A COST ANALYSIS METHOD FOR STORM CAUSED EXTENSIVE OUTAGES IN DISTRIBUTION NETWORKS

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ABSTRACT

Storms cause major disturbances and serious damage to electricity distribution yearly. In these cases the customers and networks located to rural area obviously suffer the most. The consequences of major disturbances can mainly be affected by network development and the most effective technique is underground cabling. Large-scale changes of the network structure require significant increase of yearly network investments, as the underground cabling of rural networks is relatively expensive. The relevant question is to determine the level of disturbances to which should be prepared with network investments and what are the economically reasonable boundaries that could be set for the outage time. On the other hand the impacts of extensive outages can be reduced and the outage time shortened by adding the number of maintenance personnel.

In this paper a method for evaluating the costs of extensive outage situations is proposed. One of the main results is the consideration of the major disturbances and the outage time boundaries to the costs of the network. The introduced analysis method is developed on the basis of statistical major outage information gathered by distribution company Suur-Savon Sähkö Ltd. (SSS Ltd.). Presented example calculations are carried on an area of 3100 km of distribution network that represents one sixth of the whole distribution network of SSS Ltd.

INTRODUCTION

Large disturbances in the past few years have raised public awareness and debate over the acceptable level of continuity of electricity supply. Society has found itself more dependent on electricity supply and therefore the pressure to assign regulations on continuity of supply has become evident. Customer compensation fees from long outages are already paid to the customers in many countries e.g. in Finland, where the customers start to receive compensation fees from outages over 12 h. In addition to compensation fees major disturbances cause network repair costs, which usually are higher than the possibly paid compensation fees. This type of development will make quality aspects crucial in the design and operation of electricity distribution networks.

After several serious disturbance situations during the last few years, regulators have started to set boundaries for the length of maximum allowed outage time. However, it is not easy to determine the actual economical benefits of these boundaries and the optimal level of network investments to meet the requirements. Costs caused by the major disturbances both to the customers and distribution companies have to be analysed and compared with the cost effects of setting outage time boundaries. On this basis the requirements for the major disturbance preparation level can be determined and also network investment strategies for meeting the requirements economically evaluated.

BASIS OF THE ANALYSIS METHOD

The introduced analysis method is developed on the basis of statistical data for analysing the costs caused by the major disturbances. The SSS Ltd. has gathered exhaustive data of the storm caused major disturbances over past years. A major disturbance is a situation in which over 20 % of the customers are without electricity, or the 110 kV line or the 110/20 kV primary substation or the primary transformer is out of order for several hours due a fault. In this case the 110 kV and primary substation origin interruptions have not been considered, as the goal has been to analyse weather caused disturbances in the MV and LV networks.

Two main categories of major disturbances, typical for the area, formed a backbone of the analysis. The first category (class-1) includes major disturbances that cause about 48 h outage, for average 45 % of the customers and occurs once in every 5 years (probability of occurrence during a year 0,2). The second category (class-2) depicts more severe situation in which over 50 % of customers are without electricity at the worst and managing the situation lasts for 5 days. This kind of situation has occurred approximately once in every 20 years (probability of occurrence 0,05).

As the weather phenomena are likely to change more radical in the future, the probability of large-scale major disturbances also increases. These kinds of disturbances cause the collapse of the electricity distribution and transmission system in large areas. The worst possible storm was considered to be at least 4 times as destructive than class-2 disturbance. Managing of this class-3 disturbance was defined to last 2 weeks and it considers nearly all the customers at the distribution area. The class 3 disturbance is approximated to occur once in 100 years (probability of occurrence 0,01).

MATHEMATICAL MODELS

The costs caused by major disturbances are approached by defining mathematical models for the three disturbance classes. The base of the mathematical model is describing the amount of customers without electricity as a function time during which the disturbance is cleared (clearance time). On this basis it is possible to determine customer outage costs and the amount of paid customer compensation fees. Another task is determination of repair costs of a disturbance caused destructions. For this the number of faults in the network and number of faults corrected as a function of time has to be determined. The disturbances are modelled for the entire distribution network as they typically affect to large area and because the problems in estimating the repair resources assigned for a specific part of the network during major disturbance situation. Afterwards the results can be proportioned to the studied area.

Customer outage costs

According to the statistical data the number of customers without electricity seem to follow the form exponential function until a case specific point in time. After that the number of customers without electricity reduce almost linearly. Figure 1 presents the statistic data of the proportion of customers without electricity as a function of clearance time in the class 2 disturbance and the modelled curve of the situation.

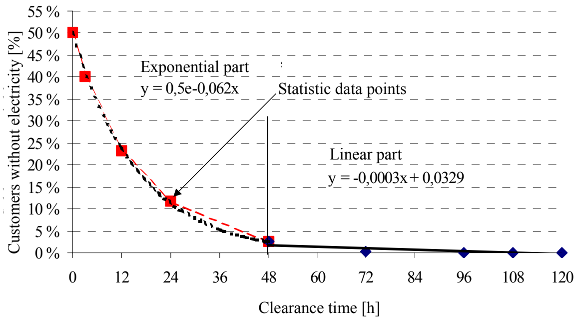

Figure 1. Mathematical model of the customers without electricity in class 2 major disturbance.

Similar models are formed also for class 1 and class 3 disturbances. The disturbance is assumed to start at the point in which the highest number of customers according to the statistics is without electricity. This simplification could be made because according to the statistics achieving that point of time occurs during the first 1-2 hours of the beginning of the event, nearly in every studied case at the area.

The customer outage costs C_{outage} are calculated on the basis of the modelled curves using the customer group-specific energy-weighted CENS (cost of energy not supplied) values with principles presented by (1)

$$C_{\text{outage}} = a \cdot \text{CENS}_{\text{A}} + \left(\int_{0}^{\text{T1}} (a \cdot e^{b \cdot t}) dt + \int_{\text{T1}}^{\text{T2}} (c \cdot t + e) dt \right) \cdot \text{CENS}_{\text{B}} \quad (1)$$

in which

a = max. number of customers without electricity after the beginning of the disturbance
b = constant coefficient based on the statistical data
c = angle factor of the linear part
e = constant coefficient of the linear part
A = CENS value €/kW
B = CENS value €/kWh

Customer compensation fees

In 2003 the amendment of electricity market act states that electricity distribution companies are to pay compensations to their customers on interruptions longer than 12 hours. The standard compensations are defined as stepwise increasing percentage of the distribution bill:

- 10 % of the distribution bill if the duration of the interruption is at least 12 hour but less than 24 hours,
- 25 % of the distribution bill if the duration of the interruption is at least 24 hour but less than 72 hours,
- 50 % of the distribution bill if the duration of the interruption is at least 72 hour but less than 120 hours and
- 100 % of the distribution bill if the duration of the interruption is at least 120 hours.

The maximum compensation is 700 euros per customer.

The modelled curve of figure 2 gives the number of customers without electricity at each defined moment of time. However, each customer receives the compensation only once. Hence, the customers receiving compensation fees of outages over 120 hours are subtracted from the customers without electricity after 72 hours and etc. In the proposed model the customer deviation is assumed to remain unchanged over the major disturbance, although in real the most demanding loads, like industry and services, would be the first ones to be recovered. The compensation fees are determined by first calculating the yearly average distribution fee per customer for each customer group. This is multiplied by the defined percentages and replaced with the maximum compensation fee if it is exceeded. Finally the compensation fees per customer at each time limit are multiplied with the number of customers and summed together.

Fault repair costs

The fault repair costs are based on the number of faults caused by the major event. The issue is approached through the statistics of actual fault repair costs of major disturbances and the company specific fault repair cost per fault during these situations. With this data it is possible to determine the number of faults and fault frequencies of low voltage (LV) and medium voltage (MV) networks during the major disturbances. These values are company specific and depend on the structure, locations and line types of the network. However, a base assumption is that the storms causing the major outage situations affect only to the aerial network. The actual fault repair costs are calculated by multiplying the number of faults with the unit repair cost of a fault.

The fault repair information is also used for determining the number of faults as a function of clearance time of a major disturbance. This is a function of total number of faults, the number of faults repaired by a person during a day and the size of the fault repair organisation. This fault number deviation has to mach with the model of customers without electricity. The repair potential and number of faults define the time in which faults are repaired. This model can be used to estimate how the fault repair time and so the clearance time of a major disturbance changes as the number of faults or the size of the organisation is changed. The main tool to affect to the number of faults is assumed to be underground (UG) cabling. As the managing time of a disturbance shortens, the curve of figure 2 is lowered so that it crosses the x-axel at the point that represents the new clearance time and customer outage costs of the event.

MAJOR DISTURBANCE COST ANALYSIS

The proposed model is used to analyse the costs caused by major disturbances to both customers and to a distribution company. Also the effects of the network and organization changes to the harm caused by the major events are studied. One goal is to determine the required network changes and their costs if the maximum outage time is limited to 72, 48, 24, 12 or 6 hours.

Study area

The studied area is in the network of the Finnish distribution company Suur-Savon Sähkö Ltd. The network consists of seven 110/20 kV primary substations and supplies 165 GWh energy to approximately 14 000 customers. The structure of the MV-network is mostly radial and 70 % of the lines are located to forests. Only interconnections between primary substations and few long feeders have backup connections. The studied network is a good representative of an average rural area network of SSS Ltd. The studied network represents approximately $^1/_6$ of the entire distribution network SSS Ltd. Key figures of the network are presented in Table 1.

Table 1. Key figures of the study area.

	LV-network (2 114 km)	MV-network (988 km)
Overhead lines	1.60 %	95.60 %
Underground cables	14.50 %	2.60 %
Aerial cables/ABC lines	82.00 %	0.40 %
Underwater cable	2.00 %	-
Covered conductor lines	-	1.40 %

Calculation parameters

In this study, investments costs of different strategies based on the component cost list of the Finnish electricity market authority. The capital costs are divided into investment costs and to financial costs. Financial costs are due to the cost of capital needed for the network investments and depict the paid interest. The financial costs are based on the net present value of the network. Operational costs include the costs of losses, maintenance and fault repairing. The customer outage costs both in normal operation situation and in major disturbances is formed using customer group-specific energy-weighted CENS values calculated on the basis of the parameters presented in table 2. The compensation fees are calculated on the basis of the customer deviation and distribution fees (table 3).

Table 2. Unit costs for power quality factors.

Customer group and energy shares	Unplanned interruption		Planned interruption		Auto-reclosures High-speed	Auto-reclosures Delayed
	[€/kW]	[€/kWh]	[€/kW]	[€/kWh]	[€/kW]	[€/kW]
Residential 51 %	0.36	4.29	0.19	2.21	0.11	0.48
Agriculture 10 %	0.45	9.38	0.23	4.8	0.20	0.62
Industry 11 %	3.52	24.45	1.38	11.47	2.19	2.87
Public 10 %	1.89	15.08	1.33	7.35	1.49	2.34
Service 18 %	2.65	29.89	0.22	22.82	1.31	2.44

Table 3. Customer deviation and customer group specific distribution fees.

Customer group	Customer deviation [%]	Distribution fee [cents/kWh]
Residential	87 %	5,1
Agriculture	6 %	4,8
Industry	1 %	2,3
Public	2 %	3,3
Service	4 %	3,3

He fault repair costs in major events are 2000 €/fault for normal organisation and 2500 €/fault for emergency personnel. The proportion of emergency resources is 30 % in all disturbances. The fault repair potential is 1 fault/person,d. The size of the repair organisation is based on company specific data. The study period is 40 years and the interest rate 5 %. Load growth is not taken into account (r = 0 %). The costs of network losses are 35 €/MWh.

Results of the analysis

In addition to the present network (A) of the study area, the major disturbance costs are calculated also defined for a network structure achieved by moving the MV-lines next to roads, applying 1 kV LV-system at the low loaded branch lines and using UG-cabling at the LV-network in conditions suitable for cable ploughing (about 80 %, the rest is built with aerial bundled cables). This kind of network solution gives the total cost optimum and is called optimal network. The network solutions that fulfil the demand of maximum outage time of 72, 48, 24, 12 and 6 hours are based on the optimal network and are achieved by increasing the amount of UG-cabling. The UG-cabling is assumed to be the only

solution to affect to the duration of disturbances.
Clearance time of the class-1 disturbance for the present and optimal network solution are 48 h and 27 h, and correspondingly for the class-2 disturbance 113 h and 60 h, and for the class-3 disturbance 410 h and 220 h. Table 4 presents the unit costs of major disturbances and their expected yearly costs. The expected yearly costs are determined on the basis of the occurrence probability of each major disturbance class. In class 1 disturbance the 72 and 48 hour limits are achieved with the existing network.

Table 4. Unit- and expected yearly costs of major disturbances.

Network solution	Total Unit costs of disturbance [k€]			Expected yearly costs [k€/a]		
	Class-1	Class 2	Class 3	Class-1	Class-2	Class-3
Present network	1 284	2 477	30 400	257	124	304
Optimal network	693	1 995	13 428	139	100	134
6 h network	70	131	54	14	6.6	0.5
12 h network	355	365	161	71	18	1.6
24 h network	615	967	570	123	48	5.7
48 h network	1 284	1 831	1 953	257	92	20
72 h network	-	1 996	3 690	-	100	37

The customer outage costs dominate the total unit costs of the major disturbances. The customer outage costs form average 80 % of the costs of major disturbances in the studied major disturbances. The rest 20 % is divided almost evenly between the fault repair costs and customer compensation fees.

The achievement of the 72, 48, 24, 12 and 6 hour maximum clearance times requires severe network changes. In the table 5 is presented the required proportions of UG-cabling for the studied major disturbance classes. Figure 2 presents the affect of increasing the size of fault repair organisation to the clearance time of class-2 disturbance. With tripling the size of the organisation, the proportion of needed UG-cabling can be reduced in the class-1 and class-2 disturbances but not in the case of the class-3.

Table 5. Proportion of UG-cabling required to achieve the defined clearance time limits in different major disturbances.

Network solution	Class-1		Class-2		Class-3	
	LV-network	MV-network	LV-network	MV-network	LV-network	MV-network
6 h network	85.3 %	87.0 %	86.5 %	100 %	96.8 %	100 %
12 h network	85.3 %	62.5 %	85.3 %	90.0 %	93.6 %	100 %
24 h network	85.3 %	13.0 %	85.3 %	69.0 %	87.1 %	100 %
48 h network	14.7 %	2.9 %	85.3 %	25.0 %	85.3 %	89.7 %
72 h network	14.7 %	2.9 %	85.3 %	3.8 %	85.3 %	77.7 %

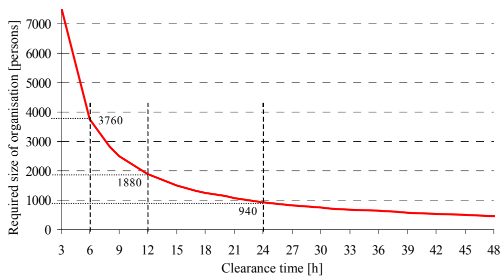

Figure 2. Required size of fault repair organization in class-2 disturbance.

The table 6 presents the sum of the total costs of all major disturbance classes and the total costs of the network solutions over the study period, including the network solutions enabling the defined clearance time limits in all situations (class-3 solutions). The costs of completely UG-cabled network are presented for comparison.

Table 6. Total costs of the network solutions and the sum of the costs of all major disturbance classes discounted over the study period.

Network solution and replacement value [M€]	Investment costs [M€]	Financial costs [M€]	Opex. [M€]	Outage [M€]	Major disturbances [M€]	Total [M€]
Present network 59.0	25.4	25.4	6.0	10.5	11.8	79.1
Optimal network 46.0	19.9	19.9	4.7	5.4	6.4	56.4
6 h network 86.8	37.3	37.2	2.9	1.0	0.1	78.4
12 h network 86.0	36.9	36.9	2.8	1.0	0.2	77.8
24 h network 84.2	36.1	36.0	2.7	1.0	0.3	76.3
48 h network 77.0	33.0	32.9	3.1	1.5	1.2	71.7
72 h network 69.6	29.8	29.9	3.3	2.1	2.1	67.2
UGC-network 88.0	37.6	37.6	2.9	1.0	0.0	79.2

As the table 6 show the costs of major disturbances over the study period of the same magnitude as the outage costs of normal operational situation. The costs of the major disturbances narrow the cost difference between the UG-cabled network solutions and the existing network. However, the costs of the optimal solution are considerably lower and the costs of major disturbances are not high enough to make the totally UG-cabled network the most economic solution. As today's customer outage parameters are designed to describe mainly few hour-long outages, they represent badly the actual harm caused to the customers by major disturbances with long clearance time. In the future the weight of these parameters is expected to increase and perhaps own customer outage parameters for major disturbances will be defined. This will surely increase the economy of the UG-cabling at the low loaded rural networks, like the presented study area.

CONCLUSIONS

The cost effects of major disturbances both to the customers and distribution companies can be modelled with the introduced calculation method. The impact of major disturbances can be reduced by increasing size of the maintenance and fault repair organisation and by changing the network structure. However, the studies have indicated that the impacts of adding personnel are smaller than the ones achieved with network rearrangements. If the capability to manage severe storms in any situation is a prime criterion, a full-scale underground cabling in both low and medium voltage networks is only workable method. This increases the costs of the distribution that mirrors to the customer's bills. There is still high level of uncertainty in pricing of the major disturbances, which origin partly from the bad predictability of the disturbances and available calculation parameters. However, modeling of the costs is needed to ensure cost efficiency of the distribution business.