DEALING WITH MAJOR STORMS IN ASSET MANAGEMENT

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ABSTRACT

The storm Dagmar hit North-Western and inner parts of Norway on Christmas Day 2011, causing devastating damages of power lines and interruptions for about 570 000 end-users. The duration varied from a few hours up to several days. A similar event happened twenty years earlier on New Year Day (1st of January 1992) more or less in the same parts of Norway. Most of the damages were in both cases caused by extensive tree-fall which also hampered the repair and restoration work. The power grid is vulnerable to natural hazards of such extent even if it is designed for and usually robust towards weather related stress. This paper gives a comparison of Dagmar and the storm on New Year Day, and with the storms Gudrun and Per in Southern Sweden in 2005 and 2007, respectively, as far as information is available. The paper also addresses the identification of critical assets and indicators to monitor vulnerabilities as part of the asset management dealing with extraordinary events.

INTRODUCTION

Dagmar was the strongest storm in Norway since 1992, when a similar storm hit almost the same parts of Norway on New Year Day. Dagmar also caused wide-area interruptions in Finland and Sweden, however, affecting Sweden to a lesser degree than by the major storms Gudrun (2005) and Per (2007). Such extraordinary or exceptional events causing wide-area interruptions with severe impact on society, are also referred to as major events, big storm events, force majeure events and blackouts or high impact low probability (HILP) events [1-5].

The storm Dagmar revealed the power lines' vulnerability towards weather related stresses and emphasized the importance of including extraordinary events in asset management. Learning from major events is important to increase the understanding of such events, to identify vulnerabilities and improve the network companies' emergency preparedness. The high societal impact and the lessons learnt have also increased the awareness of politicians and energy regulators, triggering changes in the quality of supply (QoS) regulation. Examples are the "Gudrun laws" in Sweden, mandatory risk and vulnerability analyses and monetary compensation of long interruptions lasting for more than 12 hours [6-8]. In the Norwegian compensation arrangement (USLA) the end-users are entitled to compensation after 12 hours of interruption, the amount increases in steps according to the duration [8]. This compensation comes in addition to the cost of energy not supplied arrangement (CENS) which is an incentive based regulation to ensure an optimal resource allocation when all minimum requirements are complied with and is covered by the network company [9]. There is no provision on force majeure in the Norwegian QoS regulations. The amounts of USLA and CENS, as a result of Dagmar, added up to several times the normal amounts on a yearly basis for some of the affected network companies. Hence, there has been a discussion following Dagmar whether these financial arrangements should be applied during extraordinary events or not.

This paper gives a comparison of Dagmar and the New Year Day storm with the storms Gudrun and Per in Sweden, of end-users affected, societal costs, repair costs etc., emergency preparedness and experiences, as far as the available information renders it possible. In all these major storms, the main causes of damage of the power lines and interruptions were the strong winds and extensive tree-fall. The paper also addresses the identification of critical assets and indicators to monitor vulnerabilities as part of the asset management dealing with extraordinary events.

THE POWER GRIDS VULNERABILITY TOWARDS WEATHER RELATED STRESSES - EXPERIENCES FROM STORMS

Vulnerability

Today's society is highly dependent on a reliable power supply and there is a strong focus on reliability among network companies and in the power sector in general. In an on-going research project indicators and methods are being developed for monitoring vulnerabilities in the power system, related to wide-area interruptions with severe impact on society. The work is performed in collaboration with Norwegian network companies, the transmission system operator, the energy regulator and electrical safety authority.

Vulnerability of a power system towards extraordinary events is defined to be an *expression for the problems a system faces to maintain its function if a threat leads to an unwanted event and the problems the systems faces to resume its activities after the event occurred. A system is vulnerable if it fails to carry out its intended function, the capacity is significantly reduced, or the system has problems recovering to normal function. Vulnerability is an internal characteristic of the system* [10]. Vulnerability is dependent on many factors and can mainly be divided into susceptibility and coping capacity, see Figure 1.

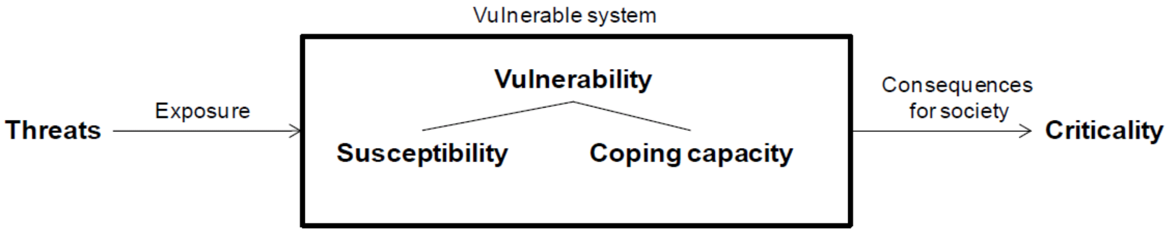

Figure 1 Vulnerability of a power system

Extraordinary events

Storms are threats that can lead to unwanted events in the power system, and may develop into extraordinary events characterized by low probability and large consequences. Extraordinary events are difficult to foresee and prepare for in a good way, even for experienced personnel. Weather related events and events caused by other natural hazards are often characterized by long-lasting interruptions and the need for extensive repair of the power system. In the case of the storms mentioned above, they hit a large geographical area and caused interruptions for many end-users. Extraordinary events tend to be an expensive experience for the network companies, making it important to focus on emergency preparedness and have good knowledge of the vulnerability of the power grid.

Affected end-users

Dagmar resulted in several faults in the main grid, but most of the faults were on the medium and low voltage levels. The main causes of the faults were strong wind and tree-fall, which resulted in wide spread interruptions with long durations [11]. Tree-fall caused extensive damages on the power lines, telecommunication lines and roads. The combination of these damages made the restoration work difficult, thus enhancing the duration of the interruptions. The numbers of end-users affected and duration of the interruptions for some of the strongest storm events in Norway and Sweden the last twenty years are presented in Table 1, and can be used to see Dagmar in perspective.

Table 1 Consequences after a selection of storms in Norway and Sweden the last twenty years

Storm	Number of affected end-users	Weighted or stipulated average duration of interruption	Longest interruption duration
New Year Day 1992, Norway	270 000	45 hours	6 days
Gudrun 2005, Sweden	730 000	79 hours	35 days
Per 2007, Sweden	440 000	?	8 days
Dagmar 2011, Norway	570 000	15 hours	10 days
Dagmar 2011, Sweden	170 000	?	15 days

In Table 1 it is shown that Gudrun and Dagmar caused interruptions for the largest amount of end-users and also the longest interruptions. The longest interruption for end-users during Gudrun was over one month, during Dagmar it was approximately 2 weeks, during Per it was 8 days and during the New Year Day storm in 1992 it was 6 days. These durations shows that even though a lot of end-users were affected during Dagmar the interruptions lasted for shorter time compared to Gudrun.

The two storms in Norway, on the New Year Day and Dagmar were quite similar. Dagmar hit a larger part of Norway, but the largest consequences appeared in the same area as the New

Year Day storm in 1992. Preliminary data from Dagmar shows that the event caused about 17,3 GWh energy not supplied and it is likely that this sum will increase when the analysis of the event is complete. The New Year Day storm caused 16,4 GWh. The development of energy not supplied for the last twenty years is shown in Figure 2, both including and excluding the data for the New Year Day storm and Dagmar in the respective years.

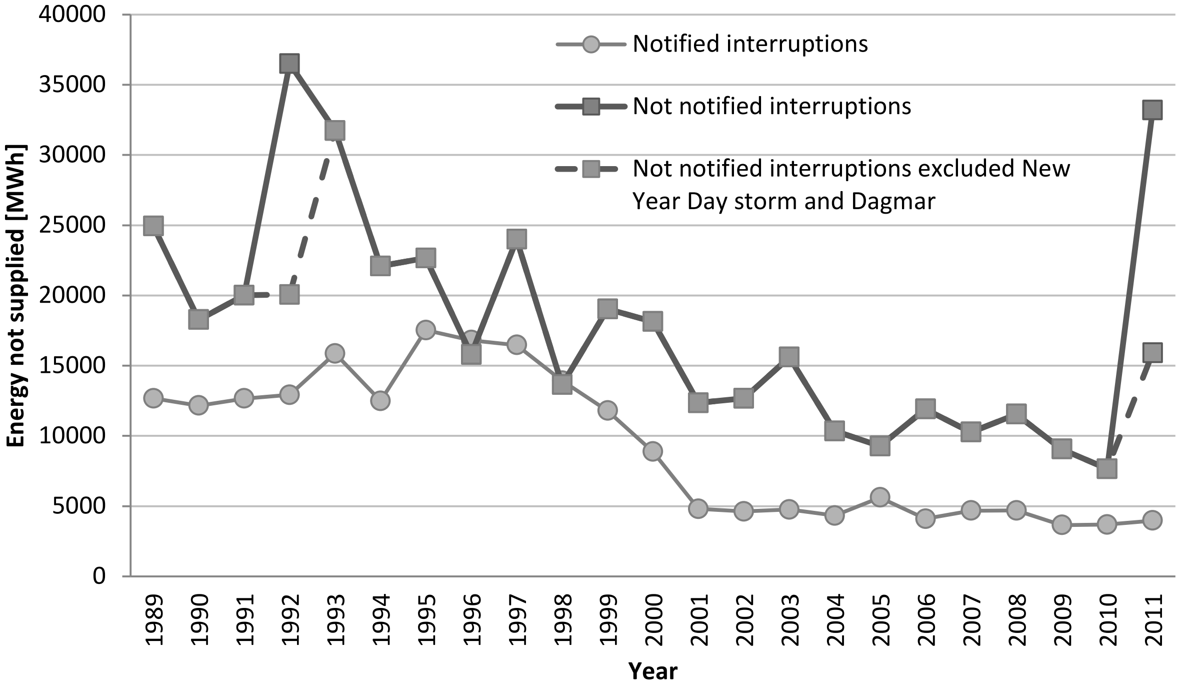

Figure 2 Development of energy not supplied in Norway the last twenty years, distributed on notified and not notified interruptions

There is an evident trend that energy not supplied (ENS) has decreased considerably over the ten year period before 2011. Even if Dagmar is excluded from the statistics in 2011, this year deviates from the trend, due to other extraordinary events and extensive faults in the power grid. The amount of ENS in 2011 without Dagmar is comparable to the year 2003 which also had more faults than the years before and after. The decreasing trend in ENS may partly be explained by the increased focus on reliable power supply in the later years. Network companies learn from previous events and improve their methods of handling similar weather related extraordinary events and the emergency preparedness. Examples of this are the increasing shares of cables in the medium voltage network [6], increased focus on reliability in regulation and practicing on the preparedness for extraordinary events.

Better coping capacity

Coping capacity is a characteristic describing how the power system is able to return to a normal situation after an unwanted event has occurred. Examples of factors that will influence the coping capacity are the knowledge of the grid operators, redundancy in the grid and the available equipment and crew for restoration after extensive damage. During Dagmar some areas were successfully operated as islands and were able to maintain operation because of local generation. This contributed a great deal to limit the consequences of the storm.

The coping capacity is assumed to have improved after the New Year Day storm, based on the reduced duration of the interruptions (on average). Both storms caused the largest damages more or less in the same area. During Dagmar a total of 570 000 end-users were affected but only approx. 35 600 for more than 24 hours. In 1992 the total amount of end-users affected was only 270 000 and approx. 52 000 for more than 24 hours. Hence, 94 % of the affected end-users were reconnected within 24 hours during Dagmar and 81 % during New Year Day storm. While extreme weather forecast was not available in advance of the storm in 1992, ahead of Dagmar such forecast enabled the network companies to prepare for the event and to activate their contingency plans. There has also been a development in the availability of equipment and tools, which contributes to more rapid restoration work.

Figure 3 shows a consequence diagram in two dimensions, illustrating disconnected load versus the stipulated duration of the interruptions, based on [12]. The consequence of an interruption is not only dependent on the duration, but also the amount of load disconnected. This parameter provides information about the magnitude of the event and the area and number of end-users affected by it. The figure shows that Dagmar had the largest disconnected load while Gudrun had the longest interruption. The Gudrun event in Norway is also included to show that although the same storm, it caused rather limited consequences in Norway and is not regarded as an extraordinary event. The figure even shows the event in Steigen in 2007, where only the regional and distribution networks were affected and a small community lost its power supply for 6 days.

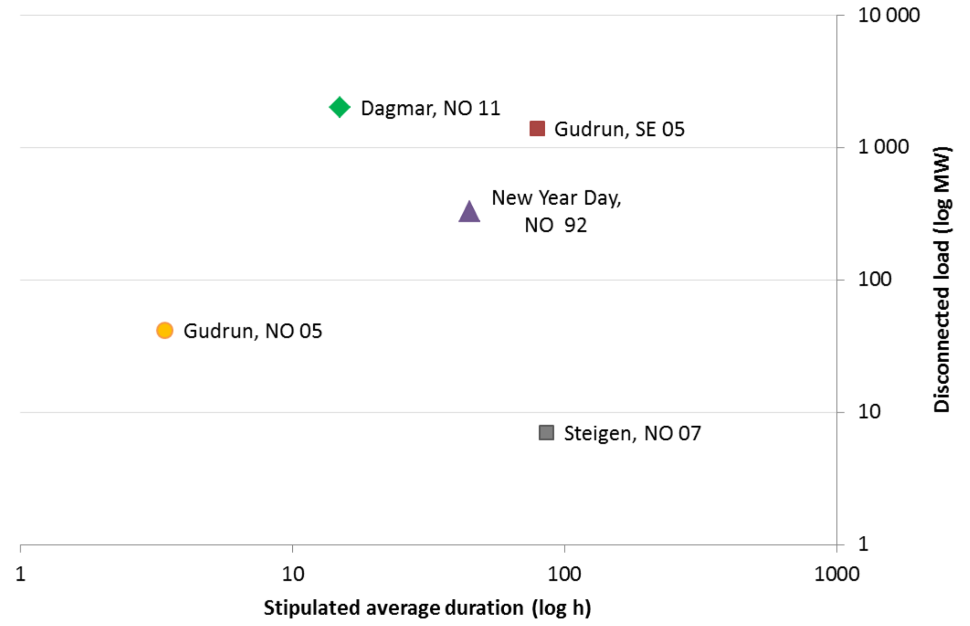

Figure 3 Consequence diagram for extraordinary historical weather events, based on [12]. Note that the values for "Dagmar, NO 11" are preliminary.

Interdependencies between critical infrastructures

The society is developing to be more and more dependent on a reliable power supply, and the dependency between different infrastructures is increasing. Dependencies that have shown to be important during extraordinary weather events are the power supply, communication and transportation. Extreme weather causes severe damages on power lines, telecommunication lines as well as roads, creating a very demanding working environment for the restoration crew. All these factors contribute to hamper the restoration work and enhance the duration of interruptions.

Communication is critical both for susceptibility and coping capacity in the power grid. During Dagmar and New Year Day storm there were devastating damages on the telecommunication lines and a lot of base stations lost power supply. This complicated the coordination of the restoration work and the distribution of information to end-users and others. During Dagmar also the emergency communication broke down in some areas, resulting in a potentially critical situation for the society and a risk for life and health. Such events underline the importance of focusing on the dependency between infrastructures in emergency preparedness plans.

The introduction of smart grid technologies will increase this dependency even more, mainly between the power and the communication systems, potentially leading to larger impact of interruptions in the future.

Economic consequences

The duration of the interruptions has a high influence on the economic consequences after wide-area interruptions. The cost of energy not supplied (CENS) is a function of duration, type of end-users affected and number of end-users affected. Due to limited detailed information about the storms Gudrun and Per, we will here only present the storm in 1992 and Dagmar in Norway. Table 2 presents a comparison of the economic consequences after these two events [13,14].

Table 2 Economic consequences of the New Year Day storm and Dagmar in Norway, referred to 2012 values in MNOK

	New Year Day 1992	Dagmar 2011, Norway
CENS/Interruption cost	225*	454
Compensation after long lasting interruptions (> 12 hours)		110
Repair cost	140	142
Total cost	365	706

* Stipulated interruption cost, CENS was introduced in 2001

The consequences of Dagmar were largest in the same area as the New Year Day storm, i.e., in North Western parts of Norway. In both cases the tree-fall required extensive restoration work, and this is reflected in comparable size of the repair cost, see Table 2. The interruption cost (CENS) is almost doubled after Dagmar compared to 1992, partly reflecting the larger amount of end-users affected and partly increased cost rates.

Table 2 only presents the direct cost because of damages in the power grid. If the total impact on society, i.e. repair of roads, buildings etc., is included the amounts would increase drastically. After the New Year Day storm the total cost was over one billion NOK (in 1992-NOK), and the cost after Dagmar can be assumed to be even larger.

INDICATORS AND METHODS FOR MONITORING VULNERABILITIES OF THE POWER GRID

Indicators

Identification of critical assets and indicators for monitoring vulnerabilities are important in the dealing with extraordinary events. Here, the term critical refers to elements with potentials for severe consequences, i.e., elements being significant for the reliability of supply. Indicators give information about different characteristics of the power system, and how vulnerable it is towards threats. Important indicators for extraordinary events related to storms are the quality of vegetation management, technical condition of the grid and knowledge and experience of the working staff. Such indicators can partly help to reduce the susceptibility towards the threat and partly to increase the coping capacity after an unwanted event has occurred and limit the consequences.

One challenge in risk and vulnerability analysis is the ability to include the most unlikely and unfortunate combinations of faults, while the network companies have to prepare for the worst scenarios. Indicators can help to identify these kinds of combinations if the indicators are identified with a reliable method and the personnel have knowledge to use them.

Vulnerability indicators should address different aspects regarding the vulnerability and cover both the susceptibility and coping capacity (cf. Figure 1). However, vulnerability can only be seen in relation to threats. Thus, vulnerability indicators should also cover threats that the system is exposed to. Finally, the criticality for society has to be considered to assess the potential of severe consequences. In principle, there is one set of indicators for each identified threat. However, the criticality and the coping capacity are more or less independent of a specific threat.

Critical assets, locations, etc., will depend on various conditions, varying among the network companies. The critical factors must be identified by each network company through a risk and vulnerability analysis using tools like preliminary hazard analysis, contingency analysis and brainstorming/ expert evaluation. Usually there is a need to combine different quantitative and qualitative methods [15].

Various categories of threats and vulnerability aspects are dealt with in the on-going project, as described in [10, 16]. Case-studies are performed for the purpose of identification of vulnerabilities and exemplifying indicators. Examples of vulnerability indicators for weather-related threats like storms are given in the following, based on a case study of the Steigen-event in Figure 2 [10].

Case study

Steigen is a small community located far north in Norway (latitude 68°) in a coastal area exposed to wind and icing. The community has less than 3000 inhabitants and is normally supplied by a single 66 kV overhead line while there is another line on hot stand-by. The stand-by line can be connected if the main line fails. Both lines are routed in a coastal area with harsh weather conditions, making them exposed to failures and bad conditions for repair work. In the actual event in January 2007 Steigen lost its power supply for nearly 6 days due to failures and breakdown of both the 66 kV lines. Extreme weather conditions and lack of daylight delayed repair considerably.

The Steigen event was triggered by heavy storm while icing was a contributing cause. This led to breakage of the line itself and damage of several pylons. The reserve line turned out not to be able to cover the load when it was connected, resulting in overheating and three subsequent line breakages. The post event fault analysis showed that these faults were caused by ageing and poor technical condition. In the ten-year period before 2007, there had only been a few faults on 66 kV lines in this area, with limited consequences. Studying this period of the fault statistics gives no indication of any serious event about to happen. In a risk and vulnerability analysis however, it can be identified that overlapping faults of both lines supplying Steigen represent a critical outage since the whole community will be affected. There is no local generation in this area, and Steigen is therefore vulnerable to the loss of both lines. If such an event happens in winter the temperature might be a critical factor. In this case it can also be noted that the weather conditions as well as seasonal lack of daylight might threaten the coping capacity in terms of delayed repair and extended duration of the blackout compared to for instance in summer time.

The case study has identified the following susceptibilities for the main power line:

- Slanting pylons and inadequate foundation
- Arcing damage on line due to previous faults
- Inadequate choice of right of way (holds for both lines).

For the reserve line the main susceptibility was the poor technical condition due to ageing and degradation. Indicators are proposed for the threats ‘storm’ and ‘loading degree’ for this small regional network. Examples are presented in Table 3.

Table 3 Examples of indicators for the regional network in Steigen, based on [10]

Threat	Indicator for threat	Indicator for susceptibility	Indicator for coping capacity	Indicator for criticality
Storm	Wind prognosis (speed, direction, duration)	Location in the terrain, how exposed to wind? Technical condition of 66 kV power lines Competence on condition evaluation Competence on risk and vulnerability analysis	Competence on repair of 66 kV power lines Availability of spare parts, and transport for repair of power lines Availability of communication systems and reserve generating units	Location of critical loads Types of end-users Temperature
Loading degree	Percentage loading compared to nominal values			
	Increase in loading degree			

The critical assets in this case are the two 66 kV overhead lines. Appropriate susceptibility indicators are therefore the technical condition of 66 kV power lines itself as well as the competence on condition evaluation. The technical condition is an important susceptibility towards both threats ‘storm’ and ‘loading degree’. Correspondingly, an appropriate indicator for coping capacity is the competence on repair of 66 kV lines as well as availability of spare parts and transport for repair of the overhead lines. Other indicators for the coping capacity are of a more general character, such as availability of communication systems and reserve generating units. From Table 3 it can be observed that the indicators for the criticality (consequences to society) are independent of the threat.

The case study revealed that the part of the main power line where the fault was located (crossing a mountain-top) was particularly exposed to strong winds. Access to the line for repair work was only possible by helicopter at this time of the year (January, lots of snow), and the coping capacity was hampered by the bad weather, snow and lack of daylight. Thus, to provide a vulnerability indicator capable of monitoring the technical condition of critical overhead lines, it is not only important to identify the critical assets (overhead lines) that are essential for the reliability of supply, but also the exposure to for instance strong winds and the access to the lines for repair and other factors of importance for the coping capacity. In this way it is possible to identify and monitor those parts of the critical lines which are the most vulnerable.

CONCLUSIONS

Dagmar is the strongest storm in Norway the last twenty years with regard to wide-area interruptions. Like the storm Gudrun in Southern Sweden in 2005, Dagmar caused devastating damages in the power grid, affecting a large amount of end-users. The event in Steigen only affected a small community but is a good example of the power grids' susceptibility towards storms and an unfortunate combination of events. Over the last twenty years the quality of supply regulation is gradually intensified and it can be assumed that the coping capacity has improved, illustrated by the decreasing trend of energy not supplied and the duration of interruptions for end-users. However, according to the meteorologists, we can expect more extreme weather in the future. It is therefore important to learn from major events like Dagmar, Gudrun and Steigen. The society will be more dependent on a reliable power supply, and it is important that network companies, the transmission system operator, the energy regulator and electrical safety authority have the right tools to deal with extraordinary events in the asset management. A good remedy for monitoring the grid is vulnerability indicators, which can cover both the susceptibility and coping capacity. Such indicators may contribute to prevent and limit the impact of major storms as well as other threats.

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