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THE RELIABILITY ANALYSIS OF DISTRIBUTION SYSTEMS WITH DIFFERENT OVERVOLTAGE PROTECTION SOLUTIONS

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Abstract – This paper presents a time-sequential simulation technique incorporating the effects of interruptions and voltage sags in the reliability cost/worth evaluation of distribution systems equipped with different overvoltage protection types. The interruption and voltage sag data for different overvoltage protection schemes was obtained from long-term measurements performed at a 110/20 kV substation. Studies conducted in a real distribution system show that the type of overvoltage protection has more impact on network reliability than has earlier been thought.

Keywords: interruption, power distribution, reliability, surge arrester, spark gap, voltage sag

1 INTRODUCTION

Most of the interruptions and voltage sags experienced by low voltage customers are caused by faults in medium voltage (MV) networks. Minimizing the number and duration of MV faults - especially short circuits – would partly lead to minimizing the effects of poor power quality and improving the reliability of the power system. In rural areas, MV power distribution systems include radially operated, overhead line feeders typically supplying dozens of pole-mounted power distribution transformers. Power distribution transformers are equipped against overvoltages either with surge arresters or spark gaps. However, the operation of different overvoltage protection equipment has a significant influence on experienced interruptions and voltage sags. Long-term measurement results concerning this matter are presented in this paper.

In addition, a reliability study of the effect of the overvoltage protection type on a distribution system is performed. The reliability study includes a time-sequential simulation technique incorporating the effects of the monthly distribution of interruptions, voltage sags and power in reliability cost/worth evaluation. The profitability of an investment in overvoltage protection is analyzed using the Internal Rate of Return –method.

2 RELIABILITY MODELS

2.1 Basic Model

In a basic reliability evaluation of a distribution system, only interruptions are taken into account. In addition, the simplest models assume the rates of failure and repair, cost and power demand to be constant [1].

In this study, in addition to the inconvenience caused by interruptions, voltage sags are also taken into account in the cost function (1).

$$C_{tot} = C_{int} + C_{sag} \qquad (1)$$

C_{tot} = annual cost of interruptions and sags (€/a)
C_{int} = annual interruption cost (€/a)
C_{sag} = annual voltage sag cost (€/a)

For radially operated MV networks, equation (2) can be used to calculate the cost caused by interruptions. The fault occurs at point *i* and the customer is located at load point *j*.

$$C_{int} = \sum_i \sum_j \lambda_{i,int}(a_j + b_j t_{ij})\Delta P_j \qquad (2)$$

$\lambda_{i,int}$ = number of interruptions (1/a)
a_j and b_j = per unit cost values for the demand and energy not supplied to load point *j*, when the interruption time is *t* (€/kW and €/kWh)
t_{ij} = interruption time (h)
ΔP_j = interrupted power (kW)

An MV fault causes an interruption in the line concerned, but it causes a voltage sag in all adjacent feeders connected to the same substation busbar. Similarly, the cost caused by experienced voltage sags is obtained by multiplying the number of sags $\lambda_{ij,sag}$ with the customer category sag prices $C_{j,sag}$ [2].

$$C_{sag} = \sum_i \sum_j \lambda_{ij,sag} C_{j,sag} \qquad (3)$$

In (3), number of sags $\lambda_{ij,sag}$ refers to sags with critical characteristics (remaining voltage lower than the critical value and sag duration longer than the critical duration). Thus, at this stage, data of the local voltage sag distribution and customer processes are needed [3]. As Figure 1 shows, it is not insignificant what voltage sag characteristics are determined as critical. Typically, for example, the annual number of voltage sags having remaining voltage U_{sag}<90% of nominal voltage is a multiple of the number of voltage sags with U_{sag}<50%.

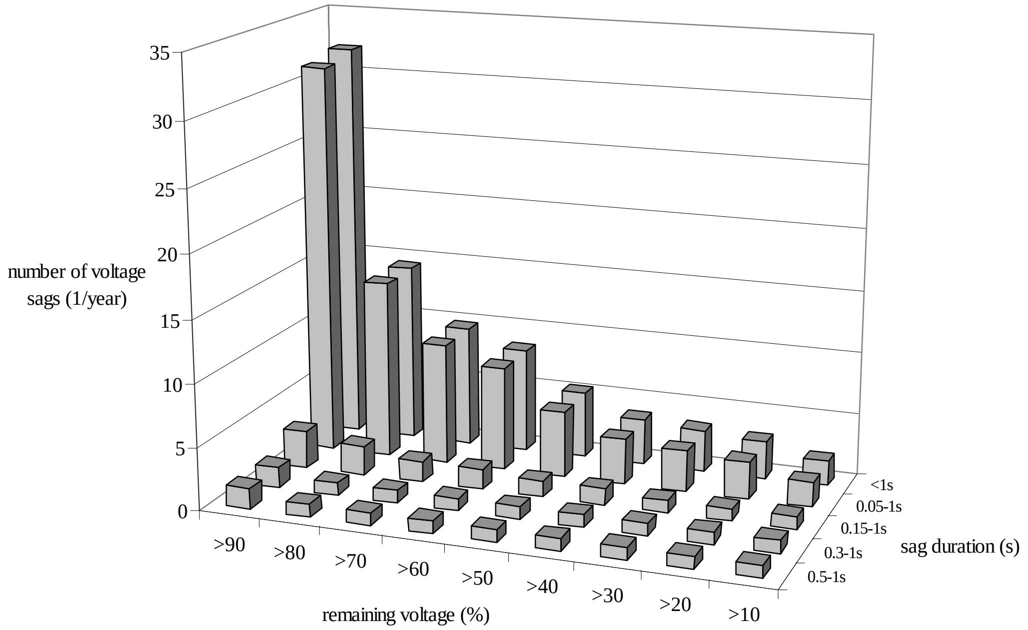

Figure 1: Cumulative sag distribution measured at an 110/20 kV substation.

2.2 Time-Varying Models

Usually, the basic reliability models do not include time-variation. However, faults do not occur constantly throughout the course of the year, and the restoration and repair times vary depending on the season and the power demand of the customers, according to the hour, day, and month. Correspondingly, the inconvenience caused by disturbances and experienced by customers depends on the time of the occurrence.

In this study, a time-varying model is applied. The year is divided into 12 discrete months. It is assumed that during each month, the fault and sag frequency and the power demand are constant. The time-varying character can be modeled by using the annual, average frequencies weighted by the chronological variation of the feature [4]. The factor *m(t)* for each month *t* is determined by dividing each monthly value (Figure 2, Figure 3) with the average value $\lambda_{int,avg}$, $\lambda_{sag,avg}$, P_{avg}.

$$\lambda_{int}(t) = m_{int}(t) * \lambda_{int,avg} \tag{4}$$

$$\lambda_{sag}(t) = m_{sag}(t) * \lambda_{sag,avg} \tag{5}$$

$$P(t) = m_{power}(t) * P_{avg} \tag{6}$$

Similarly in this study, the repair and restoration times are modelled.

Of course, other types of distributions could be applied or, instead of using a division of 12 months, the year could be divided into 52 weeks or 365 days, etc. In this study, cost/interruption and cost/voltage sag are assumed to be constant in the course of the year.

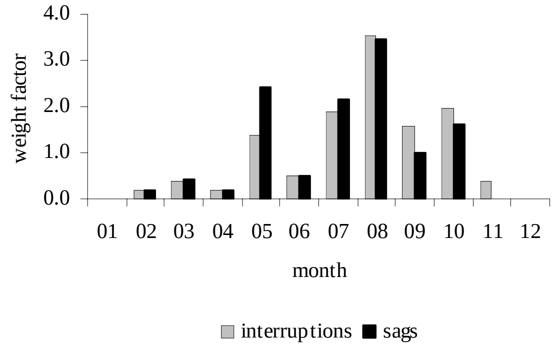

Figure 2: Monthly weight factor for interruptions and voltage sags.

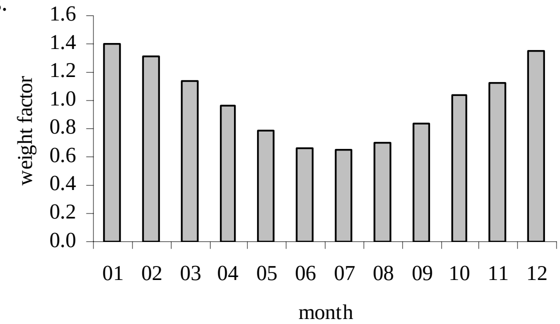

Figure 3: Monthly weight factor for power.

3 OVERVOLTAGE PROTECTION OF DISTRIBUTION TRANSFORMERS

Earth faults, switching operations and lightning cause overvoltages in MV networks. While especially lightning strokes cause steep overvoltages which may damage the windings of distribution transformers, typically spark gaps or surge arresters are installed as overvoltage protection on each distribution transformer (Figure 4).

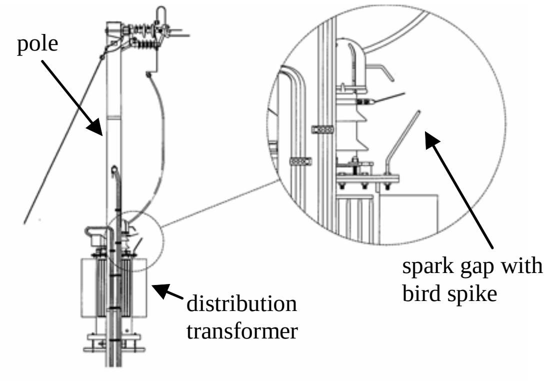

Figure 4: Pole-mounted distribution transformer with spark gaps.

From the network operation point of view, different overvoltage protection types have a markedly different influence on network behaviour. When a spark gap operates, a single-phase earth fault is created on the system and an opening of a circuit breaker is usually needed to remove the fault. If two or three parallel spark gaps are activated at the same time, a 2- or a 3-phase-to-ground short circuit enters the system. On the contrary, if surge arresters are used, and one, two or three surge arresters operate, no interruption or sagged voltages in the substation area will be experienced.

In the case of spark gaps, the experienced fault types depend on the cause of the fault (Figure 5). Lightning can directly hit the feeders causing extremely high overvoltages [5], [6]. These faults are serious causing most probably a 3-phase short circuit regardless of the overvoltage protection type. Lightning strokes in the neighbourhood of feeders may also cause overvoltages by inducing overvoltages that propagate at the same speed on each of the three phases. When they reach the nearest spark gapped transformer, often a 2- or 3-phase-to-ground short circuit will occur. In addition to lightning, spark gaps may also operate unexpectedly. The open construction makes it possible for a spark gap to unintentionally operate if, for example, a small animal (like a bird or a squirrel) or a tree branch gets between the metallic rods. A single-phase earth fault will then occur. Further, an electric arc burning in one spark gap may spread to the neighbouring spark gap. This means a 2-phase-to-ground short circuit and a more serious fault.

The operation of surge arresters causes no fault on the system. The closed structure of surge arresters prevents the access of small animals, the influence on neighbouring surge arresters and the effects of out-door weather conditions. On the other hand, surge arresters are more expensive and the detection of a broken surge arrester is difficult.

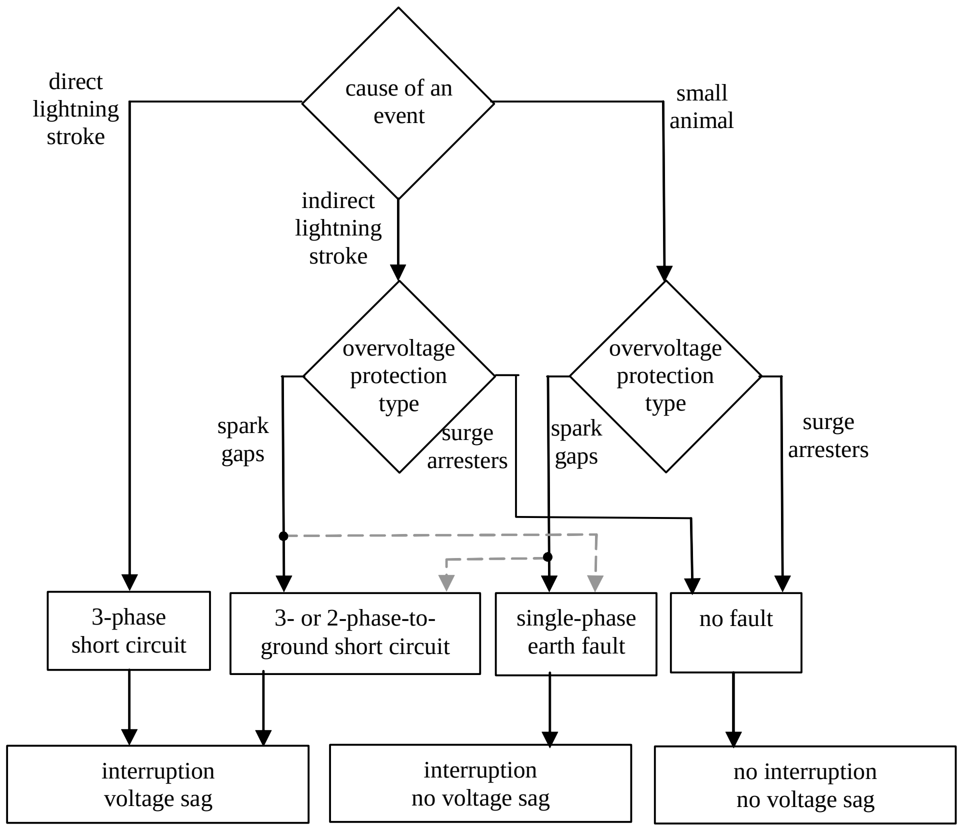

Figure 5: The influence of the cause of a disturbance and overvoltage protection type on fault types.

4 MEASUREMENT RESULTS

Long-term measurements started in June 2002 at a 110/20 kV substation located in the middle part of Finland [7]. The substation supplies a rural area with five overhead line feeders. In terms of overvoltage protection, this substation has an exceptional feature. Usually, a feeder has both spark gaps and surge arresters, depending on the power distribution transformer ratings. However, in this substation, three of the five MV feeders supply distribution transformers with only spark gaps and two other feeders have only externally gapped metal-oxide surge arresters. From a network operation point of view, these externally gapped metal-oxide surge arresters operate like surge arresters (Figure 5). Feeders are categorized into two groups: feeders with only spark gaps and feeders with only surge arresters (Table 1). The feeder groups are also comparable in other characteristics, like the total feeder length and the total number of distribution transformers.

Table 1: Categorisation of feeders.

Overvoltage protection type	Spark gaps	Surge arresters
Number of feeders	3	2
Total feeder length (km)	98	102
Number of transformers	77	82

4.1 Monthly Distribution of Interruptions and Sags

The causes of interruptions and voltage sags vary according to the season. The winter months experience snow and freezing weather and during the autumn months, hard storms with strong wind and rain cause disturbances. Lightning storms (including lightning strokes, strong wind, rain, falling tree branches and trees) occur during the summer months from May to August. Figure 6 presents the monthly distribution of faults and voltage sags measured at the 110/20 kV substation during 2004. Here an MV fault means a fault where a circuit breaker operation at the 110/20 kV substation was needed. Altogether 108 such faults occurred during the year in the substation area.

In ungrounded or compensated neutral MV networks, only short circuits cause sagged phase-to-phase voltages. However, in Figure 6 the number of voltage sags is lower than the number of short circuits. The main reason for this is that here the number of voltage sags is counted according to how many of the three phase-to-phase voltages are sagged below U_{sag}<90% of the remaining voltage during each recorded disturbance (the phase-to-phase sag on the MV side of a Dyn transformer means a phase-to-earth sag on the LV side). In addition, if a short circuit fault occurs far away from the substation, the voltages on the substation busbar do not necessarily sag below U_{sag}<90% of the remaining voltage and are not listed as a voltage sag. For these reasons the number of voltage sags may be lower than the number of short circuits. On the contrary, the number of voltage sags also includes sags caused by faults occurring in the transmission system [2]. However, their share is so small that their influence is not seen in the figure.

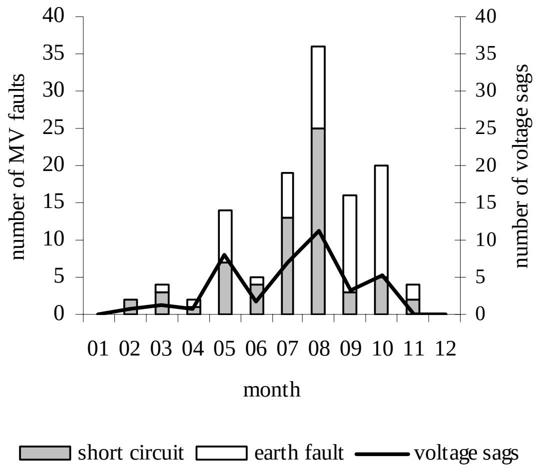

Figure 6: The number of short circuits and earth faults that occurred in the MV system, and experienced voltage sags with U_{sag}<90% during the year 2004.

4.2 Fault and Sag Frequencies

Based on the different influence the operation of each overvoltage protection type has on network behaviour, it is expected that the fault frequency of the feeders with spark gaps will be higher than the fault frequency of feeders with surge arresters (Figure 5). The fault frequency of spark gapped feeders was about eight times the fault frequency of surge arrested feeders in 2004 (Table 2). Changed fault type means an occasion where a single-phase earth fault develops after some cycles into a 2-phase-to-ground short circuit. This has been typical in spark gapped feeders [7]. There is no major difference in the share of short circuits. In spark gapped feeders, the changed fault type phenomenon increases the share of short circuits. The difference in sag frequency is mainly based on the difference in fault frequency.

Table 2: Fault characteristics of feeder categories in year 2004.

Overvoltage protection type	Spark gaps	Surge arresters
Number of faults	95	13
Fault frequency (1/100km)	96.9	12.7
Changed fault type (1/100km)	9.1	0
Fault types		
- 3-phase faults (%)	5	9
- 2-phase faults (%)	37	27
- single-phase earth faults (%)	58	64
Sag frequency (1/100km)	21.1	2.3

Most of the faults are cleared by high-speed autoreclosure (Figure 7). As expected, the share of faults cleared by high-speed autoreclosure is higher in spark gapped feeders. Altogether 4 permanent faults were experienced during 2004. Three of them occurred in spark gapped feeders and the causes of these faults were fallen trees on the 20 kV overhead line feeders. The use of surge arresters would not have prevented these faults. The permanent fault on the surge arrested feeder was caused by a broken surge arrester.

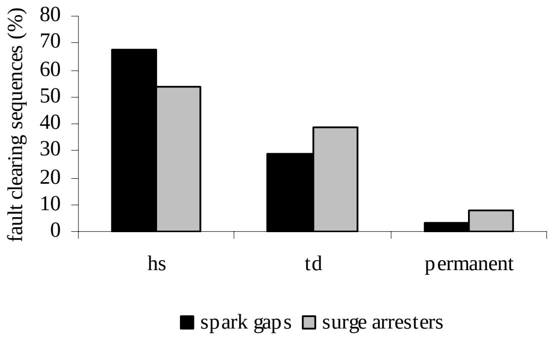

Figure 7: Shares of different fault clearing sequences.

5 RELIABILITY STUDY

In the reliability study, the monthly distributions of measured interruptions, voltage sags of remaining voltage U_{sag}<50%, power, and restoration and repair times are established. Further, the cost caused by interruptions (2) and voltage sags (3) are calculated for the feeder groups having either spark gaps or surge arresters. In the calculations, real customer data is used. Customers are categorized into the following groups: domestic, agricultural, industrial, commercial services and public services (Table 3) [8]. The number of customers in spark gapped feeders is 395, and in surge arrested feeders 826, respectively. The surge arrested feeders take about 75% of the substation power. Table 4 presents the cost parameters to be applied to (2) and (3). For interruptions times real feeder and fault type sensitive data was applied.

Table 3: Distribution of power and number of customers between different customer groups.

Customer groups	Power (%)		Customers (%)	
	Spark gaps	Surge arresters	Spark gaps	Surge arresters
Domestic	75	70	82	83
Agriculture	20	8	15	7
Industrial	1	7	<1	1
Commercial	3	7	2	3
Public	1	8	1	6

The total costs are calculated for those feeders having only spark gaps and only surge arresters (Figure 8a, Table 5). The total annual cost caused by interruptions and sags in the substation area is 84105€.

Table 4: Value used for a single voltage sag and interrupted p.u. demand and energy in each customer class [2], [8].

Customer category	Cost per sag (€)	Cost of interruption	
		for demand (€/kW)	for energy (€/kWh)
Domestic	1	0	1.4
Agriculture	1	0	11.2
Industrial	1060	4.4	18.6
Commercial	170	4.0	22.2
Public	130	1.2	7.4

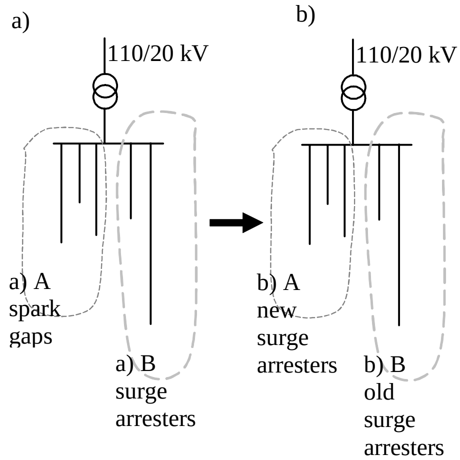

Figure 8: The feeder categories used in the reliability studies: a) original construction having three feeders with spark gaps and two feeders with surge arresters, b) invested network having only feeders with surge arresters.

Table 5: Costs of interruptions and voltage sags of the year 2004 for feeders equipped with spark gaps and with surge arresters.

Disturbance	Costs per year (€)	
	Spark gaps Figure 8a)A	Surge arresters Figure 8a)B
faults cleared by high-speed autoreclosure	1612	1429
faults cleared by time-delayed autoreclosure	633	1727
permanent faults	797	6033
Sum interruptions	3043	9189
Voltage sags	9022	62852
Sum	12064	72041
Total costs	**84105**	

The interruption costs are considerably higher in surge arrested feeders. The main reason is the profile of the customers. The surge arrested feeders supply two thirds of the substation customers who reserve 75% of the substation power. The costs caused by voltage sags are also higher in surge arrested feeders. In addition to the customer profile, the main reason for these higher costs is the nature of voltage sags: the main origin of voltage sags is the high number of short circuit faults occurring in spark gapped feeders and experienced in the whole substation area.

The network reliability can be improved by replacing the spark gaps with surge arresters (Figure 8b). The economy of the investment can be assured by comparing the savings in disturbance costs obtained for the whole substation area with the required investment costs. When such an investment is made a lower number of disturbances will be experienced. This concerns temporary faults (faults cleared by high-speed and time-delayed autoreclosure) as well as voltage sags. However, despite the replacement, permanent faults and the sags caused by 110 kV transmission system faults can not be avoided.

If it is assumed that after the investment, the fault frequency of temporary faults of the whole substation area accords with the fault characteristics of the old surge arrested feeders, the costs caused by interruptions and voltage sags can be recalculated. Table 6 presents the savings achieved by this investment. Noteworthy is that the major saving is achieved in voltage sags experienced by the customers in the old surge arrested feeders. When the number of these faults in the adjacent feeders can be reduced, a lower number of voltage sags will be experienced in the whole substation area. In this study, the annual savings in the whole substation area are 47262€.

Table 6: Savings in costs of interruptions and voltage sags for feeders of new and old surge arrested feeders.

Disturbance	Savings per year (€)	
	New surge arresters Figure 8b)A	Old surge arresters Figure 8b)B
faults cleared by high-speed autoreclosure	1410	0
faults cleared by time-delayed autorelcosure	554	0
permanent faults	0	0
Sum interruptions	1964	0
Voltage sags	5014	40284
Sum	6978	40284
Total savings	**47262**	

The profitability of the investment is analyzed using the Internal Rate of Return (IRR) calculation method [9]. The investment costs include the cost of surge arresters, the replacement work and the cost of planned interruptions caused by the replacement work. The profitability varies with the observation periods as shown in Figure 9. The price of the investment can be determined accurately but the cost of inconvenience includes uncertainty, human estimations, and individual ways of thinking. Thus, Figure 9 also shows the change in profitability obtained when sensitivity analysis is used and the disturbance costs are varied by 50%, 100%, 150% and 200% of the current cost level. In a ten-year observation period, the profitability threshold, based on an internal interest rate of roughly 10%, is almost reached. If only interruptions would have been taken into account, no profitability would have been achieved regardless of the length of the observation period.

Instead of installing surge arresters, a device having a surge arrester in series with a spark gap (externally gapped metal-oxide surge arrester) could be used instead (like is originally already installed to two of the feeders of this substation area). The price of this device is considerably lower. When using these devices the whole investment would be noticeably cheaper. If it is now assumed that the disturbance costs are 100%, the internal rate of return would, in a 10 years observation period, be 14% instead of 7% and, in 15 years, 17% instead of 11%.

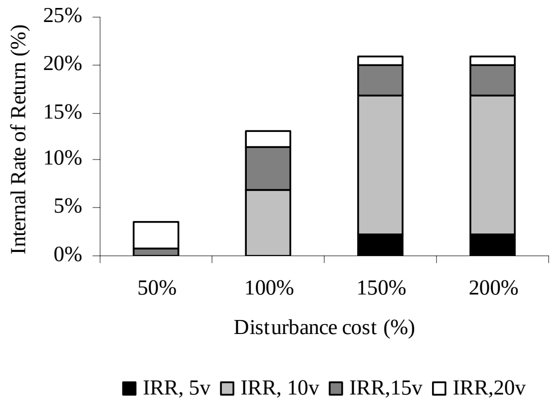

Figure 9: Profitability of investments with estimated disturbance costs.

6 CONCLUSIONS

To protect distribution transformers against lightning, each distribution transformer is typically equipped with either spark gaps or surge arresters. The overvoltage protection type has, however, a significantly different influence on caused fault types, interruptions and voltage sags. In this paper, long-term measurement results showed the customers supplied by MV feeders with surge arresters to experience only one eighth of the number of faults experienced in spark gapped feeders. In addition, the sag frequency was considerably lower in this feeder category.

A reliability study on the effect of the overvoltage protection type on a distribution system was performed. The reliability study includes a time-sequential simulation technique incorporating the effects of the monthly distribution of interruptions, voltage sags, power, and repair and restoration time in reliability cost/worth evaluation. The long-term measurement results and real customer data were used as an input in this study. The results showed that the customer profile strongly determines the experienced inconvenience in the substation area.

The profitability of investing in different overvoltage protection types was studied by comparing the replacement of spark gaps with surge arresters to the savings obtained through reduced inconvenience of interruptions and voltage sags. The profitability calculations were based on the Internal Rate of Return method. The results strongly encourage the use of surge arresters for overvoltage protection.

Choosing to invest in surge arresters was shown to be profitable. Noteworthy at this stage is that the mixed use of both spark gaps and surge arresters considerably decreases the profitability of the investment. Especially in the neighbourhood of substations, the means to limit the number of faults causing interruptions and, in particular, serious voltage sags should be supported.

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