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Asset management framework applied to power distribution for cost-effective resource allocation

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SUMMARY

There is an international tendency toward increased demand for both cost-efficiency and high reliability of power distribution systems. To meet these demands, asset management methods, including reliability analyses, have been developed. These reliability analyses often utilize only mean values and hence do not take into consideration the consequences of severe events. This paper proposes a framework for more detailed quantitative risk analysis methods. The aim is to allocate resources more cost-effectively. The suggested framework is exemplified and evaluated by implementing it within the analyses of a real power distribution system.

The main concept is to divide comprehensive projects into minor analyses and then in a final step compile the results. The proposed analysis framework can be used independently or combined with earlier proposed vulnerability methods. The latter provides a two-dimensional analysis framework. It is shown that totally different investment alternatives could be preferred depending on whether a traditional analysis method using average values is employed compared with the proposed analysis framework, which also considers severe system states. This demonstrates the risks involved in using average values and the strength of the proposed method. Furthermore, it is shown that already available information can be used for improved asset management decision support. In addition, the performed case study gives combined reliability and weather statistics useful as reference material. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: asset management; power distribution; reliability; risk analysis; vulnerability analysis

1. INTRODUCTION

Present-day society is dependent on reliable distribution of electricity. There are a lot of uncertainties regarding the future development of power distribution including political, technical, and economical [1]; however, there are huge ongoing and future developments of power systems meaning both challenges and opportunities for all parties [2], often overall referred to as Smart Grid [3]. One clear tendency is the increased amount of distributed generation, but this is still, by many distribution system operators (DSOs), mostly seen as costs [4], than, for example, an opportunity to increase the system reliability. Hence, this is not included in previously performed reliability studies included in this paper but can be future implemented in proposed analysis framework. Several DSOs have indicated dynamic line rating [5] as an interesting approach to handle, for example, the increased amount of wind power integration [6], and several research and development projects have recently been initiated in Sweden [7].

To meet ongoing climate challenges, a reliable power system infrastructure will probably play an even more important role in the future; for example, as mentioned, the increased amount of distributed generation is both a future challenge and opportunity [8]. Furthermore, there is an international tendency toward increased demand for cost-efficiency followed by new incentives such as

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performance-based tariff regulation methods [9,10]. Hence, there has to be a balance between the aims of increasing the reliability and becoming more cost-efficient [11], which motivates the introduction of more comprehensive analysis methods. This may involve, for instance, supplementing rough qualitative estimates with quantitative analysis in operation, maintenance, and investment planning. In addition, new incentives in some countries (e.g., the UK and Sweden) have made it obligatory to handle the consequences of long outages separately in risk and vulnerability analyses [12]. Taking the Swedish legislation as an example, the direct economic consequences of outages as a function of length is illustrated in Figure 1 (i.e., costs of mandatory customer compensations; repair costs and costs associated with energy not supply are excluded). This clearly shows that the consequence of a mean outage length could significantly differ from the mean consequence of all outages as a result of the cost not being linearly dependent on outage time.

Quantitative methods using reliability indices for cost-effective asset management in power distribution are presented, for example in [13]. Furthermore, reliability models, which divide power systems into two or three weather states, have been proposed [14–16]. Vulnerability analysis of power systems using reliability and risk-based methods have been presented earlier, but these methods often focus on higher system/voltage levels [17–19]. There exist approaches to using quantitative methods to prioritize maintenance actions in power systems, for instance, [14] and [20]; this paper however presents methods to allocate resources more generally.

An analysis framework utilizing more detailed input data is proposed in this paper and evaluated by analyses of a real power distribution system in collaboration with a DSO. The main idea is to divide comprehensive projects into minor analyses and then compile the results. The aim is to allocate resources more cost-effectively, including both human and economic resources and equipment, and also to capture consequences that cannot be captured by traditional analyses that are based on average data.

2. RESOURCE ALLOCATION ANALYSIS FRAMEWORK

2.1. Main concept and framework

A vulnerability analysis method, where power distribution systems can be generally divided into several system states, not necessarily weather-related, has earlier been proposed by authors of this paper [21] and is shortly summarized in this section. Different resource allocation alternatives are analyzed with respect to different system states. A system state could be a time category, a weather event, or a system function reduction/configuration.

The new analysis framework proposed in this paper can be used independently or combined with the earlier published vulnerability method. The latter provides a two-dimensional analysis framework, which divides a large complex analysis into several minor parts, which is easier to handle. The idea of the framework is to divide comprehensive projects into minor analyses and then compile the results.

Figure 1. Economic consequence of outages as a function of time exemplified by the Swedish legislation.

The main advantage, however, is to consider more conditions than the average, for example, to identify unacceptable risks and include penalties for long interruptions.

Many parts of the power system, and especially local power distribution systems, are mostly studied with average reliability indices such as System Average Interruption Duration Index (SAIDI) [time/year, customer] [22]. This is mainly because information about the systems is on this information level. The problem is that the average situation seldom exists in real life [12]. By dividing power systems into different states with respect to different risk levels, much information can be gained, such as information on how the system behaves in different situations. This information can be used to address resource allocation and investment planning, that is, by studying a more realistic model of the power system, activities can be directed for better effect.

2.2. The potential use of the model

Analysis results can, for example, be used for the following:

- Develop cost-effective investment and maintenance plans.
- Evaluate whether extra preparedness (e.g. more personnel) ought to be considered as a consequence of some categories of weather forecasts.
- Estimate an appropriate amount of reserve components and resources that could be shared with other DSOs.
- Estimate the right level of preparedness during inconvenient hours.
- Investigate when planned maintenance could be scheduled, that is, when the system has as little vulnerability as possible.
- Identify unacceptable vulnerabilities/risks.

2.3. Overview of proposed analysis framework

The resource allocation model can be described as a matrix, which is illustrated in Table I. Each row of the matrix represents a resource allocation alternative, and each column of the matrix represents a system state (S_i). The model is exemplified in Section 3 by implementation on a real power distribution system.

ΔC_i is the cost difference between keeping current status and resource allocation i and could be both positive and negative (e.g., when comparing savings needed). Traditionally, one analysis is performed for each investment alternative and then compared on the basis of a system average (A_i). If an optimization is performed taking into consideration the average, important effects could be neglected such as costs compensation for long outages. Each square in the matrix (A_{ij}) illustrates a minor analysis, which could be performed separately. The connection between the minor analyses and the compiled results taking all system states into consideration is given by Equation 1. Note that the compiled results from proposed analysis framework are not necessarily equal to the results from traditional analysis based on average values as input because proposed framework is taking more details into consideration.

$$A_i = \sum_{j=1}^N (A_{ij}P(S_j)) \quad (1)$$

Table I. Proposed resource allocation model.

Resource allocation	System state:		S_1 "normal"	S_2	...	S_N
	$\Delta Cost$	Compiled result	$1 - \sum_{j=2}^N P(S_j)$	$P(S_2)$	...	$P(S_N)$
1 no	0	A_1	A_{11}	A_{12}	...	A_{1N}
2	ΔC_2	A_2	A_{21}	A_{22}	...	A_{2N}
3	ΔC_3	A_3	A_{31}	A_{32}	...	A_{3N}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\searrow$	$\vdots$
M	ΔC_M	A_M	A_{M1}	A_{M2}	...	A_{MN}

2.4. Summary of a vulnerability analysis approach (the columns of the matrix)

2.4.1. Introduction. This section introduces the “columns” of the analysis framework matrix (Table I). The vulnerability analysis approach has earlier been published by authors of this paper [21]; however, this approach is only briefly summarized here, and the novel aspects of the present paper can be used both independently and together with earlier results as an extended analysis. The overall idea is to identify and evaluate possible states of power distribution systems using quantitative reliability analyses. Results should, thus, indicate how available resources (both human resources and equipment) could be better utilized, for example, in maintenance and holiday scheduling and in evaluating whether additional security should be deployed for certain forecasted weather conditions.

2.4.2. Method steps.

- (1) Determine the accuracy and extent of the analysis.
- (2) Identify system states.
- (3) Calculate risk indices for each state.
- (4) Perform a statistical validation.
- (5) Use the result for cost-effective resource allocation, that is, as input to investment and maintenance planning.

2.4.3. Case studies performed. To evaluate the method, an application study was performed on the basis of hourly weather measurements and about 65 000 detailed failure reports over 8 years for two power distribution systems in Sweden. Months, weekdays, and hours have been compared, and the vulnerability of several weather phenomena has been evaluated. Of the weather phenomena studied, only heavy snowfall and strong winds, especially in combination, significantly affect the reliability. Temperature (frost), rain, and snow depth have a relatively low or no impact. Risk and reliability at states that have been identified as the most critical are summarized in Table II. Lightning was not included in this study, but this weather category has in other publications been identified to have a significant effect on the reliability [23].

2.5. Model for comparison of investment scenarios (the rows of the matrix)

This section introduces the “rows” of the analysis framework matrix (Table I).

2.5.1. Method steps.

Included steps:

1. Investigate and describe the system.
2. Divide the system into proper states.
3. Develop proposals on resource allocation actions such as investments.
4. Choose economic method and assumptions
5. Choose risk analysis approaches for different states.
6. Choose proper input data and assumptions.
7. Perform analysis.
8. Evaluate and use the results.

2.5.2. A general economic analysis approach. The aim is to identify strategies taking the entire economic lifetimes into account, that is, it is recommended to perform life cycle cost (LCC) analyses [24]; see Equation 2.

$$C_{LCC} = \sum_{i=1}^L \left(\frac{C_i}{q} \right) - \frac{R}{q^L}, \quad q = \frac{1+z}{100} \quad (2)$$

where,

- C_{LCC} is the total *Life Cycle Cost*, taking the interest into consideration.
- z is the interest rate in percent determined by the company.

Table II. Vulnerability with respect to risk categories.

Risk c. ^a	$P([S])$ (%)	$SAIDI_{Unpl}^{[S]}$ *	Share (%)	c_V (variation) (%)	$SAIFI^{[S]}$ *	$R_{12}^{[S]}$ *	Share (%)	c_V (variation) (%)	$R_{24}^{[S]}$ *	Share (%)	c_V (variation) (%)
All	100	4.7	100	0.5	5.6	136	100	2	43	100	3
1	95.11	3.1	62	0.5	4.9	36	25	2	15	33	4
2	1.16	23.8	6	2.9	14.5	709	6	10	124	3	20
3	3.06	28.7	19	1.6	18.5	1513	34	5	527	38	8
4	0.09	144	3	6.4	45.1	5040	3	14	8	0	38
5	0.58	87.5	11	2.9	28.2	7324	31	4	1883	26	5

^aSystem states [S] (risk category): other (1), windy (2), snowy (3), windy and snowy (4), Severe storm (5).

- C_i is the estimated sum of all costs during year i , which is associated with the project, including incomes and so on modeled as negative costs (e.g., revenues).
- R is the sum of all residual values after the economic lifetime including residual costs (which are modeled as negative residual values).
- L is the economic lifetime.

2.5.3. How to choose risk analysis method(s). Reliability analysis is a risk method commonly used to assess the risk of outages in power distribution [22]. Trustworthy reliability analysis demands many historical fault events and is therefore not applicable in risk analysis contexts with low probabilities and major consequences [24]. Consequently,

- Reliability analysis is a proper risk analysis approach to measure the consequence of outages during normal conditions.
- Other risk analysis approaches, such as using a risk matrix, ought to be taken to assess consequences of more severe events (low probability but high consequence).

2.5.4. Important questions to consider.

- *Is it possible to take advantage of the investment in each system state?* For example, in a system with mostly overhead (OH) lines, investments such as more breakers have no or minor risk-reducing effects when the system is affected by extreme weather because several parts of the system are affected at the same time. Replacing OH lines with cable, however, has a significant effect on the risk level regardless of weather. This aspect is included in the analyses performed in this paper.
- *Are there other possible advantages and disadvantages that are not addressed in the analyses performed?* Examples are personnel issues and access to spare parts. None of this has been included in the example presented in this paper.

3. ILLUSTRATIVE EXAMPLE OF USING THE INTRODUCED METHOD

3.1. Preparation of data

The investment proposals analyzed in this section are performed on a power distribution system owned by Fortum Distribution AB, one of the largest DSOs in the Nordic countries. Fortum is an investor owned utility where the Finnish government is the majority owner. The investment proposals used as examples here have been analyzed in [25], and previously performed analyses are used as a base case for the average system state within the new analyses presented in this paper. The analyses are then further developed with the proposed framework, by combining analyses from Wallnerström and Hilber [21] and Stenberg [25] together with new analyses introduced here.

Economic input data such as costs, interest, and economic lifetime are based on interviews with Fortum Distribution, presented in [25]. The cost data are mostly based on a widely used standard cost catalogue: EBR ("elbyggnadsrationalisering", which means electrical construction rationalization if translated in English). Swedenergy, an association representing companies involved in the production, distribution and trading of electricity in Sweden, has since the 1960's annually published EBR, aimed to rationalize planning, investments, and maintenance of power systems, that is, to provide rational "standards" when constructing power systems [26].

The way in which SAIDI is calculated for each investment proposal with respect to the system average is presented in [25]. On the basis of Table II, several observations and calculations can be made that are relevant to this study, for example, the values of long outages for every system state. One observation from Table II is that 71% of all outages above 12 hours are between 12 and 24 hours and hence 29 % are above 24 hours. To provide a better overview, the reliability of each category is translated into a percentage, where the average is set to index = 100%. This is illustrated in Table III. Reliability data in Table IV are based on ~60 000 failure events during 8 years from power distribution systems owned by the same DSO and in the same region as the system analyzed in this section.

Table III. Weather states—reliability compared with average.

Weather	P [%]	SAIDI (0.05–12 hours) (%)	Outages 12–24 hours (%)	Outages >24 hours (%)
Average	—	100	100	100
Normal	95.11	66	23	35
Severe	4.22	581	943	958
Extreme	0.67	2034	5 788	3 756

SAIDI, System Average Interruption Duration Index.

Table IV. Failure rate of outages >12 hours.

	Outages >12 hours	Share (%)
Overhead line	0.0089 f/km, year	95.35
Underground cable	0.0002 f/km, year	0.41
Secondary substation + underlying 0.4 kV system	0.0025 f/l.p., year	4.24

By analyzing hourly weather data from the same 8 years reviewed from the Swedish Meteorological and Hydrological Institute, relevant weather states have been identified and the probability and reliability of states chosen have then been calculated (see paper [21] for more information). However, when proposed framework should be used in general by others, it is not always realistic to collect and perform such comprehensive data collection and calculations for every system that should be analyzed. This must however not be performed for every analysis; defined states with corresponding information can be calculated once and then reused in several analysis. Moreover, if no own data are used, general data could often be found by literature surveys. For other system states than weather and time, for example, decreased system reliability during maintenance, the new system reliability could be calculated through developing rough reliability models of the system (e.g., system reliability when possible redundancy is avail compared when it is out of service).

3.2. System description

The network was chosen in consultation with Fortum Distribution and is motivated as follows: (i) from a reliability perspective, it has historically been one of the most problematic power distribution parts; and (ii) major investments have recently been introduced. The idea is to perform hypothetic investment analyses applied to this part of the system as it was before investments (replacement of a large amount of OH line with cables). In 2001, used as reference year in the performed analyses, this part of the system had 61 km of OH lines, 15 km of underground cable, and 303 customers. It is situated in a rural area in the county of Värmland in the western part of Sweden. Today, after major investments, the amount of OH line has decreased by 69% by being replaced by underground cables.

3.3. Classification of system states

In a previously performed case study [21], this power distribution system has been divided into five weather states motivated by identified weather that affect the reliability the most. These states are defined in Table II, which also contains the probability and reliability of each of them. However, in this study, the two most extreme weather states (four to five) have been merged into one state, “extreme”; weather states two to three have been merged into one state, “severe”; and the rest of the time (state 1) is kept, and in this paper, it is called “normal”. Table V contains information of all three weather states used in this paper together with its probability and the average reliability of the system during each state.

3.4. Investment proposals

In this paper, five investment proposals have been included. These have been chosen in consultation with the DSO and included to hypothetically remain as it was in 2001, the system as it is now and three realistic but not implemented investments. The benefit with the two first proposals is

Table V. Definition of weather system states used in the example.

Defined weather states	Corresponding categories in Table II	P (%)	Reliability indices: SAIDI (hours/year) R_X (interruptions/year, 1000 customers)
Normal	1	95.11	SAIDI = 3.1, $R_{12} = 36$, $R_{24} - R_{12} = 21$, $R_{24} = 15$
Severe	2–3	4.22	SAIDI = 27.3, $R_{12} = 1\ 289$, $R_{24} - R_{12} = 877$, $R_{24} = 412$
Extreme	4–5	0.67	SAIDI = 95.6, $R_{12} = 6998$, $R_{24} - R_{12} = 5\ 383$, $R_{24} = 1\ 615$
Average	all, 1–5	100	SAIDI = 4.7, $R_{12} = 136$, $R_{24} - R_{12} = 93$, $R_{24} = 43$

SAIDI, System Average Interruption Duration Index.

that there exist real observations. In addition, there of course exist more kinds of investment proposals that would be of interest to study, but these are enough to show the principle of proposed analysis framework:

- (1) *Do nothing*, that is, keep the 2001 configuration. The potential profit of all other investment alternatives is evaluated and then compared with this option by LCC analysis (Equation 2).
- (2) *Replace OH lines with underground cables*, that is, as this system is configured today. Sixty-nine percent of the OH is replaced by underground cable.
- (3) *Changing manual disconnectors to remote controlled disconnectors*.
- (4) *Adding one new breaker*.
- (5) *Adding one secondary feeding point*.

3.5. Economic assumptions

3.5.1. General assumptions.

- Economic lifetime L : 40 years is assumed for all investments, which is the same as assumed by the regulatory authority.
- The current discount interest rate at Fortum is used (note that it is not the same as that used in the tariff regulation).

3.5.2. Costs and revenues included in performed cost analyses.

- *Investment cost*: Initial costs, for example, of installing cables and demolishing old OH line.
- *Changed outcome from tariff regulation*:
- *Reliability function included in tariff regulation*: Changes in the revenue framework due to quality adjustment. Changed reliability, SAIDI and System Average Interruption Frequency Index (SAIDI contribute most), with respect to outages 0.05–12 hours leads to a positive or negative quality adjustment in the regulation. The reliability is compared with the level of reliability before the regulatory period. The reference level is reset after each regulatory period of 4 years.
- *Changed compensation for capital costs*: The capital cost of a component consists of depreciations and the cost of tied-up capital. The regulator intends to apply capacity conservation principles by using constant real annuity. The constant annuity value is used despite actual age. DSOs who maintain their components well are thus rewarded. This part has a great impact on the result. Investments that include introducing more components are “rewarded”, while demolishing old components is “penalized”.
- *Repair costs*: Adding or removing equipment or lines might affect the yearly repair costs. These costs are based on interviews with the DSO of the studied system.
- *Customer compensation for long outages*: If the investment alternatives have an effect on outages ≥ 12 hours, the yearly amount of customer compensation might change.

3.5.3. Costs not included in the performed cost analyses.

- *Consequences of breaking the functional requirement of 24 hours*: Since 2011, outages above 24 hours are not tolerated by law in Sweden. These consequences are, however, considered in this paper by an additional risk analysis approach as a complement to the cost analyses.

- *Goodwill effects*: Severe and/or a large number of outages could damage the trademark of the company. Many companies also operate in other competitive markets, not only operating in power distribution which is considered as a natural monopoly.
- *Possible costs or incomes after the economic lifetime* (i.e., L in Equation 2)
- *Possible consequences of other quality aspects*: For example, outages < 0.05 hours.

3.6. Choosing risk analysis methods

Trustworthy reliability analysis demands many historical fault events, which have been available for this power distribution system according to outages 0.05–12 hours. Outages > 12 hours, with severe consequences, but relatively low probability, lack adequate statistics. Therefore, another risk analysis approach is used to evaluate these risks, while reliability analysis is used to evaluate outages for 0.05–12 hours. Both the reliability analysis and the risk analysis of long outages are presented in this subsection.

3.6.1. Reliability analysis method. System Average Interruption Duration Index (defined in e.g., [22]) is the reliability index used in this paper to illustrate mean reliability. Only outages of 0.05–12 hours are included, because of Swedish tariff regulation [24]. When studying one system state (Table V) at a time, “conditional” reliability indices are calculated. If $Y\%$ of SAIDI can be traced to state S , see Equation 3:

$$SAIDI^S[\text{hours/year, customer} \mid \text{State } S] = \frac{0.01Y * SAIDI}{P(S)} \quad (3)$$

In Equation 3, $P(S)$ is the probability of state S .

A new reliability index category, R_T , was introduced in [21]. The category allows flexibility in the design of the indices, to adjust to different laws or DSO policies on long outages. R_T is the average number of outages above T hours during 1 year per 1000 customers:

$$R_T = 1000 \frac{\sum_i (\lambda_{\geq T,i} N_i)}{\sum_i N_i} [\text{number outages} > T \text{ hr/year, } 1\,000 \text{ cust.}] \quad (4)$$

In Equation 4, $\lambda_{\geq T,i}$ is the sum of customer outages/year in load point i (LP_i) caused by outages $\geq T$ hours, and N_i is number of customers in LP_i . In Sweden, 12 and 24 hours are most important, that is, R_{12} and R_{24} , while 18 hours, that is R_{18} , is the limit of the first compensation level in the UK. If an outage interval, $T1$ to $T2$, is of interest (e.g., 12–24 hours of outages), this is provided by calculating $R_{T1} - R_{T2}$.

3.6.2. Risk analysis approach to handling long outages. A simple but commonly used definition of the risk value [27] is exemplified in Equation 5, where P is a number associated with a determined probability category, while C is a number associated with a determined consequence category. The risk value could then be used as input to decide if and how the risk should be treated.

$$\text{Risk value} = P * C \quad (5)$$

A common approach to assessing a risk or comparing and prioritizing risks is the use of *risk matrices* [28]. The probability and the consequence are first estimated and divided into determined categories. The categorization could be made by either qualitative or quantitative methods. The probability and consequence categories give two axes with a resulting two-dimensional matrix with estimated risk values or proposed action measures. Proposed probability and consequence categories for the risk analysis performed are illustrated in Table VI.

In the example presented here, 0.67% of the time with the most “extreme” weather is assumed to give an increased probability to vindicate mitigating factors. On the basis of Tables II and VI, the mean consequence value can be calculated as 4.75; see Equation 6:

Table VI. Probability and consequence categories.

Probability categories		Consequence categories	
R_T (# long interruptions/year, 1000 customers), see Equation 4	P	Length of the outage (hours)	C
<5	0	<0.05	0
5–15	1	0.05–12	Reliability analysis
15–30	2	12–24	2
30–50	3	>24 ^a	4
50–100	4	>24	5
>100	5		

^aDuring severe weather and hence there is an increased probability that mitigating factors can be argued by the DSO. Information from regulatory authority (translated from Swedish): "... Only in exceptional cases is the DSO allowed to deviate from the 24-hour requirement. [...] The great majority of all outages, however, are within the DSO's responsibility of control."

$$P([\text{extreme weather when } > 24\text{-hour outages}] * 4 + (1 - P([\text{extreme weather when } > 24\text{-hour outages}]) * 5 = \frac{0.0067 * 1615}{43} * 4 + \left(1 - \frac{0.0067 * 1615}{43}\right) * 5 \approx 4.75 \quad (6)$$

Proposed actions based on risk value:

- *Risk value* <8: Primarily base decisions on other analyses (e.g., cost analysis and SAIDI). If, however, the DSO is considering between two or more investment proposals, this value may be decisive.
- *Risk value* 8–12: Primarily reject this investment proposal. If no proposal with risk value <8 exists, or if such proposals exist but are significant less attractive with respect to other factors, a proposal within this category can be selected. However, in such cases, it should be considered whether the proposal can be modified or supplemented with more investments.
- *Risk value* >12: Never choose this alternative. If no other adequate alternatives exist, develop new investment proposals.

3.7. Calculations made on the basis of proposed resource allocation model

3.7.1. Overview. On the basis of Table V and the results from Stenberg [25], each system state with its associated probability and each project proposals with its associated Δcost have been put into the analysis framework illustrated by Table I; see Table VII. Table VIII complements Table VII by adding risk and reliability analysis results into each matrix cell.

3.7.2. Traditional analysis using average reliability as input. This subsection concerns the calculation of the columns *average (traditional)* and *normal* in Table VIII.

Assumptions on how reliability is affected by investments during normal weather states:

- Average SAIDI for each investment proposal is based on the study of Stenberg [25]. SAIDI of the weather state *normal* is transformed from the average values, calculated by using Table III [21].

Table VII. Resource allocation model of this example.

Resource allocation	System state		" Normal "	" Severe "	" Extreme "
	ΔLCC [k\$]	Av.	95.11 %	4.22 %	0.67 %
Today	0	A ₁	A ₁₁	A ₁₂	A ₁₃
Cables	+2841	A ₂	A ₂₁	A ₂₂	A ₂₃
Remote disconnecter	−12.9	A ₃	A ₃₁	A ₃₂	A ₃₃
Breaker	+2.5	A ₄	A ₄₁	A ₄₂	A ₄₃
Secondary feeder	+2.7	A ₅	A ₅₁	A ₅₂	A ₅₃

LCC, life cycle cost; Av., average.

Table VIII. Calculation of risk and reliability.

	Average (traditional) ^a	Normal	Severe	Extreme
<i>P</i> (%)	100	95.11	4.22	0.67
Today	SAIDI = 10.49, R ₁₂ –R ₂₄ = 93, R ₂₄ = 43, Risk = 8/15	SAIDI = 6.92, R ₁₂ –R ₂₄ = 21.00, R ₂₄ = 15.00	SAIDI = 60.95, R ₁₂ –R ₂₄ = 877.00, R ₂₄ = 412.00	SAIDI = 213.37, R ₁₂ –R ₂₄ = 5383.00, R ₂₄ = 1615.00
Cables	SAIDI = 6.21, R ₁₂ –R ₂₄ = 29, R ₂₄ = 13, Risk = 4/4.75	SAIDI = 4.10, R ₁₂ –R ₂₄ = 6.51, R ₂₄ = 4.65	SAIDI = 36.08, R ₁₂ –R ₂₄ = 271.87, R ₂₄ = 127.72	SAIDI = 126.31, R ₁₂ –R ₂₄ = 1668.73, R ₂₄ = 519.25
Remote disconnectors	SAIDI = 5.81, R ₁₂ –R ₂₄ = 51, R ₂₄ = 24, Risk = 8/9.50	SAIDI = 3.83, R ₁₂ –R ₂₄ = 11.73, R ₂₄ = 8.40	SAIDI = 47.35, R ₁₂ –R ₂₄ = 678.97, R ₂₄ = 320.96	SAIDI = 213.37, R ₁₂ –R ₂₄ = 5383.00, R ₂₄ = 1615.00
Breaker	SAIDI = 9.36, R ₁ –R ₂₄ = 83, R ₂₄ = 38, Risk = 8/14.25	SAIDI = 6.18, R ₁₂ –R ₂₄ = 19.09, R ₂₄ = 13.30	SAIDI = 57.67, R ₁₂ –R ₂₄ = 829.85, R ₂₄ = 388.02	SAIDI = 213.37, R ₁₂ –R ₂₄ = 5383.00, R ₂₄ = 1615.00
Secondary feeder	SAIDI = 9.87, R ₁₂ –R ₂₄ = 88, R ₂₄ = 41, Risk = 8/14.25	SAIDI = 6.51, R ₁₂ –R ₂₄ = 20.24, R ₂₄ = 14.35	SAIDI = 59.15, R ₁₂ –R ₂₄ = 853.42, R ₂₄ = 402.39	SAIDI = 213.37, R ₁₂ –R ₂₄ = 5383.00, R ₂₄ = 1615.00

^aNote, the average results is based on traditional calculations and not including all assumptions that have been made for *Severe* and *Extreme*, $0.9511 * \text{Normal} + 0.0422 * \text{Severe} + 0.0067 * \text{Extreme} \neq \text{Average (traditional)}$, but equal to new average presented in Table IX.

- Long outages:
- From Table IV, there is a 45.5 times higher probability that 1 km of OH line leads to an outage above 12 hours compared with 1 km of underground cable. Furthermore, OH lines contribute to more than 95% of all long outages. Therefore, in this paper, the number of long outages is assumed to change proportionally with the change in the percentage of OH lines. Here, the decrement is 69%.
- For other investments included here, the decrease in long outages is assumed to be in proportion to the decrease in SAIDI during calculation on *normal* or *average* weather.

Traditionally, asset management is based on reliability analysis calculating system average combined with cost analyses. Here, economic outage consequences are included (repair, regulation, and customer compensation) in the cost analyses, and hence, the traditional analysis can be performed by only comparing calculated LCC. Here, as shown in Table VIII, only the investment proposal of remote disconnectors is better than doing nothing and will therefore be proposed as most profitable if this method is used.

The LCC, however, has not included possible legal effects of violating the functional requirement or incurring abstract costs such as damage to the trademark. To capture these consequences, the traditional analysis is complemented by the proposed risk analysis. If the analysis is performed by using normal state, the proposal will be the same because the investment proposal with the lowest LCC has an acceptable risk.

When looking at average reliability, it is obvious that the present-day reliability has to be improved. Only the cable investment proposal provides a fully satisfactory result; however, this investment is significant more costly than all the others, and in this cases, remote disconnector investment is still the best option because risk value 10 can be accepted if all fully acceptable alternatives are significantly less attractive, that is, significantly more expensive (Section 3.6.2). However, one should consider complementing or slightly improving the remote disconnector proposal to decrease the risk value if this is not too costly.

3.7.3. Severe and extreme weather. This subsection concerns the calculation of the columns *severe* and *extreme* in Table VIII.

Table IX. Compile results and calculate new average.

	New average	Average (traditional)
Cables	Same result as traditional analysis	SAIDI=6.21, $R_{12}-R_{24}=29$, $R_{24}=13$, Risk = 4/4.75
Remote disconnectors	SAIDI=6.97 (+1.16) $R_{12}-R_{24}=75.9$ (+24.9) $R_{24}=32.4$ (+8.9) Risk = 8/14.25 (+0/4.75)	SAIDI=5.81, $R_{12}-R_{24}=51$, $R_{24}=24$, Risk value = 8/9.50
Other investment proposals	Rejected by traditional analysis (Table VIII) not better results with proposed method	

SAIDI, System Average Interruption Duration Index.

Assumptions that the reliability is affected by investments:

- *Cable investment proposal*:
- When changing from OH lines to underground cables, the probability of long outages is assumed to decrease proportionally to the decrease in the OH line despite weather state, motivated by the fact that underground cables are not exposed to these kinds of weather states. Here, the decrement is 69% (same as in the *normal* weather state).
- SAIDI is assumed to be transformed by using Table III.
- *Other investments included here* are as follows:
- In *extreme weather*, these investments are assumed not to be better than doing nothing, motivated by the fact that a large part of the system is affected at the same time, and therefore, these investments cannot be used at all.
- In *severe weather*, these investments are assumed to be possible to use half of the time. This is calculated by taking the average value by using Table III [21] and from reliability indices of doing nothing.

4. DISCUSSION, EVALUATION, AND FUTURE WORK

4.1. Discussion and evaluation of the results using the proposed analysis framework

When taking into consideration the risk of long outages and deeper analyses of each system state, the proposal of a remote disconnector is no longer attractive, as shown in Table IX. Despite the cost of the cable proposal, this is the only proposal that fulfills all the demands. Hence, either the expensive alternative of replacing OH lines with cables should be chosen or a new investment proposal should be developed, for example, replacing fewer OH lines and combining this with other investments.

4.2. Future work

More case studies investigating the difficult balance between increased incentives of, on the one hand, cost-efficiency and, on the other hand, reliability would be of interest, especially because the demand for reliable power delivery for both average reliability and major events is likely to increase.

Risk (e.g., reliability) and cost analyses have to concenter future challenges and changes in electric power systems, including an increased amount of distributed generation and various Smart Grid concepts.

5. CONCLUSIONS

An analysis framework is proposed in this paper. The aim is to allocate resources more cost-effectively and to capture severe events disregarded by methods, which only calculate mean values. Different

resource allocation proposals can be compared with respect both to average system reliability and to risk and vulnerability analyses of single system states such as severe weather.

An implementation on a real power distribution system has been performed. In addition to an evaluation of the proposed analysis framework, this implementation gives combined reliability and weather statistics useful as reference material.

In this paper, it is shown that totally different investment alternatives may be preferred, depending on whether a traditional analysis method using average values is used or the proposed analysis framework which also considers severe system states. This demonstrates the risks involved in using average values, and it is also shown that already available information can be used for improved asset management decision support.

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6. LIST OF SYMBOLS AND ABBREVIATIONS

6.1. Symbols

λ	Failure rate [failures/year]
A_i	Analysis of resource allocation i based on system average
A_{ij}	Analysis of resource allocation i when system in state j
C_i	Estimation of all cost during year i
ΔC_i	Cost difference between keeping current status and resource allocation i
C_{LCC}	Total LCC (life cycle cost)
C_V	Coefficient of variation
L	Economic lifetime
M	Number of resource allocation alternatives included in the analysis
N	Number of system states alternatives included in the analysis
N_i	Number of customers in load point i
R	Sum of all residual values and costs after the economic lifetime
R_X	Risk index concerning long outages above X hours
S_i	System state i
z	Interest rate [%]

6.2. Abbreviations

C	Consequence (category)
cust.	customers
DSO	Distribution system operator
hr	hour
int.	interruptions
LCC	Life cycle cost
LP_i	Load point i
OH	Overhead
P	Probability (category)
SAIDI	System Average Interruption Duration Index [hr/cust.,yr]
SAIFI	System Average Interruption Frequency Index [int./cust.,yr]
UK	United Kingdom
yr	year

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