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The effect of weather on grid systems and the reliability of electricity supply

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Abstract A reliable public electricity supply depends in part on a reliable electricity grid system to transmit and distribute electrical power from generating stations to consumers. The grid system comprises many components that are exposed to the weather and can experience faults as a result of weather events. As climate change is expected to alter the number and severity of weather events, then the reliability of the grid and hence the reliability of electricity supplies can be affected. This paper reviews the effects of weather events on grid systems, illustrated by reference to experience on the grid systems in Europe and North America. It is shown that the effects on the high voltage transmission networks are different from the effects on lower voltage distribution networks and that generally the most significant extreme weather is high winds. Some remedial measures that can mitigate the effects of weather events are also described.

1 Introduction

A reliable electricity supply is an essential resource for modern life: in developed countries, electricity users expect that electricity will almost always be available wherever and whenever it is needed. Developing countries aspire to a reliable electricity supply, as it is a necessary precondition for economic development. Reliability of electricity supply is important; an interruption to supply has direct and indirect financial consequences that are generally many times greater than the value of the electricity not supplied, especially for large blackout events (Eurelectric 2004; Newman et al. 2011; Supplementary Material).

A reliable electricity supply requires a sufficient number of electricity-generating plants with secure sources of fuel or energy. But it also requires a reliable electrical grid system to transmit the power from the generating plants to centres of demand and distribute it to consumers. As many faults on grid systems are related to weather events, a change in weather patterns can change the frequency of grid system faults and hence affect the reliability of electricity supply to consumers and the cost of maintaining the grid system.

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Significant changes in climate are expected during the 21st century, and these are summarised, for example, by Houghton (2004). There will be changes to both means and extremes, and the changes will be different in different geographical regions. The global average temperature is expected to rise by between 2 °C and 6 °C, and associated with this will be an increase in the number of extremely warm days. The temperature rise will cause a sea level rise and an increase in average precipitation with more really heavy showers and more intense thunderstorms in some areas, but an increased risk of drought in others. Peak wind intensities will also tend to increase. There is uncertainty over the magnitude of the changes because of uncertainty about future emissions of greenhouse gases.

The effects of these anticipated changes in weather patterns on electricity generation, transmission and distribution are beginning to receive attention (Overbye et al. 2007; EPRI 2008; EPRI 2009; Beard et al. 2010; National Grid 2010; ENA 2011). This paper discusses the effects of weather on grid systems and how this affects the reliability of electricity supply to consumers, illustrated by examples from Europe and North America. The effects of changes in weather patterns on power generation or consumer demand are not discussed.

Section 2 of this paper describes the general design of grid systems, while section 3 illustrates that a substantial percentage of faults on grid systems and of interruptions to electricity supply are the result of weather events. Section 4 describes the effect of different weather events and some possible remedial actions, and section 5 draws some overall conclusions.

2 The design of grid systems

In most countries the public electricity system comprises a single network (the grid system) that connects the power stations and other power sources to electricity consumers, and may also connect to neighbouring countries. The grid system comprises:

- Overhead lines;
- Underground cables;
- Substations (switchyards) with switching facilities where overhead lines and underground cables are interconnected;
- Transformers to connect parts of the network operating at different voltages;
- Electrical protection and metering equipment;
- Communication and control systems; and
- Control centres.

The grid system can be considered as comprising two kinds of networks with different characteristics: the transmission network(s), and the distribution network(s).

The transmission network comprises those parts of the system operating at very high voltage (generally greater than 100 kV), which are used to transmit large amounts of power for long distances between large power stations and load centres. The distribution networks comprise those parts of the grid system operated at lower voltages that are used to transmit smaller amounts of power over shorter distances from the transmission network to individual consumers.

The large majority of circuits on transmission networks are overhead lines rather than underground cables because of their ease of installation and maintenance and because their cost is lower by a factor of about ten (Parsons-Brinkerhoff 2012). The cost differential is less at lower voltages but most distribution networks still have a large proportion of overhead lines except in urban areas; typical North American networks have 75 % overhead lines (Reed 2008). Generally, electricity substations are outdoor designs, with the more expensive indoor substations limited to city centres or exposed coastal locations. Because overhead lines and outdoor substations are exposed to the weather, it follows that weather conditions can affect the operation of the transmission or distribution networks.

Overhead lines on the transmission network are carried on tall steel lattice towers, while on distribution networks they are carried on smaller steel lattice towers or on wooden or concrete poles. The greater height of transmission towers means their overhead lines are more vulnerable to lightning strikes than distribution networks, but the lower height of the towers or poles in distribution networks means that their conductors are more vulnerable to damage by falling trees.

In order to meet the expectations of governments and consumers for a reliable electricity supply, the grid system operators in many countries design and operate their systems in accordance with published 'reliability standards' which aim to minimise events that interrupt electricity supplies to consumers (e.g., National Grid 2009; for further examples see Supplementary Material). The reliability standards do not generally consider weather conditions, but are concerned with ensuring that the system has sufficient redundancy so that anticipated faults, whatever their cause, do not generally lead to undesirable consequences such as disconnection of large amounts of consumer demand or overloading and cascade tripping of other circuits. The standards may be graded so that more redundancy is provided in parts of the network where faults could have more significant consequences. Building and operating a network with redundancy will be more expensive than a network with none; it is estimated that the cost of the transmission network in Great Britain is around 1.8 times the cost of the theoretical minimum network that has no redundancy (National Grid 2011).

As a consequence of such 'security standards' policies no consumers should lose supply for random single faults on a transmission network; loss of supply should require two or more faults to occur close together, while the blackout of a large area should require multiple faults. Distribution networks generally have a lesser degree of redundancy, so that although a single fault on a low voltage part of a distribution network may cause a number of consumers to lose supply, the area affected would be small.

Individual components in the grid systems (transmission towers, transformers, etc.) are generally designed in accordance with national or international standards, which aim to ensure that the component is robust against the currently expected range of environmental conditions for the country (e.g., ambient temperature, wind speed, etc.). For example the European Standard (BSI 2001) for overhead lines includes the wind loading specification, with each country specifying its own maximum wind loading.

3 Weather and faults

A 'fault' is any unplanned event that causes a circuit or an item of equipment in a network to be switched out of service, either automatically by the electrical protection system or manually in response to an alarm signal. Faults can arise from many causes such as equipment failure, human error, malicious damage, earthquakes, tsunamis or geomagnetic storms in addition to weather events. However, in Europe and North America, weather events are a main cause of a significant percentage of individual faults and of events involving loss of supply to consumers.

As an illustration Fig. 1 shows the number of faults each year on the high voltage transmission network over a period of nearly 30 years in one geographical area of Great Britain. There is a large variation in the number of faults from year to year but overall more than half the faults have been attributed to weather events. A similar pattern was observed in other areas of Great Britain. Because of the designed redundancy of the transmission system, only a small minority of the faults in Fig. 1 led to loss of supply to consumers. The author has

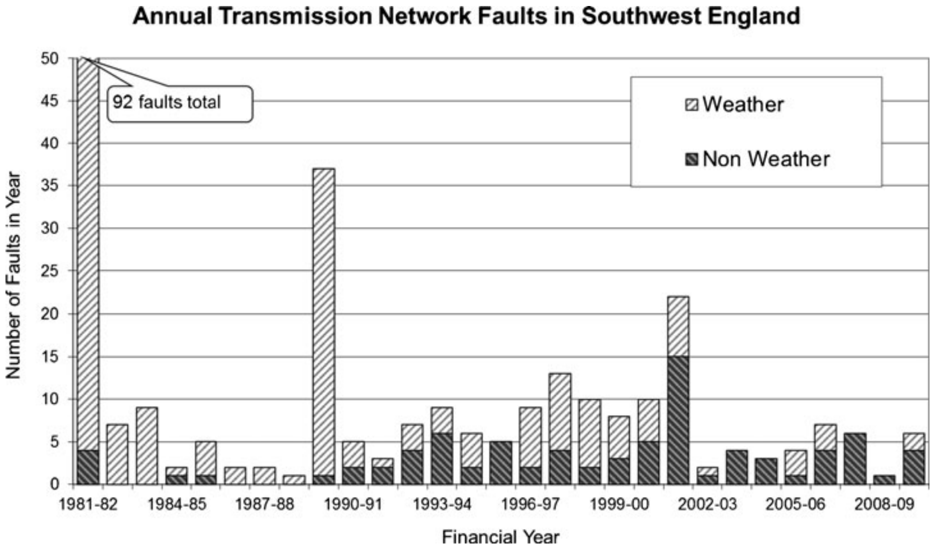

Fig. 1 Faults on the transmission system in Southwest England

analysed all the reported loss-of-supply events in England and Wales from 1990 to 2010 (Supplementary Material), and there are on average ten such events per year. Nearly half of the larger events and around half of the energy not supplied were attributed to weather events.

The author and Hines et al. (2009) have separately analysed data for loss-of-supply events in North America. The conclusion is that around half of all the events, and nearly three-quarters of the larger events, were caused by weather events (Supplementary Material). Ten of the 15 largest blackout events (which affected more than a million consumers) had an extreme weather event as the primary cause.

The Electric Power Research Institute (EPRI 2000a) presented data on loss of supplies to consumers in eleven different US distribution utilities; Brown (2002) reported an analysis of the major causes of interruptions in three US distribution utilities. In each case, weather events were a major cause of loss of supply, although there were significant differences between the utilities on which type of weather was the main cause. An analysis of failures on the medium voltage distribution network in Finland by Martikainen et al. (2007) showed that about 56 % of the failures were related to the weather.

4 Effects of weather events

4.1 Temperature effects

During the 21st century, global average temperature could increase by as much as 6 °C (Houghton 2004). The direct effect of an increase in average temperature on transmission or distribution is to limit or reduce the maximum power rating of equipment and to increase the energy losses. The impact is similar to the effect of a small increase in power flow. Hence, the mitigation of higher temperature in the future requires just a small extension to the measures used routinely to accommodate increasing power flows due to growth in consumer demand and changing generation patterns (Supplementary Material).

The rating of overhead lines is generally dictated by the sag on the line (Brown 2002; Bayliss and Hardy 2007); the minimum safety clearance distance below the conductor limits the maximum temperature of the line. If trees are growing beneath an overhead line and have not been trimmed recently, then on really hot days there is a risk of multiple flashover faults to the trees. This was partly the initiating cause of the major USA-Canada blackout in 2003 (U.S.-Canada Power Outage Task Force 2004). The main remedial measure is to ensure adequate cutting of trees growing below overhead lines.

4.2 High winds, storms, and hurricanes

High winds can lead to faults and damage to overhead lines, caused by debris being blown against the lines, trees being blown over onto the lines and ultimately utility poles being blown over or transmission towers buckling in extremely high winds.

In the analysis of major loss-of-supply events in North America by Hines et al. (2009), around half of the events had wind, storm, hurricane or tornado as a main cause. Davidson et al. (2003) and Winkler et al. (2010) have analysed and modelled the effect of hurricanes in the Gulf and Carolinas regions of the USA. Reed (2008) analysed the effect of winter storms in the Pacific Northwest of the USA. General conclusions from these papers are:

- In most hurricanes and storms, the majority of consumer interruptions are due to damage to the distribution networks and not the transmission network;
- Trees cause more than half of the damage to distribution networks;
- Damage is related to the square of the peak wind speed;
- Only in the most severe storms is significant damage done to the transmission network.

The experience from storms in Europe also is that the majority of customer disconnections are due to trees damaging distribution networks, and only the most severe storms cause damage to the transmission network. (Examples are given in the Supplementary Material.)

Direct wind damage to the network towers and poles and substation structures, is minimised by designing them to withstand the maximum expected wind loadings (e.g., BSI 2001), and by frequent inspection of their integrity. Damage by trees can be limited by more rigorous management of trees growing near overhead lines, but utility companies do not have unlimited rights to cut trees. Such ‘vegetation management’ is the largest maintenance budget item in many US utilities with a total spend in the USA of more than $2billion per year (Brown 2002). It may be possible to reduce the cost of vegetation management by improved practices (ENA 2007; EPRI 2000a), more appropriate design (EPRI 2006b) or by improved system monitoring (Russell et al. 2007).

Problems related to trees may also be reduced by the following actions:

- Rerouting of overhead lines to avoid forested areas (Martikainen et al. 2007);
- Replacement of overhead lines in forested areas with underground cables (EPRI 2000b; Eurelectric 2006);
- Replacement of the normal bare conductors in medium and low voltage circuits with covered or insulated conductors to reduce faults due to momentary contact with swaying trees (Eurelectric 2006);
- Installation of ‘weak links’ in overhead line conductors, so that falling trees break the conductors and do not damage poles or towers (Eurelectric 2006).

Florida Power & Light (2006) announced a ‘Storm Secure Program’ that will use several of these measures to make its network more resilient to future hurricanes. Electricité de France introduced similar measures after a severe storm in France in December 1999; similar measures are being considered in Sweden and Latvia following a severe storm in 2005 (Eurelectric 2006).

4.3 Ice and snow

Heavy snow and the accumulation of ice can cause failures of overhead lines, towers or poles because of their weight. A layer of ice increases the cross-sectional area of the overhead line conductors, thus increasing the risk of collapse in high winds. The weight of snow on trees can also cause them to fall and damage lines. Under certain wind conditions ice can build up on overhead line conductors to form a streamlined airfoil shape, which can lead to large vertical oscillations, known as 'conductor galloping' (Bayliss and Hardy 2007; Brown 2002). This can cause fatigue failure of the lines or supports.

The extreme ice and snow event is the 'ice storm', which occurs when super-cooled rain, in combination with strong wind, freezes in contact with trees or structures, rapidly forming a thick layer of ice. Two recent examples of ice storms were:

- Canada and North East USA, January 1998 (EPRI 1998; NERC 2001; Eurelectric 2006). Several hundred transmission towers and tens of thousands of wooden poles on the distribution networks were destroyed and over two million consumers lost electricity supply;
- Germany, November 2005 (Broström et al. 2007). Around 70 transmission towers were broken and around 200,000 people lost electricity supplies.

In regions likely to experience ice and snow, the transmission towers and lines are designed to allow for the maximum expected ice and wind loading (Bayliss and Hardy 2007), but there is a limit to what is practicable. For example, in the 1998 Canadian event, ice reached a thickness of 70–90 mm on overhead lines. The Ontario Hydro design was for 25 mm of ice on 230 kV and 115 kV lines and 50 mm on 500 kV lines, while the requirement of the Canadian Standards Association was for only 12.5 mm of ice (Eurelectric 2006).

Musilek et al. (2009) have developed a method for forecasting the rate of accretion of ice on overhead lines. Broström and Söder (2005, 2007), Broström et al. (2007) and Chouinard and Erfani (2006) have developed methods for modelling and predicting the effect of ice storms on transmission circuits.

Under freezing conditions, ice and snow can build up on insulators, bridging the insulators and providing a conducting path, leading to flashover (short-circuit) faults. The risk of this fault mechanism can be reduced by a suitably designed insulator (Berlijn et al. 2007).

4.4 Lightning

The ionised gases produced by lightning strikes on or near overhead line conductors can cause flashover (short-circuit) faults so that the circuit is disconnected by the electrical protection. Generally, such faults are transient and are removed by de-energising the circuit, so that the circuit can rapidly be restored to service. However, the voltage surge caused by the lightning strike may travel along the overhead lines and cause damage to equipment such as transformer windings. EPRI (2006a) has estimated that the direct cost to utilities in the USA of damaged or destroyed equipment due to lightning is around \$1 billion per year.

The frequency of thunderstorms with lightning varies considerably with location (e.g., in the USA, lightning is common in Florida, the Gulf Coast, and an area of the mid west, but much less frequent on the Pacific Coast, or the New England states). EPRI (2006a) comment that lightning strikes are the most common cause of transmission line outages in the USA, but the analysis of major loss-of-supply events by Hines et al. (2009), suggests that only 8 % of the events had lightning as a main cause.

It is standard practice on overhead line transmission circuits to fit earth wires above the live conductors to reduce the risk of direct lightning strikes to the live conductors; protective earth wires are also sometimes fitted above substation structures. To protect against damage from voltage surges it is usual to fit spark gaps and surge arresters. It is not practicable to provide a similar level of protection on all lower voltage distribution networks (Brown 2002), but the lower height of overhead lines means that direct lightning strikes are less common than indirect strikes to adjacent structures which cause less severe voltage surges. Ways of improving the protection of overhead lines and associated equipment from lightning strikes are described by Bayliss and Hardy (2007), EPRI (2006a, b) and IEEE (1997). These include adding an earth wire above the live conductors on distribution circuits, which adds about 10 % to the cost of the line, or by improving the earthing of towers, adding an earthed bonding wire to wooden poles, or using better surge arresters.

4.5 Rain, floods, and landslides

Heavy rain is normally associated with strong winds or lightning, which are more likely to cause faults than the rain. Very heavy rain occasionally causes flashover faults (short-circuits) across insulators, but changes to the design of insulators can reduce the risk of this (EPRI 2007). Heavy rain can cause water ingress into high voltage insulators and switchgear, leading to internal flashovers and catastrophic failures, but careful maintenance can minimise the risk of such faults.

A more significant consequence of a prolonged period of heavy rain is flooding and landslides. Floods near the coast can also be caused by high winds or storm surges that damage flood defences (e.g., Hurricane Katrina), with the risk increasing because of the expected sea level rise from climate change. Flooding does not generally pose a threat to overhead lines; the main threat is to equipment such as switchgear, transformers and control cubicles mounted at ground level in substations. If such equipment is submerged or damaged by water, it is likely to take many weeks to repair or replace.

The analysis of large loss-of-supply events in North America by Hines et al. (2009) does not list flood as a separate cause, although a lot of the damage from Hurricane Katrina in 2005 resulted from flooding. Chapman (2006) confirmed that poles and lines in the New Orleans area were surprisingly resilient during and after Hurricane Katrina, but that the distribution network substations were susceptible to flooding.

Landslides and avalanches in mountainous area can occur following very heavy rain or snow, and can damage overhead lines or underground cables. However, the greatest impact would result from a major substation or control centre being damaged.

The main remedial action against flooding or landsides for new installations is to avoid locating them in areas that are at risk. For existing installations in a flood risk area, routine reassessments of the risk should be carried out to establish the necessary flood defences. For substations in Great Britain, the Energy Networks Association (ENA 2009) advises a target resilience defence level of 1:1000 years, plus 20 % increase in river flow or 300 mm to allow for climate change, plus a margin for data error.

4.6 Drought

Transmission and distribution systems do not generally use water for cooling, so cooling arrangements would not be affected by a prolonged drought. However, a long period of dry weather can cause the ground to dry out, which reduces the thermal conductivity of the soil, reducing the rating of underground cables (Martikainen et al. 2007), and thereby adding to the derating already due to higher temperatures. Drying of the subsoil can also reduce its electrical conductivity, which would require changes to earthing systems (National Grid 2010; ENA 2011).

A more significant effect of a drought is that vegetation dries out and increases the risk of fires. Overhead lines can initiate wildfires in drought conditions, if vegetation comes into contact with the overhead line conductors and is ignited by flashovers (Mitchell 2009; Sunrise Powerlink Project 2008). Smoke from fires can cause repeated arcing faults on an overhead line because the ionized air in the smoke can become a conductor of electricity. When a fire occurs near an overhead line, wood poles can burn and the conductors and insulators can be damaged (Sunrise Powerlink Project 2008).

The analysis by Hines et al. (2009) indicates that around 5 % of loss-of-supply events in North America that affected more than 50,000 consumers had fire as a cause. None of the loss-of-supply events in England and Wales discussed in section 3 was caused by fire.

To reduce the risk of damage from fire, careful attention should be paid to control of vegetation under and near overhead lines. Covered or insulated conductors on overhead lines can be used to remove the risk of ignition if a tree or branch should brush against them.

5 Discussion and conclusions

This paper has summarised the effects of weather on electricity transmission and distribution systems, and illustrated this by reference to experience in Europe and North America.

In discussing the effect of weather on grid systems it is useful to distinguish three basic weather conditions, which in this paper are named 'normal', 'adverse' and 'extreme', and defined below. (This is similar to the three weather states model proposed by Billinton et al. (2002).)

In 'normal' weather, which is the majority of the time, faults due to weather are occasional isolated events. As a consequence of the redundancy in the system resulting from the 'reliability standards' discussed in section 2, single faults on the transmission network should have no effect on supplies to consumers, whilst single faults on a distribution network should affect only a few consumers in a limited area.

In 'adverse' weather, there are multiple weather-related faults in an area in a short period of time. When circuit outages due to faults on a transmission network overlap, consumers can lose supply. If multiple faults occur on a distribution network, then many consumers can be affected in total, and the time to restore supplies is likely to be longer than in normal weather (Reed 2008). Periods of adverse weather generally last for a few hours or days, and the system can return to normal operation after the return to normal weather.

In 'extreme' weather there are multiple faults and the network suffers significant physical damage that will be costly and time-consuming to repair. As a consequence many consumers can lose supply, and the system cannot return to normal operation soon after the return to normal weather. As extreme weather implies conditions beyond design limits, it should be rare.

An important consideration is whether the loss of electricity supply due to adverse or extreme weather can spread beyond the area immediately affected by the weather to cause a major system blackout. The U.S.-Canada Power Outage Task Force (2004) analysed the causes of the 2003 USA-Canada event and seven earlier major blackouts. Although some blackouts had weather events as an initiating cause, the Task Force concluded that the major blackouts had a number of common factors that caused the event to grow from a limited grid disturbance to a major blackout, by cascade tripping of circuits. These factors were mainly related to the way that the systems were managed, and not to the nature of the initiating events. The Task Force made a number of recommendations related to the design and management of the transmission networks, to reduce the risk of similar large cascading events in future; Eurelectric (2004) has made similar recommendations.

Climate change is expected to lead to a global increase in average temperature. However, as described in section 4.1 the direct effect of this on energy losses and equipment rating is small in comparison with the effect of changes in consumer demand and generation patterns.

More significantly, climate change is expected to cause changes in precipitation, wind speeds and the severity of thunderstorms, with increases in some areas and reductions in others; these change are likely to cause a change in the frequency of faults on the transmission and distribution systems. Where these systems have been designed with suitable redundancy an increase in the number of faults due to weather events in 'normal weather' should not cause a significant increase in loss-of-supply events. An increase in the number of periods of 'adverse' weather is likely to increase the number of occasions when consumers experience a loss of supply, but proper attention to the management of the networks can prevent these events growing to be major blackouts.

Of more significance are 'extreme' weather events that cause significant damage to the networks. Individual items of equipment for transmission and distribution networks are generally designed in accordance with national or international standards that have been developed over many years to be generally adequate for the current range of weather conditions. As new equipment is expected to have an operational life of 30–50 years it will be necessary to reassess the design standards for new equipment against the expected increase in severity of events during the equipment lifetime. The changes in requirements may be different in different geographical areas. A recent assessment in Great Britain (National Grid 2009; ENA 2011) concluded that there is no immediate need for an increase in standards relating to wind, but that a significant number of substations will need improved flood defences. By contrast, a recent assessment in the USA (Peters et al. 2006) concluded that improved resistance against hurricane force winds is needed.

However, the most difficult problem with high winds in Europe and North America arises from damage to distribution networks caused by trees, which may be made worse if climate change increases the duration of the growing season. Selective use of the remedial measures described in section 4.2 may allow this risk to be partly mitigated.

Electricity consumers bear the financial and other consequences of loss of electricity supply, while the cost of building, strengthening, maintaining and operating the transmission and distribution networks to minimise loss of supply is borne initially by the companies that own and operate them. In some jurisdictions, the network companies have a financial incentive to achieve a given level of reliability, but this can exclude *force majeure* events such as major storms (Peters et al. 2006). In other jurisdictions (e.g., Great Britain) the expenditure by the network operators is effectively controlled by an energy regulator, which may restrict investments that go beyond present standards. For these reasons, governments may need to consider carefully if the electricity companies have the right incentives and powers to invest in strengthening their networks for future climate change, for the general economic good.

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