RESILIENCE OF FINNISH ELECTRICITY DISTRIBUTION NETWORKS AGAINST EXTREME WEATHER CONDITIONS

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ABSTRACT

Extreme weather conditions threaten Finnish electricity distribution networks that are mostly built as overhead lines. This paper presents selected methods and technologies that can be taken to improve the networks' resilience during different phases of a disruptive event.

INTRODUCTION

Weather-related vulnerabilities and interruptions in electricity supply are very topical as Finland has seen several extreme weather events in recent years that have affected hundreds of thousands of people. Climate change is even expected to increase the amount and the extent of extreme weather events and at the same time is also driving societies to replace fossil fuels with renewable energy sources in energy production. The revised Electricity Market Act obligates distribution system operators (DSOs) to improve their distribution networks' resilience against extreme weather, too. Much of the electricity distribution networks in Finland are close to the end of their life cycle anyway, which makes it advisable and cost-effective to start replacing the old network with more resilient smart grid network, starting from the most vulnerable parts of the network.

ELECTRICITY DISTRIBUTION NETWORK VULNERABILITIES

The most vulnerable part of the electricity distribution system to extreme weather conditions is overhead lines that can be damaged by trees and tree branches falling onto them during storms. Heavy snowfall or accumulation of wet snow can also bend trees onto the bare conductors, which will lead to customers connected to that circuit to lose access to electricity supply until the trees are removed and the equipment reset. A toppled tree can also bring down pylons used for holding up the overhead lines. Whether or not the ground is frozen has a significant impact on the extent of storm damages.

More than 90 % of the electricity supply interruptions experienced by consumers in Finland are due to faults in distribution networks [1]. Disruptions occur in regional and transmission networks as well, but in meshed networks they can typically be isolated and bypassed in a way that they do not reach the customers. In disruptions in the distribution networks, medium-voltage networks play a major role. A fault in the medium-voltage network that cannot be cleared with automatic reclosing operations triggers network protection that typically leaves several hundreds of customers without access to electricity until the fault is isolated and the electricity flow can be rerouted. Of the medium-voltage network of 1-45 kV, only 16.2 % is underground cables, which leaves 83.8 % of the medium-voltage network vulnerable to the impacts of extreme weather conditions [2]. Additionally, 51 % of the bare overhead lines, and 56 % of all overhead lines of the medium-voltage network are located in forests [3]. During the span of 2010-2014, average of 56 % of interruptions per year were caused by extreme weather, causing an average of 72.2 % of the interruptions time-wise per year [2]. The average total duration of interruptions a customer experienced, including also planned interruptions, was 3.98 hours, i.e. 3 hours and 59 minutes. The total interruption duration average ranged from 1.85 hours in 2014 to 8.15 hours in 2011.

Table 1 Interruption amounts caused by different types of extreme weather (% of total interruption amounts).

Impact of extreme weather	2014	2013	2012	2011	2010	Average (2010-2014)
Wind and storm	25	39	22	37	22	29
Snow and ice loads	12	7	24	14	19	15,2
Thunderstorm	17	9	7	11	10	10,8
Other weather	1	1	1	1	1	1
Extreme weather TOTAL	**55**	**56**	**54**	**63**	**52**	**56**

Table 2 Interruption durations caused by different types of extreme weather (% of total interruption durations).

Impact of extreme weather	2014	2013	2012	2011	2010	Average (2010-2014)
Wind and storm	31	69	25	69	51	49
Snow and ice loads	19	4	31	11	12	15,4
Thunderstorm	13	6	4	3	9	7
Other weather	1	1	1	0	1	0,8
Extreme weather TOTAL	**64**	**80**	**61**	**83**	**73**	**72,2**

During 2010-2014, average of 29 % of all interruptions per year in the electricity supply in Finland were caused by lengthy, strong winds formed by low-pressure storms or recurring storm fronts, making them by far the biggest individual threat to electricity distribution network stability. Duration-wise, winds and storms formed an even bigger share of the total, average of 49 % of the total duration of interruptions per year. On average, they caused 1.71 interruptions per customer per year in countryside (cabling rate below 30 %), 0.37 interruptions in urban areas (cabling rate 30-75 %), and 0.04 interruptions in city areas (cabling rate over 75 %). The average interruption durations caused by winds and storms per customer per year on average were 4.55 hours in countryside, 0.64 hours in urban areas, and 0.03 hours in city areas. [2]

DSOs do not own the land beneath the power lines, and even though they have the right to clear the trees that pose a risk for the lines [4], strong wind can cause a tree or a part of it from outside the designated tree-clearance area, or right-of-way, to topple or break onto the overhead line. The width of the right-of-way depends on the type of the power line; for bare 20 kV overhead lines it is usually 10 metres, for 20 kV insulated conductors 6 meters. The width is agreed with the land owner in a contract on the power line right-of-way [5].

During 2010-2014, an average of 15.2 % of all interruptions in electricity supply per year were caused by snow and ice loads. Of the total duration of the interruptions, snow and ice loads were responsible for 15.4 % per year on average. They caused 0.92 interruptions on countryside per year, 0.11 interruptions in urban areas, and 0.02 interruptions in city areas on average. The total durations caused by snow and ice loads per year were 1.25 hours on countryside, 0.13 hours in urban areas and 0.02 hours in city areas on average. [2]

NETWORK RESILIENCE IMPROVEMENTS

Figure 1 Crisis management cycle

The methods discussed in this paper are divided into the four phases of the crisis management cycle: preparedness, response, recovery and mitigation. Even though extreme weather events and conditions are erratic in nature and their occurrence unpredictable, their occasional emergence and recurrence is virtually inevitable. Preparedness is the phase before a crisis has happened, where DSOs, municipalities, rescue authorities and other parties responsible for critical infrastructure or governmental services make plans on how to respond to a given incident. Following an occurring crisis, response phase is where preparedness plans are executed and there are attempts to reduce further damages. Recovery phase includes actions taken to return to the normal situation following a crisis. Mitigation phase measures are implemented in order to prevent future emergencies or at least to decrease their likelihood, or to minimize the effects of an unavoidable event. This will feed back into the preparedness phase with updated plans in place to deal with future emergencies.

<u>Preparedness: Adjacent forest management, inspections and emergency power systems</u>

Where overhead lines are located in forests, surrounding their rights-of-way is the adjacent forest that is outside the right-of-way, but from which trees can still, due to strong wind or heavy snow loads, bend and connect with the overhead lines or fall-in onto them. While it is essential to keep the rights-of-way cleared from trees and anything else that could threaten the overhead lines hanging above, understanding and managing the adjacent forest is also a key to reducing tree-related disruptions in electricity distribution. The goal is to achieve an adjacent forest with such a structure that it will grow into withstanding the strains put on it by snow loads and storms better than an unmanaged forest.

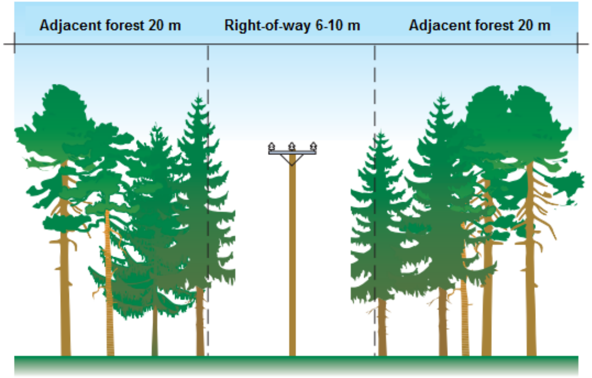

Figure 2 Typical widths of a right-of-way cleared of any trees and adjacent forests surrounding it. [5]

Benefits of the management of the adjacent forests are fast and wide effectiveness and moderate costs. Management of adjacent forests during seedling and first thinning phases reduces bending of broad-leaved trees in particular onto the overhead lines under the weight of heavy snow loads. Thinnings help remaining trees grow more robust quicker, which also mitigates impacts of storms long-term and is also a benefit for landowners as a healthy forest returns best profits. Management of the adjacent forests can be done by landowners, but also by DSOs with the landowner’s permission, usually by purchasing the services from forestry companies. [3]

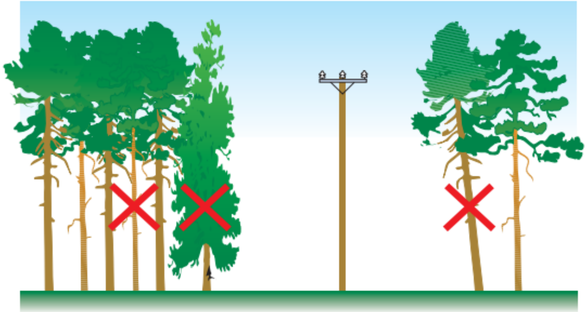

Figure 3 Damaged or tilted trees as well as tall but slender broad-leaved trees should be removed from the adjacent forests. [5]

Periodic inspections of the electricity distribution network are necessary for estimating the maintenance needs of the network and for detecting faulty or damaged network components. The inspections have traditionally been made patrolling the rights-of-way by foot, by all-terrain vehicles or by snowmobiles. [6]

Aerial inspections from helicopters can make the periodic inspections more effective and more standardized. The network condition can be efficiently and reliably inspected by equipping the helicopters with different sensory devices to cost-effectively maximize the observation data. The devices may include, for example, two 2D cameras for photographing front and back, a camera for an overview and an airborne laser scanning (ALS) system [6]. ALS produces accurate topographic data without the need for any field surveying. Sometimes a thermographic camera can also be included. The aerial inspections are usually done by photographing both frontwards and backwards from the helicopter, or sometimes flying adjacent to the overhead lines. The gathered data can then later be virtually “flown” again on a computer, which allows for detailed observations of the network.

Helicopter inspections are also essential for forming situational awareness during and after a blackout. Finding and accessing the fault locations by ground vehicles or by foot can be difficult or impossible right after a storm or a heavy snow-fall before roads have been cleared, which is when the use of helicopters is particularly advantageous.

Even with increased underground cabling rate and proper adjacent forest management, disruptions in electricity distribution are bound to happen occasionally. Thus, owners of critical infrastructures (e.g. water supply and wastewater treatment), municipalities, authorities and other critical customers (e.g. farms, hospitals) should consider emergency power systems to secure electricity supply in case of a blackout.

Response: Situational awareness

Council of State states in its Decision in Principle from 2010 that in order to function, every organization needs information about its environment and the events happening in it, and their impacts on the organizations own operations [7]. The Decision in Principle defines situational awareness as a presentation of a situation or performance abilities based on a collection of sporadic pieces of information. The situational awareness should provide decision-makers and their assistants an understanding of what has happened, circumstances that led to that, the goals of different stakeholders, and potential alternatives on how the event still might develop. In short, the idea of situational awareness is to understand what led to the event, what is happening at the moment, and what is likely to happen next. Situational awareness is a tool for quick decision-making and actions based on good understanding of an event and reliable predictions on its evolution.

The significance of situational awareness is emphasized during disruptive events, where broad decisions must be made quickly. During extreme weather conditions, such as winter storms, DSOs might suddenly experience lots of new faults within a short time period, and keeping on top of the situation gets difficult fast. The Electricity Market Act states that a grid operator must, in a disruptive situation, cooperate with other grid operators as well as rescue authorities, police, and other relevant authorities to clear the faults and limit their effects [4]. It also states that the operator must participate in forming the situational awareness within their operating area, and also deliver the necessary information to the authority responsible for forming situational awareness.

A DSO’s situational awareness may include information about the network and the status of its topology, faults and storm damages, customers and their priorities, weather conditions, available resources, materials and spare parts and operations related to electricity distribution. Information for the situational awareness should mainly come directly from the back-end systems to ensure that the situational awareness stays current. Forming situational awareness quickly requires active scouting that takes advantage of multiple simultaneous methods or tools, such as helicopter inspections, smart meters, reports from customers and ground staff and by patrolling the grounds and utilizing unmanned aerial vehicles. Aerial photographs taken from the stratosphere could be used to form situational awareness and estimate the extent of storm damages during broad blackouts [6]; however, accurate photographs would need to be delivered quickly to keep the information current.

Recovery: Distributed generation and microgrids

Distributed generation (DG) and distributed energy resources as a whole are an essential aspect of smart grid as a future of the distribution network. They can help improve power quality and reliability of power supply. Integration of DG into the electrical grid can help reduce the amount of energy lost in distribution because production happens close to the load and reduce environmental impacts because renewable energy sources are usually used. Other benefits of DG integration can include peak load shaving, increased overall energy efficiency, relieved distribution congestion, voltage support and better quality of supply at lower costs. It can also help defer investments to upgrade existing generation, transmission and distribution systems [8].

DG can help consumers and businesses to become less dependent on centralized energy production and more self-sufficient energy-wise. Use of, for instance, small-scale wind turbines or solar panels for electricity production can help improve the security of supply like a diesel generator can, although there are distinctions between them. Whereas a diesel generator can produce uniform quality electricity on demand if refuelled properly but is noisy and runs with fossil fuel, solar power system produces clean energy with hardly any marginal cost given that there is enough insolation. A combination of a solar power system and a battery can, however, reduce the need for an actual backup power generator and the investment and fuel costs associated with it because of a lower need for electricity generation [9]. Another benefit of DG is that consumers may become more aware of their energy consumption than previously, which may lead them to make more conscious and energy-efficient decisions in their every-day life.

Contrary to the traditional, centralized electrical grid, a microgrid is a localized small-scale, typically low-voltage, grid that utilizes smart grid features and often includes DG and backup power generation. In case a fault occurs on the main grid, a microgrid can be separated from it automatically or manually and continue to function as an island. A microgrid’s ability to sustain its operations while the main grid is experiencing disruptions means customers or communities within the microgrid will experience less power outages. Mitigating the grid disturbances this way makes these communities more energy self-sufficient and helps them to strengthen their grid resilience. Local power generation and storage allow critical facilities to operate independent of the main grid when necessary and prevent blackouts.

Mitigation: Placement of overhead lines, underground cabling, UAVs

As the objective of building the networks has today shifted from minimizing material costs to improving reliability and security of supply, building new lines next to roads is advisable for many reasons. Firstly, lines that are located next to a road are significantly easier to maintain and repair in case of a fault. Secondly, moving the existing lines and building new ones next to roads almost halves the number of tree-related faults in those parts of the network [1]. Placing the lines alongside roads is also a more environment-friendly solution as it utilizes the areas already once cleared for road use. Furthermore, the lines should be installed on that side of the road towards which the wind usually blows to further reduce the risk of a tree falling onto the line.

The single most effective technological solution to improve the resilience of the electricity distribution networks is underground cabling, because it replaces the most vulnerable and disruption-prone part of the networks, the overhead lines. Underground cables are not affected by storms, snow loads, lightning or other extreme weather conditions. While natural phenomena was the reason for averagely 47.8 % of all interruptions on bare overhead conductors per year during 2010-2014, in underground cables the corresponding share was just 4.4 %. The disruption frequencies in underground cables were only 0.06 faults per 100 kilometres, whereas on bare overhead conductors they were 5.82 (Table 3) [2]. Underground cables reserve much narrower surrounding strip of land compared to overhead lines. Use of underground cabling is also more environmentally friendly in a sense that it does not require maintenance of a wide right-of-way and the adjacent forest, and neither do underground cables interfere with wildlife. Burying the cables may also increase property values compared to overhead lines.

Table 3 Nature-related disruption frequency in lines and cables (disruption amounts per 100 kilometres of different types of power lines). [2]

Power line type	**2014**	**2013**	**2012**	**2011**	**2010**	**Average (2010-2014)**
Bare overhead conductor	5,57	6,42	5	6,43	5,68	5,82
PAS insulated overhead line	0,38	0,45	0,37	0,39	0,27	0,37
Aerial cable	0,22	0,35	0,15	0,14	0,06	0,18
Underground cable	0,04	0,03	0,03	0,05	0,14	0,06

Advancements in electric motors and battery technologies in the past 10 years have made unmanned aerial vehicles (UAVs) an appealing alternative to helicopters in network inspections, and they are expected to provide virtually the same benefits as traditional helicopters but for a significantly lower price [6].

Modern UAVs can be operated by an autopilot assisted by satellite navigation and an inertial measurement unit along a pre-programmed route. Operators of the UAV can observe the flight via a video link and if necessary, take manual control of the UAV. Utilization of UAVs in periodic inspections of the electricity distribution network is likely to become techno-economically competitive compared to traditional helicopter flights in the near future [6]. Utilizing them during extensive blackouts for gathering situational awareness data will take slightly longer as it requires operating partly within controlled airspace. In locating faults in single, geographically restricted areas, UAVs will be practical very soon.

CONCLUSIONS

Medium-voltage bare overhead lines located in forests were found to be by far the most vulnerable part of the electricity distribution network as a single tree toppling or bending onto the line due to storms or snow loads can cause a disruption. They are also a major part of the distribution network, forming more than half of it. Strong winds and storms were found to cause the largest share of weather-related disruptions, followed by snow loads.

The resilience of the electricity distribution networks can be significantly improved by proper adjacent forest management, aerial inspections, situational awareness systems, DG and microgrids, better placement of overhead lines, underground cabling and emergency power systems.

REFERENCES

[1] E. Lakervi and J. Partanen, 'Sähkönjakelutekniikka'. Gaudeamus, p. 294, 2008.
[2] Finnish Energy, 'Sähkön keskeytystilastot', 2010-2014. http://energia.fi/tilastot-ja-julkaisut/sahkotilastot/sahkon-keskeytystilastot.
[3] TAPIO, 'Keskijännitteisten ilmajohtojen toimintavarmuuden parantaminen', 2013. http://185.26.50.147/wp-content/uploads/2015/05/Osaraporttien_tiivistelma.pdf
[4] Finlex, 'Sähkömarkkinalaki', 2013. http://www.finlex.fi/fi/laki/alkup/2013/20130588
[5] Finnish Energy, 'Johtoalueiden vierimetsien hoito', 2010. https://www.oulunenergia.fi/sites/default/files/attachments/johtoalueiden_vierimetsien_hoito.pdf
[6] J. Tervo, 'Lentorobotit sähköverkon tarkastuksissa', 2014. http://energia.fi/sites/default/files/lentorobotit_sahkoverkon_tarkastuksissa_2014.pdf
[7] Council of State of Finland, 'Decision in Principle', 2010. http://www.defmin.fi/files/1696/Yhteiskunnan_turvallisuusstrategia_2010.pdf.
[8] P. Chiradeja, 'Benefit of Distributed Generation: A Line Loss Reduction Analysis', 2005. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1546964&tag=1
[9] R. Pasonen and H. Hoang, 'Micrograds and DER in community planning', 2014. http://www.vtt.fi/inf/pdf/technology/2014/T189.pdf