DEVELOPING INDICATORS FOR MONITORING VULNERABILITY OF POWER LINES – CASE STUDIES

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ABSTRACT

This paper shows how information from vulnerability analyses and existing maintenance management systems can be combined with information about threats and criticality to establish vulnerability indicators for power lines. The development of indicators to monitor the vulnerability regarding weather related threats is addressed and the methodology is demonstrated for two case studies using data from two different network companies and selected critical power lines in their supply areas.

INTRODUCTION

Modern society is increasingly dependent on a secure electricity supply. At the same time, the power system is vulnerable with possible severe consequences for society when wide-area interruptions occur. The control of these vulnerabilities with adequate indicators is an essential part of power system asset management. In particular, indicators and data on an aggregate level could help to monitor and predict the vulnerabilities in quantitative terms [1]. A research project in collaboration with network companies and authorities seeks to reduce this gap by developing indicators that can be used to monitor vulnerabilities. Case studies are performed together with two network companies with the goal of developing vulnerability indicators for power lines based on a profound framework and indicator development process.

VULNERABILITY FRAMEWORK

A clear definition of the vulnerability framework serves as basis for the indicator development for power lines.

Definition of vulnerability

The following definition of vulnerability is used as the basis for the development of vulnerability indicators [2]: *Vulnerability is an expression for the problems a system faces to maintain its function if a threat leads to an unwanted event and the problems the system faces to resume its activities after the event occurred. Vulnerability is an internal characteristic of the system.*

Theoretical framework

The vulnerability framework is based on several dimensions that together form a complete picture of vulnerability ([3], [4]) and is applied to the power system [2]. These dimensions are *threats*, *susceptibility*, *coping capacity*, and *criticality*. The vulnerable system is exposed to threats. The degree of vulnerability is determined by the susceptibility and the coping capacity of the system, whereas the dimension criticality describes the consequences for the users of the infrastructure if the system does not carry out its intended function. While vulnerability is regarded as an internal characteristic of the system itself, threats and criticality are external dimensions as illustrated in Figure 1.

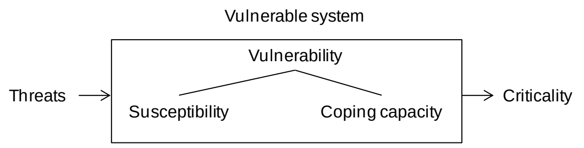

Figure 1 Vulnerability framework with different dimensions

Leading and lagging indicators

Several types of indicators are suitable for monitoring the vulnerability of power systems, such as leading, lagging, activity based or outcome based indicators [5]. The main focus of these case studies was on lagging indicators. In addition, the possibility of developing leading indicators was briefly investigated. These indicators are defined as:

- Lagging indicator: Information about the current vulnerability and how it has been in the past.
- Leading indicator: Information about how the vulnerability of the system will develop in the future.

INDICATOR DEVELOPMENT

Different approaches for the development of indicators are applied in different sectors and based on these approaches the process for developing vulnerability indicators are defined in [2]. The process can be subdivided in three steps; development of a framework, design of indicators and testing in practice. Several activities have to be performed in each step as presented in Figure 2.

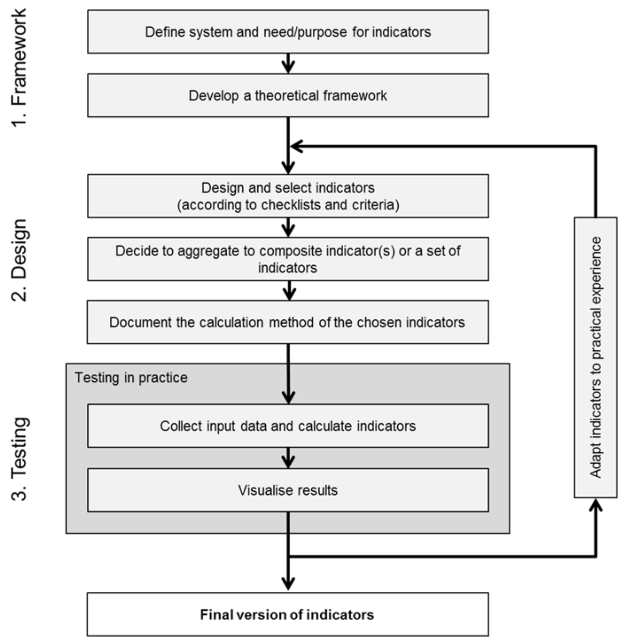

Figure 2 Indicator development process [2]

In the following, some aspects related to the indicator design phase needing special consideration are discussed.

Identification of critical assets

It can be necessary to identify the critical assets in the power grid to limit the effort of collecting data and developing indicators. Critical outages, localisations and operating states are identified as a part of the vulnerability analysis. This means identifying events that may lead to interruption of supply to the critical loads, using different methods, ranging from more advanced approaches like simulations and contingency analysis to expert evaluation and previous experience. Examples of such events are single or multiple outages, including common mode events, of systems or components.

Outage of one or more power lines is a typical example of an event leading to interruption of critical loads. Therefore power lines at weather exposed locations or supplying critical loads are identified as critical assets and the case studies are focusing on these. Also history confirms that storms and the resulting break down of power lines are a major cause for wide-area interruptions in Scandinavia ([6], [7]).

Assigning values to indicators

In general, indicator values can be assigned with three different approaches:

- Expert assessments (subjective)
- Calculation based on data (objective)
- Mixture of subjective and objective approach

Expert assessments are based on experts and their knowledge. One would ask them directly how they would evaluate an indicator based on a given scale. The answers present the subjective opinion of the experts and therefore the approach is completely dependent on finding the right experts with knowledge needed for assigning a value to the indicator of interest. The second approach calculates the indicator based on data. This approach is more demanding since it is dependent on several factors. First of all, one has to decide what data should be used to calculate the indicator. Second, a calculation rule has to be established and the scale of the indicator has to be defined. It is also important that the indicator value is explained and set in context so that other can understand the indicator value. A mixture of both approaches is also possible and a usual method. Then experts would give their opinion based on data or models.

CASE STUDIES – POWER LINES

In the case studies the development of vulnerability indicators for power lines is based on the described development process. The case studies were performed with network companies to develop vulnerability indicators for critical power lines in the distribution and the regional network. Lagging indicators were developed with a focus on the condition of selected power line and in approaches for developing leading indicators briefly investigated. All indicator values are estimated per electricity pole location to find special vulnerable points in the network. It was decided to establish four indicators that cover all dimensions of vulnerability, but only selected aspects per dimension as illustrated in Figure 3.

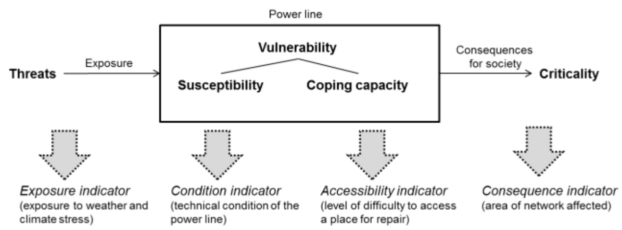

Figure 3 Selected vulnerability indicators for the case study of power lines

The indicator for threat focuses on weather and climate stresses that either can cause an immediate failure or can lead to deterioration in the technical condition of the power line. Susceptibility is covered by an indicator that presents the technical condition of the power line based on data from periodically conducted maintenance inspections. Coping capacity is described by an indicator that looks into the accessibility of the pole location for repair work if a failure occurs. This is estimated based on the time needed to reach that location. Consequences for society are measured with an indicator that is based on the location of critical loads and power switches in the network.

The assignment of values to the indicators is based on different data sources and methods. The indicator for technical condition is calculated based on data that are obtained from maintenance inspections. Deviations from specified checklist points are translated into a reduction of

the condition of the electricity pole. The other indicators are not calculated, but based on an expert assessment of available information material.
All indicators use the same scale from 0 to 100 where 0 is regarded as the worst value and 100 the best, in steps of 20. For the technical condition, the steps are set to 25 based on the maintenance system. It was chosen to use the same scale for all indicators mainly to allow for comparison of different indicators and a straight forward aggregation of indicators. Table 1 summarizes the main characteristics of the developed indicators.

Table 1 Selected approaches for vulnerability indicators

	Method	Data source	Scale
Exposure	Expert assessment based on available information	Reports about corrosivity, wind speed and ice loads	0 (extreme) 100 (little) Steps of 20
Condition	Calculation based on data	Reported deviations from maintenance inspections	0 (very poor) 100 (perfect) Steps of 25
Accessi-bility	Expert assessment based on available information	Map material	0 (hard) 100 (easy) Steps of 20
Conse-quence	Expert assessment based on available information	Location of circuit breakers and location of critical loads	0 (critical) 100 (little) Steps of 20

Aggregation challenge

When studying a power line it will usually be necessary to aggregate indicators into a composite indicator or a smaller set of indicators, either because the number of indicators is large or that the goal is to summarise the multi-dimensional aspects of vulnerability. In general, two different aggregation approaches and the combination of these approaches can be used. The first approach is to aggregate the same indicators from a lower to a higher system level. The second approach is to aggregate different indicators to a combined indicator that includes information of all these indicators. Both approaches can also be used together as illustrated in Figure 4 and which were applied in the case studies.
There are at least two challenges when aggregating indicators. The first one is the scale and unit of the indicators, and the second to decide on an aggregation rule securing that no crucial information is lost through the aggregation process.
The scale used for the indicators is important if several different indicators shall be integrated into one combined indicator. These indicators need similar scales. However, for the aggregation to higher system level the scale is not of such importance as long as different indicators are not combined together.

Different aggregation rules can be applied. One simple rule is to use the average value when aggregating. However, the average could hide especially vulnerable components at lower levels. Therefore, a weighted average can be a more appropriate method and in the case it was chosen to use this method for both aggregating and combing indicators. The chosen weighting method gives a larger weight to low indicator values and therefore it is possible to sustain the information of low values also on the aggregated level. The specific aggregation rule should be chosen by experts while securing that relevant information is kept during the aggregation.
The four indicators are calculated at electricity pole level and aggregated to indicators for the whole power line with the aforementioned aggregation rule. The aggregated indicators can be used to give a snapshot of the vulnerability situation of the power line and can also be used to understand which vulnerability dimension is most critical. In addition, the four indicators were aggregated together to a combined indicator for vulnerability. This indicator can give indication for especially critical locations in the power line from a vulnerability perspective or can be used as the only one indicator at the aggregated level.

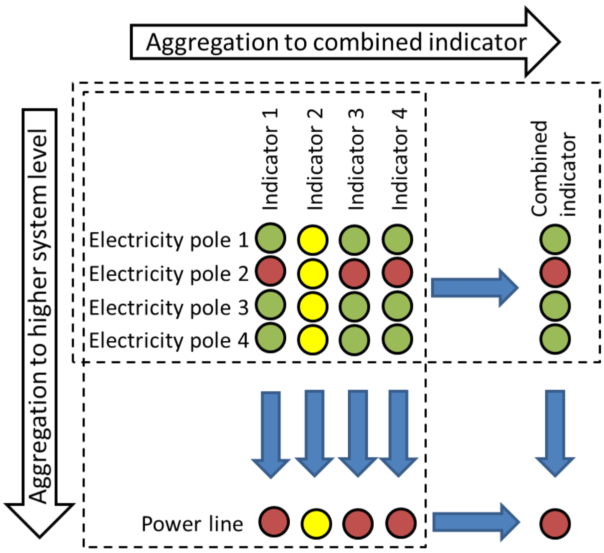

Figure 4 Approaches for indicator aggregation

Results

The results are displayed with different colour coding to emphasise the critical indicator values. Vulnerability indicator values were calculated for two power lines in the regional grid and two in the distribution grid. Results from one of the regional grid lines are presented in this paper. Figure 5 shows an extraction of results at the single pole level, while Figure 6 shows aggregated results at the power line level. At both levels, indicators describing different dimensions of vulnerability were aggregated to a combined indicator.

Pole ID	Exposure	Condition	Accessibility	Consequence	Combined
16	40	0	40	20	23
11	60	0	40	20	24
1	60	0	40	20	24
77	60	50	20	20	31
87	60	50	20	20	31
71	60	100	20	20	32
72	60	100	20	20	32
73	60	100	20	20	32
74	60	100	20	20	32
75	60	100	20	20	32

Figure 5 Poles with lowest combined indicator value

After aggregating the indicators, the results for the power line show that the condition indicator has a very high value, i.e., very good condition, exposure and accessibility is average, while the potential consequences are considered critical. However, the aggregated values have to be treated carefully, since they are directly dependent on the aggregation method and weighting.

Exposure	Condition	Accessibility	Consequence	Combined
59	92	51	17	41

Figure 6 Aggregated indicators for a power line case study

Developing leading indicators

In addition to the development of lagging indicators, the possibility of developing leading indicators was investigated. Two main approaches were identified as promising. A bottom-up approach based on extensive modelling of underlying factors, and a top-down approach based on external drivers. In a bottom-up approach, the future prediction is based on changes in the underlying factors. The challenge of this approach is to determine the dependencies of the different underlying factors so that these can be modelled. A top-down approach focuses exclusively on the external drivers that affect the vulnerability. Prognoses for external drivers may be based on models (for example climate, operating stress) or expert assessments.

DISCUSSION

One important lesson learned from the case study was that it is hard to find data of the required quality to assign values to the indicators at electricity pole level. Most of the indicator values were therefore assigned based on subjective assessment. A more data based approach to assign values to the indicators would be preferable to allow for a fast update of the indicators when new data are available in the maintenance system and to use the method more quickly for several critical power lines. In addition, the specification of weights for aggregation has quite an influence on final results and should be subject for a more thorough analysis. Weights should be chosen in a way that the aggregated indicators get values as would be expected from an expert user.

CONCLUSIONS

A framework for developing vulnerability indicators was presented and applied to several case studies that focused on the vulnerability of power lines. Indicator values were assigned by using available data from the maintenance systems combined with expert evaluations at the network companies. Based on this work, several conclusions can be drawn:

- The vulnerability framework is applicable to measure the vulnerability of power lines with indicators.
- More effort is required for developing a set of indicators that represent the whole vulnerability picture – some example indicators are tested, but a consistent set is still missing
- Weighting and aggregation rules should be evaluated to represent the understanding of vulnerability on an aggregated level.
- Leading indicators are a remaining challenge and more effort has to be invested in the further work to design leading indicators.

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