VULNERABILITY IN POWER SYSTEMS
- THE EFFECT OF MAINTENANCE AND REINVESTMENTS

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ABSTRACT

Maintenance and reinvestments are vital parts of asset management for electricity transmission and distribution companies. They become even more important as the infrastructure ages and society's dependence on a secure electricity supply increases.

This paper discusses how maintenance and reinvestments affect vulnerability in the power system. Several historic blackouts were studied, and the Bow-tie model was used as a common structure to identify threats, unwanted events, barriers and vulnerabilities. Special focus was on determining whether barriers related to maintenance and reinvestment were present and adequate to protect against or limit the consequences of power system failures.

As expected, the analysis of the case studies reveals that several barriers had inherent weaknesses or that the threats were of a larger magnitude than the barriers were designed for. There is a need for indicators to describe this type of vulnerability, and analysis of historic blackouts provides valuable insight. Better knowledge about barriers can support identification and establishment of indicators to monitor and manage vulnerability.

Keywords: Vulnerability, Electricity, Power system, Maintenance and reinvestments, Bow-tie model, Barriers

INTRODUCTION

Modern society is increasingly more dependent on a secure electricity supply. At the same time, the power system is expected to undergo major changes in the coming years, raising questions such as: How do changing power flows, distributed generation and climatic change affect the vulnerability of the ageing power system? What is a sufficient level of maintenance and reinvestment? Is the energy industry developing its competence sufficiently to meet the new challenges?

Previous studies have revealed that there is a need for new knowledge for monitoring and managing vulnerability; see e.g. (Kjolle et al., 2006). Ongoing projects at SINTEF Energy

Research[1] seek to reduce this gap by developing methods and indicators to identify vulnerabilities related to wide-area interruptions with severe impact on society.

This paper addresses a part of this picture, focusing on how maintenance and reinvestment actions affect vulnerability, and the need for indicators to monitor and manage these effects.

FRAMEWORK

Vulnerability is primarily associated with events which have a potentially severe impact on society. For power system failures this implies long interruption duration, many people affected and/or loss of service in interconnected infrastructures such as transport, telecom and water supply. Power system failures with these kinds of extensive consequences are often referred to as blackouts.

Several historic blackouts have been studied, and the Bow-tie model was used as a common structure for the analysis. The framework is further described in (Kjolle et al., 2010). The focus of this paper is 1) how maintenance and reinvestment work as barriers to prevent power system failures and limit their consequence, and 2) how analysis of past events can reveal flaws in such barriers and help identify vulnerabilities.

The Bow-tie model

Figure 1 shows a so-called Bow-tie model for the event power system failure. The model describes the relations between threats, causes and consequences of an unwanted event. Threats and chain of causes are shown to the left, and chain of consequences is shown to the right. A number of barriers exist to prevent threats from developing into unwanted events and to prevent or reduce the consequences. The barriers can be grouped in four types according to their function:

- Prevent component failure (B1)
- Prevent power system failure (B2)
- Facilitate restoration (B3)
- Reduce end-users consequences (B4)

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[1] *Vulnerability and security in a changing power system: www.sintef.no/Projectweb/Vulnerability-and-security/*, *Risk based Distribution System Asset Management: www.energy.sintef.no/Prosjekt/RISKDSAM/*

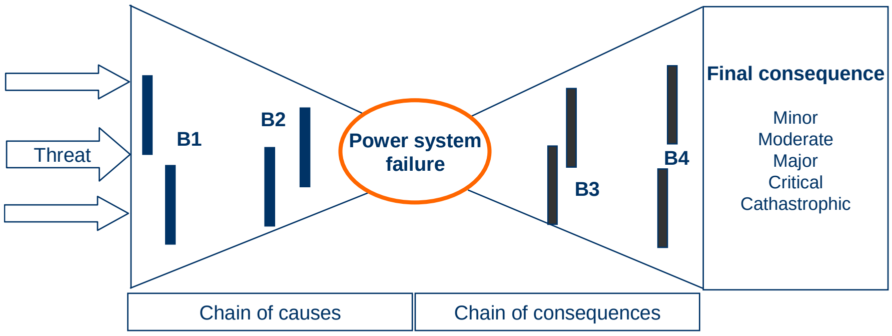

Figure 1 *A Bow tie model for the event power system failure. B1- B4 indicates different barriers.*

With reference to Figure 1, a system is vulnerable towards a threat when:

- There is a potential for severe consequences, and
- There is an insufficient number of barriers or the existing barriers have weaknesses, i.e. they may fail to function as intended.

Thus, in order to describe vulnerability, there is a need for indicators that provide information about the presence of threats, potential consequences, and the existence and adequacy of barriers.

Barrier analysis

Barriers can be defined as *"something that can either prevent an event from taking place or protect against its consequence"* (Hollnagel, 2004) or *"tasks that are necessary to adequately control a specific hazard"* (Rosness et al., 2004). This conception of the term "barrier" is not limited to physical systems such as fences or safety belts, but also include less tangible measures, such as procedures, rules and work culture.

Barrier analysis is a common discipline within accident investigation and system design (see e.g. Haddon, 1980 and Rosness et al., 2004), and involves identifying possible paths from threats to vulnerable targets, as well as identifying how introduction or reinforcement of barriers can limit or close these paths.

Figure 1 illustrates the presence of different barriers in the Bow-tie model. Another common illustration of the concept of different barriers is Reasons' Swiss cheese model (Figure 2). This model shows how a system with inadequate barriers (represented by holes in slices of cheese) allows threats to evolve into events with severe consequences.

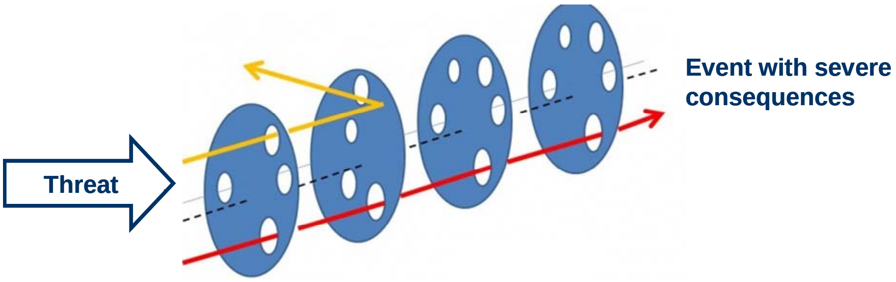

Figure 2   The Swiss cheese model (Reason, 1997)

Maintenance and reinvestment as barriers

Maintenance can be divided into two main categories: preventive maintenance and corrective maintenance (IEC, 1990).

Preventive maintenance includes activities to maintain or improve the condition of assets, or to provide information about assets and their condition (often referred to as condition monitoring). Vegetation management, i.e. trimming of vegetation near overhead lines, is a considerable part of the preventive maintenance.

Reinvestment typically involves more comprehensive and expensive measures (replacement or modification) than preventive maintenance, but the two activities are closely related. Corrective maintenance involves restoration of supply and repairs after failure.

In our study we regard maintenance and reinvestments as barriers to prevent power system failures and to reduce the consequences. In accordance with Hollnagel's definition, preventive maintenance (including vegetation management and reinvestment) are barriers which prevent the event power system failure, while corrective maintenance are barriers that reduce the consequences of such events.

Blackouts studied

Blackouts are often caused by a combination of different circumstances or events. Examples include coinciding failures in the main grid, failures in combination with malfunction of protection, planned outages or inadequate system operator response, and adverse weather causing wide-area damage on power lines.

Even though blackouts have a low probability of occurrence (often referred to as High Impact Low Probability events), they *do* happen. During the last decade, Western societies have experienced several such incidents. For the purpose of this paper, a handful of blackouts in the Nordic electricity system have been chosen for study, see Table 1.

Table 1: Blackouts studied

Country, year	**Initiating causes**	**Consequences in the power system** - End-users interrupted - Stipulated duration	**Main sources of reference**
Norway 2004	Breakage of line joint, delayed protection response	Blackout of an area in Western Norway - 0.25 million - 0.5 h	(Doorman et al., 2004), (Statnett, 2004)
Sweden 2005	Storm Gudrun, extreme wind	Extensive damage of overhead lines Extensive loss of supply - 0.7 million - 1 day – 5 weeks	(Swedish Energy Agency, 2007), (Swedish Energy Agency, 2005)
Norway 2007	Storm and icing	Loss of both lines to the community Steigen. - 0.0018 million - 6 days	(Kjølle et al., 2007)
Norway 2007	Fire in cable ditch at Oslo central station	Damage of power and telecom cables, evacuation of the central station. 80 000 train passengers and 25 000 telecom customers affected - 0.1 million - 10-20 h	(DSB, 2008)

RESULTS

Information about the blackouts was structured according to the Bow-tie model, and the analysis aimed to answer the following questions:

- How did barriers fail to protect against emerging threats?
- What kind of indicators could have provided ex-ante information about the events and potential consequences?

For now, the scope of the study is focused on the contribution of maintenance and reinvestment, keeping in mind that this must be supplemented by analysis of other types of barriers.

How did the barriers fail to protect against the emerging threats?

The blackouts studied are quite different in terms of identified vulnerabilities and barriers, but they do have some common determinants. All the blackouts include barriers that failed or at least had improvement potentials.

For the events caused by adverse weather (Swedish storm Gudrun, and adverse weather conditions in Steigen, Norway), barriers related to restoration of supply, access to alternative supply and relevant information were identified as having the largest potential for improvement. In addition, the case of Steigen revealed a need for better condition monitoring. Of course, enforcement of components to withstand higher wind and ice loads, and more use of cables would have reduced the systems' vulnerability towards climatic stress, but one must keep in mind that these are comprehensive measures, and there is a limit to what the component and system should be dimensioned to withstand.

The extent of the failures, combined with damaged roads and communication systems was a major challenge for the maintenance crews during the storm Gudrun. Restoration and repairs were conducted for weeks with many people involved. Challenges included availability of personnel and other resources, organisation of the work and communication. For the case of Steigen, failure of the regional grid was limited to two lines, but the weather conditions delayed repair work for several days, even though personnel and equipment were available.

For the other events analysed (Western Norway and Oslo Central Station) the main contributors were flaws in system-related barriers such as redundancy, operator response, and protection schemes, but some barriers related to maintenance also revealed inherent weaknesses. The blackout in Western Norway was initiated by the breakage of a single component (line joint) due to mechanical degradation followed by delayed protection response. Condition monitoring of the line and testing/improvement of protection settings could perhaps have prevented the event, but the main vulnerability was (and still is) the limited transmission capacity into the area.

The blackout at Oslo Central Station differs somewhat from the rest by the fact that 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. However, the event was initiated by a permanent earth fault caused by damage from digging, and the type of cable affected is known to be susceptible to this type of earth faults.

Table *2* shows a summary of the findings related to how different maintenance and reinvestment related barriers contributed to the course of events for the analysed blackouts. Note that the improvement potential as well as the costs of enforcement vary significantly between the different barriers identified. In addition, flaws in barriers *not* related to maintenance and reinvestment contributed significantly to the course of events, and this is not included in Table *2*.

Table 2 *Summary of threats/ vulnerabilities and barriers for the blackouts studied.*
X indicates that the analysis revealed an improvement potential for the barrier.

Threats/vulnerabilities	**Possible barriers**		W. Norway 04	Sweden 05 Storm Gudrun	Norway 07 Steigen	Norway 07 Oslo Central St.
Natural hazard: Strong wind, icing	Preventing failure	Strength and design of construction		X	X	
Contact with vegetation		Vegetation management and / or more use of cables		X		
Installation/construction flaws		Better instructions/competence and choice of design, material and right-of-ways	X		X	
Deterioration of components		Condition monitoring and maintenance/reinvestment	X		X	X
Inadequate protection		Testing of protection schemes and settings	X			
Lack of personnel or other resources	Restoration	Adequate access to personnel and materials		X		
Communication problems during restoration		Good communication channels and back-up in communication infrastructure		X		
Insufficient coordination and work procedures		Good and known restoration plan Coordination and clarification of responsibility		X		X

What kind of indicators could have provided ex-ante information about the events and potential consequences?

The rationale for looking at historic events is that they can help identify critical barriers, and that this information can be used to describe vulnerability and establish vulnerability indicators. Such indicators must say something about the presence and magnitude of threats and the presence and adequacy of barriers. The analysis presented in this paper has focused on the latter, more precisely the presence and adequacy of barriers related to maintenance and reinvestments.

From Table *2*, a need for indicators providing information about the following barriers can be found:

- Dimension criteria, components
- Quality of construction
- Presence of components with inadequate design
- Vegetation management adequacy
- Degree and quality of condition monitoring
- Condition indicators for selected components
- Personnel and material availability for restoration
- Availability of communication system in emergency situations
- Quality of plans, procedures etc, including clarification of responsibilities.

Such indicators must be combined with knowledge about threats and criticality of components, systems and functions. It is expected to be a challenge to establish good leading indicators, i.e. indicators which say something about vulnerability prior to events; however, analysis of past events and historic data will give valuable insight. Other sources of information include experiences from emergency training, surveys, technical data and condition info for components etc.

To answer the question of whether or not indicators could have provided ex-ante information about the events studied is difficult. Our best answer is that in order to do so, there is a need for indicators that describe relevant threats and barriers, and that information about such indicators is generally lacking. The aim is that better knowledge about threats and barriers can provide vulnerability indicators which help reduce the occurrence of large power system failures in the future.

DISCUSSION AND CONCLUSION

The study of previous blackouts has, as expected, revealed that several barriers related to maintenance and reinvestment had inherent weaknesses and/or the threats were of a larger magnitude than the barriers were designed for. There is a need for indicators to describe this type of vulnerability, and we believe that analysis of historic blackouts provide valuable insight about vulnerabilities and barriers.

To analyse past events looking for flaws in barriers is a common approach to accident analysis. The rationale is that "*We will see the effects of barriers and the barriers can be improved. Incidents can inform us about unexpected interactions or dependencies between barriers*" (Rosness et al., 2004*).* Nevertheless it is important to keep in mind to combine this historic knowledge with simulations and expectations for the future.

Better knowledge concerning the importance of barriers can support the identification and establishment of vulnerability indicators. In this paper, the focus has been on barriers related to maintenance and reinvestment, but it is important to also consider other factors which affect vulnerability in power systems. Identification of methods and indicators addressing "the full picture" is part of ongoing work of two projects at SINTEF Energy Research: *Vulnerability and security in a changing power system* and *Risk based Distribution System Asset Management.* This paper should be studied within this context.

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