20. SE – SS 43601 21. VE – ASCE 10-90
3.8	Any re-calculation of structure strength with use factors? 1. CN4 – Re-calculation should be made 2. DE1 – Under investigation 3. FR – Supports damaged are re-calculated with pressure of ultimate wind 4. JP – We apply tower types to the actual load condition on site with some margin. (Ex. Tower design type for 400 m span length (wind and weight) and 20 degree of line angle is applied to a site, which has 378 m span length and 17 degree of line angle). After the storm we calculated the strength of the collapsed towers taking the actual site condition into account for the purpose of pursuing the cause of the failure as well as assessing the strength of the existing towers.
3.9	Any innovative solutions for increasing reliability? 1. BE – Ranking of most sensitive towers 2. CA2 – Deicing by electrical methods 3. CN4 – Increase of load assumptions 4. CZ – No single system on double system towers allowed 5. FR – RTE will implement generic reinforcement solutions, also referred to as “Kits” 6. JP – We have adopted snow accretion resistant means such as snow-resistant plastic rings and smooth-body conductors with fins, which are described in 1997 Cigre Sendai colloquium paper. 7. NO – Improved forest cleaning 8. NZ – Two of the towers had akimbo arms, fitted a few years earlier to raise the conductor, that were not designed to swing 90 degrees without clashing. It is possible that one of the failures of Akimbos was due to bending on the post insulator. We have ensured that any subsequent akimbo support arrangements do allow for free 90 degree rotation in either direction. 9. PL – Ice load warning system 10. SE1 – Weak links, ground cables (replaces overhead distribution lines)

3.10	Was a review of strength coordination undertaken? 1. CN4 – A review should be undertaken 2. CZ – Lawful revision of CSN in the year 1978 3. DE1 – Will be done 4. FR – The strength coordination between supports has been improved 5. NO – After the event
3.11	Have new design rules been considered since the event? 1. BE – National regulation adapted to current design rules reviewed in 1985 2. CN1 – It seems no change of design rules, but climate parameters are reconsidered. 3. CN4 – Constitute new design rules 4. CZ – Combination ice + wind 5. DE1 – Increase of ice load assumptions 6. DE3 – Increased ice loads, modification of wind assumptions 7. FR – See CIGRE report 8. IT1 – New national standard under development 9. NO – New wind loads 10. NZ – The expected 1300 year return period combination of winds was considered outside reasonable levels, however for this key HVDC line, a subsequent review is planned of all spans on the line for any combination of towers and line directions, to ensure that we do not have a similar situation. 11. RU – 36 m/s (code PUE-7) 12. SE3 – CEN but NNA
3.12	Did you collect ice data according to the ice observation sheets of CIGRE Technical Brochure 179 (TF 22.06.01)? 1. CA1 – Ice data was collected but not exactly according to the brochure 2. CN4 – Collected data when event break upon 3. IT1 – Only in areas with big ice formations (by ice weighing spans and experimental stations)
3.13	Any other relevant data/circumstances? 1. CA1 – Presumably wind downburst from field observations and limited witness accounts 2. DE1 – Impact of tower age was studied 3. DE3 – Terrain more than 600 m above O.D. 4. NO – Severe topographic influence discovered 5. NZ – An extreme combination of line direction for the worst possible transverse load, lee effect, location of line in wide valley, types of towers, severity of storm. 6. PL – We treat this rather as local specific climatic conditions 7. SE1 – Climate changes? (no frozen soil at this time of the year) - New type of forest, fast growing trees but not so strong 8. SE3 – Extreme ice with many broken conductors (is not considered in our very well established standard with good experience) 9. ZA – We had problems relating to pollution events.
4.	**Are the Reports on Big Storm Events and the Mitigation Actions available?**
4.1	Are there relevant reports available (events/actions)? 1. CA2 – Some but very limited 2. FR – CIGRE Session 2002 – 22-105 and 2 RTE documents “Reinforcement kits for anti-cascade towers” and “The RTE security plan” 3. IT1 – At the moment the data are not public (only internal company report) 4. JP – A report for the event was made for in-company use only. It is not accessible to the public and neither written in English. However I might be able to pick up some relevant information from the report as I showed in this questionnaire if certain items are specified. 5. NL – There has been a change in the former Dutch Standard NEN 1060 after icing problems

	in the late 80's. After the snowstorm of 25 November 2005, there are no mitigation actions till now, so there is no report. We are starting to investigate if there are some actions needed 6. NZ – Attached to email 7. RU – Only in Russian available 8. SE1 & 2 – Only reports in Swedish are available. 9. SE3 – A presentation attached. The definition "Hurricane" may be wrong but all english reporting used that word. 10. US3 – Newspaper reports
4.2	Are they updated and accessible to the public? 1. DE1 – www.rwe.com (temporary) 2. JP – See 4.1. 3. NO – Not updated 4. NZ – Updated, but for research reference only. 5. VE – Venezuela doesn´t have big storm events. However we are interesting in this information.
4.3	Please forward before April 1, 2006 an electronic/paper copy to jan.rogier@skynet.be : Dr. Jan Rogier, CIGRE WG B2.06 Convenor Koning Albertlaan, 10 B-2820 Bonheiden, Belgium

E. Questionnaire issued

To the SC B2 Members and Observers
To the SC B2 WG Convenors and Secretaries,

Dear Colleagues,

We have the honor to invite you to respond to the one page Questionnaire in attachment **"Lessons to be Drawn from Big Storm Events"**, issued on behalf of TF 07 of CIGRE WG B2.06 "Principles of Overhead Line Design". Big Storm Events are the Nature's own full scale tests for existing Overhead Lines.

The aim of this Questionnaire is:

- to **identify** big storm events worldwide;
- to **collect** relevant information on those storm events, especially on the **actions** taken after the storm event, such as:
  - the innovative solutions for **increasing structural reliability** (or upgrading) of the (damaged) existing lines;
  - the **review of design rules** for new overhead lines;
- to **assess** and to **compare** these actions taken after big storm events;
- to **share** information on mitigation actions and lessons in preparedness.

The idea to share this information grew strongly after the severe storm events in Canada, begin 1998 and in France, end 1999.

The objective of the Questionnaire is consistent with the current Terms of Reference of CIGRE WG B2.06:

*"WG B2.06 deals with methods to **improve electrical and mechanical design** of Overhead Line systems, including Reliability Based Design methods, taking into account the better knowledge of **meteorological issues**."*

There are four General Questions:

- 1. How would you **define** a "Big Storm Event"?
- 2. What would you like to see **discussed** in an Electra Report and/or in a Cigré Technical Brochure?
- 3. Do you want to reply to **some questions** on "Big Storm Events"?
- 4. Are the **reports** on Big Storm Events and the Mitigation Actions available?

In general, the sub-questions in the one page Questionnaire are quite simple. The answer is mostly "yes", "no" or a specific value. The last column entitled "Comment" can be used by the responder for additional information or clarification. If your comments are too comprehensive, please use a separate paper and refer to the Item number of the Questionnaire.

This Questionnaire is sent not only to the SC B2 Members, Observers, WG Convenors and Secretaries, but also to the Members of WG B2.06 (OHL Design), 08 (OHL Supports), 13 (Management for OHL) and 16 (Meteorology for OHL), because they are also dealing with either Storm Events or Mitigation Actions.

Any Member of SC B2 or any Member of a WG of SC B2 may answer Questions 1 and 2, even if he didn't suffer any Big Storm Event. For the General Questions 3 and 4 on reports and data about the Big Storm Events and the Mitigation Actions taken after those Events, we recommend the WG Members to come in contact with the SC B2 Member of his country for a common answer. WG B2.06 thought that a Questionnaire was the best way to collect all relevant reports. Moreover it was an excellent opportunity to involve all Members in the discussion about the definition of a Big Storm Event (Question 1) and about the scope of the Electra Report/Technical Brochure (Question 2).

We already announced this Questionnaire during the SC B2 2004 Session in Paris. This announcement was repeated during the Technical Committee Meeting of SC B2 in Brasilia in 2005. The Questionnaire is now ready.

On behalf of WG B2.06, we would like to appreciate to receive your answers before April 1, 2006, so that they can be discussed during our next WG B2.06 Meeting in Montreal, Canada on May 8-9, 2006. Please inform us about the delay if you need more time to collect and select the existing relevant data and reports.

Some Colleagues from WG B2.06 and WG B2.16 advised us to clarify the following questions:

- Item 1: In order to identify Big Storm Events, WG B2.06 suggested an appropriate definition. However WG B2.06 found it useful to ask the CIGRE Colleagues to validate the definition of Big Storm Events.
- Item 1.1 to 1.9: You are authorized to rank the answers 1.1 to 1.9, especially when you responded "yes" to nearly all questions. Please indicate in the column "Comment" 1 for the most relevant criterion, 2 for the second most relevant criterion, etc.
- Item 1.6 to 1.8: The criteria on actions taken after Big Storm Events have been included in this list of definitions since the collection of existing reports on the actions taken after big storm events was the major objective of the one page Questionnaire.
- Item 1.9: This question gives options for alternative topics. In principle information about only extreme loadings only covered by IEC 60826 or TB 178 is requested (particularly wind, ice or combined wind and ice loadings). However, salt sea and man made (anthropogenic) pollution in combination of wind and/or ice is often classified as a "wind/ice" event. In order to avoid confusion, we also accept information about severe pollution of lines.
- Item 3: In principle the Questions 3 are superfluous if the reports on Big Storm Events and Mitigation Actions are available. Nevertheless the answers to Questions 3 provide a quick overview and facilitate the comparison between Big Storm Events.
- Item 3.1, 3.4, 3.8, 3.9 and 3.10: For more information about the definitions, please consult IEC 60826 or TB 178.

- Item 3.3: Please inform about the influence of local terrain, if relevant.
- Item 3.6: If the information about the number of failed lines or supports is not available, please indicate another representative value that characterize the extent of the damage.
- Item 3.8: The use factor is dealing with the real line parameters versus line design parameters (e.g. real/design wind span).
- Item 3.12: Following the ice and wind storm in parts of Europe on November 25-26, 2005, several questions are now discussed relating to design loads as well as design rules for overhead power lines. It would have been easier and more adequate to answer these questions if appropriate field observations were made, according to the ice observation sheets of CIGRE TB 179 "Guidelines for field measurement of ice loadings on overhead power line conductors" issued by Task Force 22.01.06 (Convenor Svein Fikke, Norway) on February 2001. Most of the evidences of nature are lost if such systematic observations were not taken. In order to assess the number and relevance of the measurements, this topical question has been included in the Questionnaire.
- Item 4.3: Strictly speaking, this is the most important question of the Questionnaire. It is dealing with the existing reports on Big Storm Events and the Mitigation Actions. In general those reports are known and accessible to the public. Only the National Committee can confirm whether these reports are updated and still valid. The last updated reports have never been compared.

If you have still some other questions, please do not hesitate to contact us.

Finally, on behalf of CIGRE WG B2.06, we would like to thank you in advance for your kind collaboration.

One page Questionnaire on "Lessons to be Drawn from Big Storm Events" – Jan. 27, 2006				
Issued by TF 07 of CIGRE WG B2.06 "Principles of Overhead Line Design"				
Item	**Question**	**Yes**	**No**	**Comment**
1.	**How would you define a "Big Storm Event" (please rank all criteria that apply)?**			
1.1	Climatic load **in excess** of normal design load?			
1.2	**Widespread** climatic load?			
1.3	Major damage to the system?			
1.4	Major outages?			
1.5	Impact on population?			
1.6	Use of emergency restoration systems?			
1.7	Involved innovative solutions for increasing structural reliability (upgrading):			
1.7.1	- By decreasing impact of climatic limit loads?			
1.7.2	- By increasing strength of line components?			
1.8	Required a review of design rules for new lines?			
1.9	Other (e.g. salt sea or man made pollution with ice/wind)?			
2.	**What would you like to see discussed in an Electra Report on "Big Storm Events"?**			
2.1	To observe mitigation actions rather than the storm event?			
2.2	To compare worldwide experience on mitigation actions?			
2.3	To identify and assess pro-active and re-active actions, including design code changes for new lines?			
2.4	To share lessons in preparedness?			
2.5	Other?			
3.	**Questions on Big Storm Events (please repeat Item 3 as necessary)**			
3.1	Type of loading exceeded (see IEC 60826 or TB 178):			
3.1.1	- Wind load only?			
3.1.2	- Ice load only? Type of ice?			
3.1.3	- Combined wind and ice loads? Type of ice?			
3.2	Date (day, month, year)?			
3.3	Location (country, region)?			
3.4	**Magnitude** of event (see IEC 60826 or TB 178):			
3.4.1	- Gust wind speed (3 sec; 10 m height; terrain category)?			
3.4.2	- Ice thickness (& density) or ice mass per unit length?			
3.5	**Extent** of event (km²)?			
3.6	Number and type of supports (or lines) failed/damaged?			
3.7	Reference to original design criteria (code or regulation)?			
3.8	Any re-calculation of structure strength with use factors?			
3.9	Any innovative solutions for increasing reliability?			
3.10	Was a review of strength coordination undertaken?			
3.11	Have new design rules been considered since the event?			
3.12	Did you collect ice data according TB 179 (TF 22.06.01)?			
3.13	Any other relevant data/circumstances?			
4.	**Are the Reports on Big Storm Events and the Mitigation Actions available?**			
4.1	Are there relevant reports available (events/actions)?			
4.2	Are they updated and accessible to the public?			
Please give your name, company, country and email address				

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