A FRAMEWORK FOR HANDLING HIGH IMPACT LOW PROBABILITY (HILP) EVENTS

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ABSTRACT

This paper describes a framework for handling HILP events. The framework uses a bow-tie model to structure some previous blackouts and extraordinary events in terms of identification of threats, unwanted events, consequences, emergency preparedness, vulnerabilities and barriers. The results of this analysis will be used in further work to identify needs for indicators and tools to monitor vulnerabilities.

INTRODUCTION

Wide-area interruptions in the electricity supply have severe impacts on society's critical functions. Such extraordinary events with high societal impact happen once in a while but are regarded to have low probability, and are often referred to as HILP (High Impact Low Probability) events.

In risk based asset management it is important to find the right trade-off between investments and maintenance on one side and the security of electricity supply (SoS) and societal impact of interruptions on the other. The security of supply is challenged by the ageing infrastructure, increasing climatic stress (e.g. wind, icing) and increased utilization of components etc. At the same time the distribution system is under change with growing shares of renewable distributed generation, transition to smart networks etc.

The quality and level of maintenance of the networks is of great concern for the authorities. For instance the new EU Directive on common rules for the internal electricity market states that these aspects should be monitored as part of the security of supply [1].

Controlling risks and vulnerabilities related to HILP events is an essential part of asset management. Previous studies have shown that there is a lack of knowledge on what is a sufficient or acceptable level of SoS and there is an identified need for a common framework to analyse extraordinary events [2]. New methods and tools are needed to deal with risks and vulnerabilities of the electricity system related to the future challenges.

This paper describes a framework for handling HILP events. The framework is under development in an ongoing research project in collaboration with Norwegian stakeholders, i.e. the energy regulator and electricity safety authority, the transmission system operator (TSO) and several distribution system operators (DSO). The framework described in this paper is used to structure and analyse some previous blackouts and extraordinary events. The results of this analysis will be used in further work to identify needs for indicators and tools to monitor vulnerabilities.

BLACKOUTS AND EXTRAORDINARY EVENTS

Power system failures occur occasionally in both the transmission and the distribution systems, most often with minor consequences. While the power system at the transmission level is usually dimensioned and operated according to the N-1 criterion, distribution systems are mostly operated as radials and any component outage due to a failure will lead to interruption of electricity supply. The duration may be rather limited depending on reserve supply possibilities, e.g. by closing open ring main units.

In distribution systems blackouts with severe consequences will most likely be caused by a combination of events, e.g. a storm causing damage on power lines or failures resulting in loss of service in interconnected infrastructures such as transport and telecommunication. The term blackout is here used for wide-area interruptions with severe consequences for society. These kinds of extraordinary or exceptional events [3] involving coinciding failures are regarded to have low probability but severe consequences. Many blackouts that have occurred during the last decades are thoroughly described in the literature [e.g. 4, 5, 6]. Some of these were selected for further analysis in the project using the framework described in this paper:

- Canada 1998 – Ice storm
- US / Canada 2003 – Cascade
- Sweden/Denmark 2003 – Voltage collapse
- Western Norway 2004 – Delayed protection response
- Sweden 2005 – Storm Gudrun
- Norway 2007 – Steigen: Storm and icing
- Norway 2007 – Oslo: Cable fire

The results of the analysis are illustrated for the three last events on the list, which are most relevant for the distribution system level.

FRAMEWORK FOR HILP EVENTS

The framework uses the bow tie-model as a starting point to describe the relations between main causes and consequences of an unwanted event. An example is given in Figure 1 below. The main unwanted events to be considered here are power system failures and the consequences in terms of wide-area interruptions or blackouts. This is shown in the figure below together with major categories of threats.

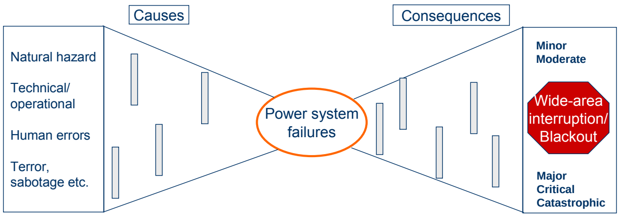

Figure 1 Threats, unwanted event, consequences and barriers

The threats include natural hazard (e.g. a major storm), technical/operational causes (e.g. ageing of overhead lines), human errors (e.g. digging) and antagonistic causes such as terror or sabotage. The threats might lead to power system failures through a set of causes, while the failure(s) might lead to minor or severe consequences through a set of circumstances. Figure 2 shows examples of types of consequences of interruptions for end-users and society.

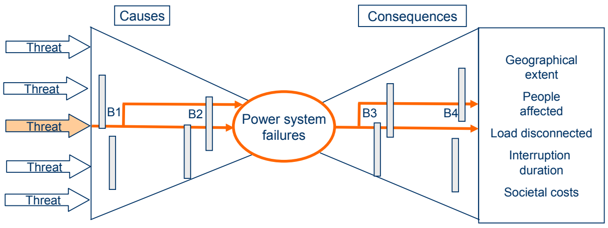

Figure 2 Chain of events and different barriers (B1- 4)

Figure 2 also illustrates that a certain threat may lead to a chain of events or different possible paths leading to the unwanted event. Likewise there may be different paths leading to various consequences. As indicated in the figure, a number of barriers exist to avoid threats to develop into unwanted events and to prevent or reduce the consequences. A system is more vulnerable towards the relevant threats if the barriers are weak or malfunctioning. There are different component or system oriented barriers to prevent failures, and different barriers related to restoration of supply and the end-users' consequences.

With reference to Figure 2 the barriers can be suitably grouped in four different types illustrated by examples:

- Prevent component failure (B1)
  - Vegetation management
- Prevent power system failure (B2)
  - Testing of protection settings
- Facilitate restoration (B3)
  - Standardisation of spare parts
- Reduce end-users consequences (B4)
  - Reserve supply units

In risk and vulnerability analysis of electric power systems a major challenge is to identify chains of events that could lead to wide-area interruptions. It is necessary to have knowledge about the underlying causes, and to determine and evaluate the consequences of these events.

There are several ways to describe the consequences of power system failures. Consequences can for instance be classified according to the amount of disconnected load and stipulated average (weighted) duration [2]. Figure 3 gives an example of a consequence diagram using the two dimensions for the studied blackouts. The duration is stipulated based on energy not supplied divided by interrupted power or end-user duration weighted by number of customers.

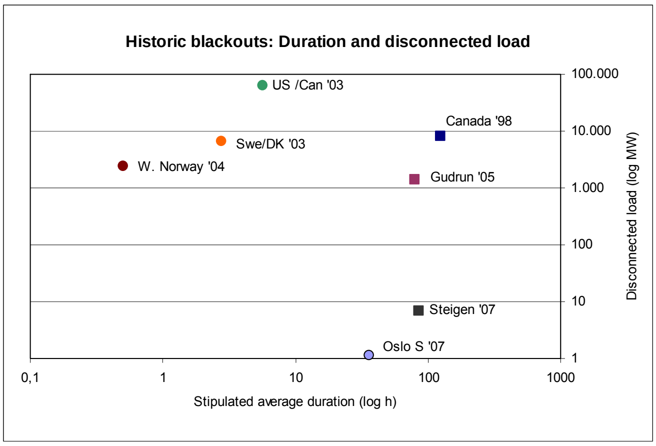

Figure 3 Consequence diagram

Blackouts normally involve loss of service in connected infrastructures such as transport, telecommunication and water supply. These consequences must be described to reveal the total societal consequences and the socio-economic costs, complementing illustrations like Figure 3.

ANALYSIS OF EVENTS

The results of the analysis using the framework are illustrated for the events in the distribution/sub-transmission systems, the storm Gudrun in Sweden (2005) and two extraordinary events in Norway in 2007: The loss of both power lines to the community Steigen caused by storm and icing and the cable fire at Oslo central station. As seen from Figure 3 these are rather small in terms of disconnected load compared with the events that have occurred in the transmission system, but they are large in terms of duration (especially the two weather-related events).

The bow-tie framework described in the previous chapter is used to structure the analysis, bringing the following aspects into focus [7]:

- Threats
- Unwanted events
- Final consequences for end-users
- Emergency preparedness, restoration of supply
- Vulnerabilities and barriers.

The events are briefly described in the following and the results are summarised at the end of the chapter.

Storm Gudrun, Sweden 2005 [6]

In January 2005 the storm "Gudrun" caused severe damage to electricity lines, other infrastructure and forests in southern Sweden. Extreme winds swept over the area, damaging more than 30 000 km of power lines (mainly distribution) and leaving 730 000 end-users without power. Millions of trees were uprooted or broken and caused severe damage as they hit the infrastructure.

The extent of the power failures in combination with unavailable roads and destroyed communication networks made the restoration of supply a challenging task. There was also a shortage of personnel and resources. Assistance was received from the military, volunteers and from network companies outside the affected area, including other countries. Approximately 50 % of the supply was restored within 24 hours, but thousands of end-users were without electricity for more than 20 days.

Gudrun was the worst storm in Sweden for 80 years. Forestry is a major industry in the area, making the infrastructure extra vulnerable in harsh weather conditions because it had to withstand both the strong winds and falling and broken trees and branches. Most of the area is quite sparsely populated, with long distribution lines and (at the time) limited use of underground cables.

Breakdown of both power lines to Steigen, Norway 2007 [8]

Steigen, which is a small community with less than 3000 inhabitants in Northern Norway, lost its power supply for nearly 6 days in January 2007 due to failures and breakdown of both 66 kV lines supplying the community. This event was triggered by heavy storm, and the repair work was delayed by the bad weather and lack of daylight. Power supply was partially and temporarily restored using a few reserve supply units, and the available capacity in the network was shared between the different zones by rotating connections.

Steigen is normally supplied by one 66 kV line while the other line is on stand-by (hot). However, this "stand-by line" which was more than 50 years old had deteriorated and the technical condition severely weakened. Both lines are routed in areas with harsh weather conditions, making them exposed to failures and bad conditions for repair work. There is no local generation in this area, and Steigen is vulnerable to the loss of both lines.

Fire at Oslo central station, Norway 2007 [9]

In November 2007 a minor fire in an 11 kV cable caused a power outage and evacuation of Oslo central station (Oslo S). There were ICT cables in the same culvert and several communication systems were interrupted, including train operation services and internet and phone services. 80 000 train passengers and more than 25000 telephone and internet customers were affected. It took 16 hours before the electricity supply was restored and another 4-5 hours before the central station was reopened for the public and the train traffic was resumed.

The cause of the fire was a permanent earth fault on another cable on the same transformer circuit, caused by digging activity in the area. The fact that many cables were placed in the same culvert and / or within the same fire cell made the system vulnerable. In addition there were a limited number of emergency generators available, which were not sufficiently tested, and thus did not function properly. The emergency preparedness was not adequately planned, and areas of responsibility were not properly defined.

Summary of events

The events are structured according to the bow-tie model and aspects as described above. Threats to the electricity system and unwanted events are summarised for the three extraordinary events in Table 1. "Gudrun '05" and "Steigen '07" were both caused by natural hazard, while "Oslo S '07" was initiated by human errors (digging). They all caused unwanted events in terms of power system failures on overhead lines and cables.

Table 1 Threats and unwanted events

Event	Threats	Unwanted events
Gudrun '05	Strong winds. Falling trees.	Severe damage to lines (distribution). Telecommunication, rail and road outage.
Steigen '07	Strong winds. Icing. Ageing.	Line breakages (regional and distribution).
Oslo S '07	Construction work.	Cable damage (distribution). Fire in cable culvert incl. ICT.

The consequences are given in Figure 3 above in terms of disconnected load and stipulated duration, while the restoration of supply and vulnerabilities are briefly described in the text above.
For the events caused by adverse weather (storm Gudrun, and the storm in Steigen), barriers related to the

facilitation of restoration and limiting end-users consequences by alternative energy supply and better information were identified as having the largest potentials for improvement. In Steigen for instance, there are plans for a hydro power station which will cover the whole consumption and improve the situation considerably in case of blackouts.

The extent of the failures, combined with damaged roads and communication system, and availability of personnel and other resources were major challenges during the storm Gudrun. For the case of Steigen the weather conditions delayed repair work for several days, even though personnel and equipment were available.

For the blackout at Oslo Central station the consequences in the power system were rather limited compared to the other events studied. The problems here were mostly related to inadequate back-up systems in connected infrastructure.

Table 2 shows a summary of the findings related to how different weak or inadequate barriers contributed to the course of events for the analysed blackouts.

Table 2 Inadequate barriers as contributing factors to the extraordinary events (partly based on [5])

Barriers	Sweden '05	Steigen '07	Oslo '07
Prevent component failure			
Strength and design of construction	●	O	O
Vegetation management and adequate choice of right-of-ways	●	O	
Condition monitoring		●	
Prevent power system failure			
Redundancy; reserve capacity		●	●
System operation response			O
Facilitate restoration			
Good and known restoration plan	O	O	O
Access to personnel and material	●		
Communication	●		
Coordination and clarification of responsibility	●	●	●
Reduce end-users consequences			
Alternative energy supply	●	●	●
Back-up in connected infrastructure			●
Information to the public	●	●	
*● Improvement potential. **O**: Some improvement potential*			

CONCLUSIONS AND FURTHER WORK

This paper has described a framework for analysing blackouts and extraordinary (HILP) events in the power system. The bow-tie model was used to structure the events in terms of identification of threats, unwanted events, consequences, emergency preparedness, vulnerabilities and barriers. The results of this analysis will be used in the further work concerning the identification of needs for indicators and tools to monitor vulnerabilities. In order to describe vulnerability, it is necessary to describe threats and presence and adequacy of barriers. The study of previous blackouts has, as expected, revealed that several barriers had inherent weaknesses and / or the threats were of a larger magnitude than the barriers were designed for. There is a need for indicators and models to describe such vulnerabilities. The described framework will help to classify events, identify barriers and vulnerability indicators, as well as need for tools to analyse HILP events.

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