PUBLICATION II

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A Method for Estimating the Frequency and Cost of Voltage Sags

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***Abstract*—The annual number and cost of voltage sags were determined for five Finnish distribution companies. The method of fault positions was applied for the calculation of voltage sag frequency. The economic consequences were assessed by multiplying the sag frequency and cost by the number of customers. The cost of a single sag was taken from a survey that had been carried out in three Nordic countries in the mid 1990s. This paper proposes a method for retrieving sag-related information from statistics originally prepared for other purposes. In addition, this paper provides an estimate of the total annual sag-related cost for each of the companies considered in this study and for each customer category. The total cost per company appeared to be much higher than had generally been assumed.**

***Index Terms*—Power distribution, power quality, power system modeling.**

I. Introduction

A VOLTAGE SAG is a sudden reduction of the supply voltage followed by a voltage recovery after a short period of time. In medium voltage distribution networks, voltage sags are mainly caused by power system faults. In comparison with interruptions, voltage sags affect a larger number of customers and for some customers voltage sags may cause extremely serious problems [1]–[3].

In this paper, the average annual frequency and cost of voltage sags for customers of five small-scale Finnish power distribution companies are evaluated. The threshold of interest was taken to be when the remaining voltage U was less than or equal to 50% of the nominal $(U < 50\%)$. Due to the inherent strength of transmission and subtransmission systems and their rather low fault frequency, [4], [5], HV system faults seldom cause sags deeper than the threshold level in the MV network. For this reason, only sags caused by medium voltage faults are considered. The results show how the sag costs depend on the distribution network characteristics.

The annual sag frequency as a function of sag magnitude is one tool for evaluating the importance of sags. Another even more important tool is to assess the annual cost of voltage problems that are associated with sags. The annual sag frequency experienced by a customer is required as an input for this study. The other essential input data is the approximate cost that one sag imposes on a customer. The required data was obtained from a Nordic survey completed in 1994. In the questionnaire, the customers were divided into five categories: domestic, agricultural, industrial, commercial services, and public services. The third variable needed for determining the sag cost is the number of customers in each category. These numbers were obtained from a Finnish survey for five utility companies still in existence. Multiplying the sag frequency, sag cost of a customer category and number of customers in the category gives an estimate of the annual cost that sags impose on the network of each company under consideration.

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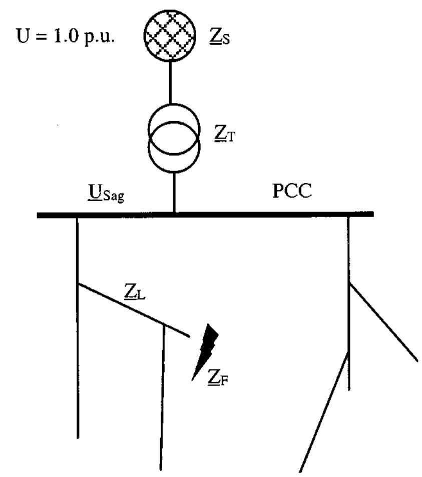

Fig. 1. Calculating voltages during a voltage sag.

II. Magnitude and Frequency of Voltage Sags

Voltage sags can generally be characterized by the sag magnitude, the sag duration, and the annual sag frequency.

A. Sag Magnitude

When analyzing a radially supplied distribution network, the voltage sag can be modeled using Fig. 1 and [6], [7].

$$\underline{U}_{\mathrm{Sag}} = \frac{\underline{Z}_L + \underline{Z}_F}{\underline{Z}_S + \underline{Z}_T + \underline{Z}_L + \underline{Z}_F} * 1.0 \text{ p.u.} \tag{1}$$

where

- U_{Sag} voltage sag magnitude (p.u.);
- Z_L feeder impedance from the substation to the fault location;
- Z_F fault impedance;
- Z_S source impedance;
- Z_T transformer impedance.

Equation (1) can also be written as

$$\underline{U}_{\mathrm{Sag}} = (\underline{Z}_L + \underline{Z}_F) * \underline{I}_F \tag{2}$$

where I_F is the fault current.

The pre-event voltage is assumed to be 1.0 p.u. and load currents are not taken into account. The voltage sag can be determined either as the voltage drop or as the remaining voltage at the PCC, the point of common coupling. In this paper, the voltage sag magnitude refers to the remaining voltage at the PCC (1).

When assuming a fault impedance of $Z_F = 0\ \Omega$, pessimistic values for voltage sag characteristics are obtained. To improve the assessment a fault impedance model can be applied. Fault impedance modeling has been of interest in the area of distance relays as the fault impedance causes inaccuracy in the distance measurement of these relays. Based on field tests conducted in the 1930s, A. R. van C. Warrington indicated that in the case of short circuits in overhead line networks, the fault impedance is mainly made up of the resistance of an electric arc. The fault resistance can then be modeled in stable conditions according to the Warrington formula [8], [9].

$$R_F = \frac{8750}{I_F^{1.4}} * \frac{l}{0.305} \tag{3}$$

where R_F is the fault resistance (Ω); I_F is the fault current (A); and l is the length of the electric arc (m).

By combining (2) and (3), the fault current can be solved by iteration. Further, the fault resistance can be solved using (3) and the voltage sag using (1).

B. Frequency of Voltage Sags

It is also necessary to be able to estimate how often customers experience sags. This estimation requires a probabilistic approach and network reliability data [10], [11]. The fault frequency rates of network components are combined with the sag analysis result. By these means, a sag distribution (sag magnitude, duration, and frequency) can be determined for each customer. Often a cumulative sag frequency, consisting of sags that have a remaining voltage below the threshold magnitude and lasting longer than the threshold duration, is of interest.

The network reliability data is typically derived from permanent faults. This input data is not satisfactory when evaluating the frequency of voltage sags, however. There are two main limitations:

1) The fault statistics do not typically include data about the fault type (three phase/phase-to-phase/earth fault/etc.). Different fault types are associated with different voltage sag characteristics and thus their relative shares should be determined. For example, in high impedance earthed medium voltage distribution networks only short circuits on the MV side cause voltage sags on the LV side and thus MV earth faults should be omitted. Three and two-phase short circuits cause different voltage sag characteristics and this should also be taken into account. In symmetrical three-phase short circuit faults, all the phase voltages sag equally. In the case of two-phase short circuit faults, two of the phase voltages sag and the third phase voltage remains unaffected (see Fig. 2). Depending on the connections of the transformers and equipment, the phase to neutral or phase to phase voltages must be examined.

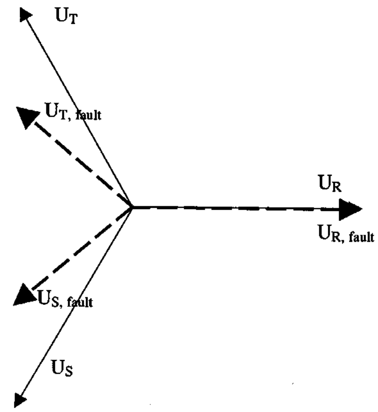

Fig. 2. Phase to neutral voltages before (solid line) and during (dashed line) a phase to phase fault.

2) Fault statistics usually consider only permanent faults. If autoreclosing arrangements are in use the number of faults cleared by time-delayed and high-speed autoreclosure have to be estimated by some other means. The share of each fault type differs in faults cleared by high-speed, time-delayed autoreclosure or in permanent faults. Thus, the remarks mentioned above in point 1. should be applied to each fault clearing type. For example, the share of earth faults is typically surprisingly high in faults cleared by high-speed autoreclosure.

One aim of the study presented in this paper is to discover the average annual sag frequency (where $U < 50\%$) that the LV customers of each distribution company will experience because of faults in radially supplied medium voltage (20 kV) distribution networks. In Finland, MV networks either have isolated neutrals or are earthed via coils. Thus earth faults do not cause any sags on the LV customer side and are therefore omitted in this study. The sag distributions that are caused by permanent faults are first calculated. In this step, a single line diagram network model is used and the sags are computed as if all the permanent faults were three-phase faults. When the critical sag magnitude is chosen to be $U = 50\%$, the effect of two-phase short circuits as opposed to three-phase short circuits can be taken into account by a single factor. Further, when calculating the sag frequency with fault frequency input data determined from permanent faults, the different fault clearing types and the shares of the different fault types are taken into account by modifying the initial sag distribution

$$f(U_{\text{Sag}}) = f_{pf}(U_{\text{Sag}}) * \left(p_{sc,pf} + \frac{n_{td}}{n_{pf}} * p_{sc,td} + \frac{n_{hs}}{n_{pf}} * p_{sc,hs}\right) * (p_{sc,3} + (1 - p_{sc,3}) * k_{2/3}) \tag{4}$$

where

$f(U_{\text{Sag}})$ voltage sag distribution (magnitude and frequency) experienced by all the customers;

$f_{pf}(U_{\text{Sag}})$ voltage sag distribution computed by a single line diagram and using fault frequency of all permanent faults;

$p_{sc,pf}$ share of short circuits in permanent faults;

$p_{sc,td}$ share of short circuits in faults cleared by time-delayed autoreclosure;
$p_{sc,hs}$ share of short circuits in faults cleared by high-speed autoreclosure;
n_{pf} number of permanent faults;
n_{td} number of faults cleared by time-delayed autoreclosure;
n_{hs} number of faults cleared by high-speed autoreclosure;
$p_{sc,3}$ share of three-phase short circuits in all short circuit faults;
$k_{2/3}$ sag influence of a two-phase short circuit fault compared to a three-phase short circuit fault.

During the operation of protection systems, there may exist several sequential voltage sags. When evaluating the number of voltage sags it has to be determined how such sequences are handled. In (4), one fault causes only a single voltage sag. No additional factor incorporating the possible effect of sequential voltage sags has been used.

III. Input Data for Case Studies

The case studies were based on 20 kV data from five Finnish utility companies, three rural and two urban. The data used in the calculations was obtained from an automation project that had been conducted by these companies (Table I) [12].

The rural utilities had one 20 MVA transformer and a source impedance of $\underline{Z}_S = (0.6 + j1.5)\ \Omega$ while the urban utilities had one 40 MVA transformer and a source impedance of $\underline{Z}_S = (0.1 + j0.3)\ \Omega$. It was assumed that the rural companies had overhead line networks and utilized autoreclosing for protection but that the urban companies had underground cable networks without autoreclosing. Earth faults were omitted because of the Finnish practice of earthing the MV system neutral.

The average fault frequency was collected from permanent fault data. This data does not take into account either different fault clearing types or fault types. Thus, the correction factors of (4), $(p_{sc,pf}, p_{sc,td}, p_{sc,hs}, n_{pf}, n_{td}, n_{hs}, p_{sc,3})$ have to be assessed by some other means (see Fig. 3).

The question relating to the share of short circuits compared to the sum of earth and short circuit faults in permanent faults and in faults cleared during autoreclosing sequences is complicated and no single answer exists. The shares differ from one company to another and only some tentative values could be given. For example, in [13], it was found that the share of earth faults was greater in the isolated neutral substations than in the compensated neutral case. Values of $p_{sc,pf} = 50\%$, $p_{sc,td} = 30\%$, and $p_{sc,hs} = 30\%$ were applied in these case studies [13]. These figures would need further investigation and detailed data from each company.

The number of faults cleared by an autoreclosing sequence as compared to permanent faults (n_{pf}, n_{td}, n_{hs}) was obtained from the national interruption statistics [4]. This data was compared to data taken from a more detailed measuring project [13] and was found to be in close agreement. Accordingly, values of 7% for permanent faults, 17% for faults cleared by time-delayed autoreclosure, and 76% for faults cleared by high-speed autoreclosure were used. This data was only applied to rural companies because in the cable networks of urban companies autoreclosing is not used.

TABLE I
Input Data for the Case Studies

	R1	R2	R3	U1	U2
Number of substations	32	8	37	9	4
Number of feeders	173	43	239	100	50
Total feeder length (km)	51.7	32.6	34.0	6.3	11.1
Main feeder length (km)	20.0	20.7	13.0	5.0	9.0
Laterals per feeder	2.8	14.0	20.0	1.0	1.1
Feeder resistance (Ω/km)	0.50	0.54	0.39	0.17	0.18
Feeder reactance (Ω/km)	0.40	0.34	0.37	0.12	0.12
Fault frequency (1/100 km/a)	3.4	3.8	6.0	4.4	4.5

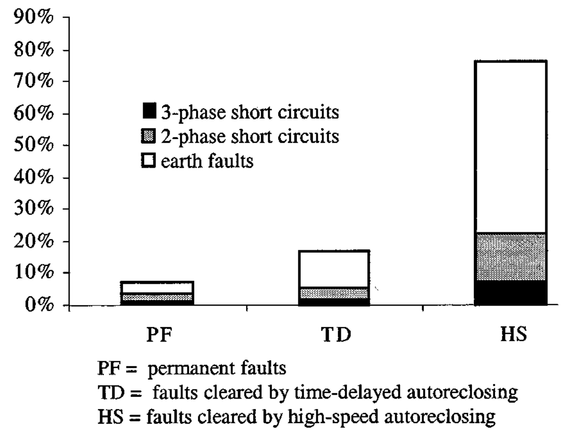

Fig. 3. Proportions of different faults in case distribution networks where autoreclosing arrangements were in use.

The ratio between three- and two-phase short circuits was evaluated and a value of $p_{sc,3} = 33\%$ for three-phase short circuits was adopted [13]. This data would also require detailed studies on each company because the division between three and two-phase short circuits is typically different in overhead line and cable networks. The share may also differ according to the fault clearing system used but for simplicity, this was not taken into account in (4).

In the case of a two-phase short circuit, two of the phase voltages sag but the third is unaffected. When a two-phase short circuit in a medium voltage network transfers through a delta/star connected distribution transformer, only one phase voltage on the low voltage side is seriously affected. In these calculations the aim was to evaluate the sag frequency of sags where $U < 50\%$ experienced by low voltage customers because of faults in medium voltage distribution networks. It was assumed that all low voltage customers are connected between a phase voltage and neutral. Thus, the value for $k_{2/3}$ is 33%.

Accordingly, the following values were assigned:

$$p_{sc,pf} = 50\% \quad n_{pf} = 1.0 \quad p_{sc,3} = 33\% \quad k_{2/3} = 33\%$$
$$p_{sc,td} = 30\% \quad n_{td} = 2.4 \text{ (rural)}, \quad n_{td} = 0 \text{ (urban)}$$
$$p_{sc,hs} = 30\% \quad n_{hs} = 10.9 \text{ (rural)}, \quad n_{hs} = 0 \text{ (urban)}.$$

In voltage sag frequency calculations, the fault impedance model (3), assuming an electric arc length of $l = 1.73$ m, was applied for the case studies of rural companies. The electric arc length represents the length of a semicircle having a diameter of 1.1 m, the distance between two phases of 20 kV overhead line networks. In the case studies of urban companies, a fault resistance of 0 Ω was assumed.

IV. Results of the Sag Frequency Calculations

As an output of the sag frequency calculations, the cumulative sag frequencies are obtained for the five distribution companies. In Table II, the sag frequencies having a voltage of $U < 50\%$ and $U < 80\%$ are presented.

Sags $U < 50\%$ are assumed to cause tripping or malfunction in most of the load types. Shallower sags would not necessarily affect some loads at all. On the other hand, the voltage sag frequency of shallower voltage sags is typically significantly higher than the sag frequency of deeper voltage sags [14]. Thus, the decision concerning what the critical voltage magnitude taken into account in the studies is has a strong effect on the sag frequency and cost. For instance, the sag frequency where $U < 80\%$ is typically many times higher than the sag frequency where $U < 50\%$.

In Table II, the voltage sag frequency results for $U < 50\%$ reveal quite low numbers. It has to be kept in mind that these results only include voltage sags caused by faults in the medium voltage network. Voltage sags caused by transmission system faults are not considered.

It should be realized that the input data used in the case studies contains inaccuracies. Another important point to note is that the use of the fault impedance model may underestimate the sag magnitude and hence the frequency of especially severe sags. If the fault impedance were to be neglected then, for $U < 50\%$, the sag frequency should be multiplied by a factor of about 2.5, depending on the (rural) company in question Fig. 4.

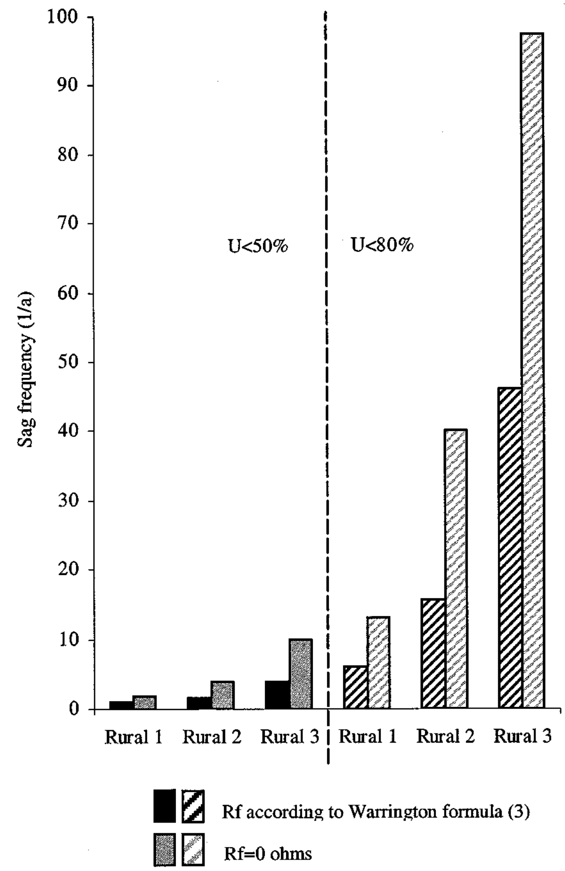

Fig. 4. Effect of fault resistance on cumulative sag frequencies.

TABLE II
AVERAGE SAG FREQUENCY (1/A) FOR EACH DISTRIBUTION COMPANY

	U < 50 %	U < 80 %
Rural 1	1.0	6.0
Rural 2	1.7	15.9
Rural 3	4.1	46.8
Urban 1	0.7	0.8
Urban 2	0.7	1.6

V. The Costs Associated With Voltage Sags

Assessing the economic value of voltage sags for distribution companies is not a simple task. There does not exist sufficiently accurate data concerning the prevailing sag frequencies and characteristics of a single company, not to mention a single customer. Furthermore, the value of the sag- associated inconvenience or disruption for the customer is an extremely subjective matter. Only rough estimates can thus be obtained. However, the increasing significance of voltage sags as a power quality problem justifies the use of such estimation as long as no better methods exist. As the results of this case study point out, the effects of voltage sags should be taken seriously and, accordingly, be given a high (negative) value as a power quality issue.

A. Sag Frequency

The method for retrieving the annual sag frequencies experienced by customers for the five Finnish utilities is described above. The sag frequencies for $U < 50\%$, presented in Table II, were applied as input data in the sag cost calculation.

B. Number of Customers

Finnish power companies usually categorize their customers into the following groups: domestic, agricultural, industrial, commercial services, and public services. This classification defines some characteristics for customers in a single category, even though the categories consist of rather heterogeneous electricity users. In particular, the industrial customers may vary considerably in size, annual energy and "electrical behavior". The number of customers in each case study utility is found in Table III.

TABLE III
NUMBER OF CUSTOMERS IN THE UTILITIES UNDER CONSIDERATION

Customer category	Rural 1	Rural 2	Rural 3	Urban 1	Urban 2
Domestic	45,500	11,650	117,650	102,050	107,250
Agricultural	14,250	1,100	10,900	300	300
Industrial	500	150	1,950	1,400	700
Commercial	3,450	850	6,050	7,200	4,450
Public	1,650	300	2,550	1,100	1,050
Total	65,350	14,050	139,100	112,050	113,750

TABLE IV
COST OF AN EVENT ACCORDING TO PREVIOUS SURVEYS [1],[15],[16]

Customer category	Type of event	Cost per event, €
Domestic	Short interruption	1
Agricultural	Short interruption	1
Industrial	Voltage sag, 50 %, 200 ms	1,200
Commercial	Short interruption	210
Public	Short interruption	280

C. Price of a Single Voltage Sag

Traditionally, power company customers tend to overvalue the inconvenience due to sags and interruptions but are not willing to pay for the measures utilities take for their prevention. The realistic price attributable to a single sag is found somewhere between these two extreme views. The relevant value should be derived from the real direct and indirect economic consequences of a sag. For example, the sag price for an industrial process which trips due to a sag in the voltage supply should at least cover shutting down the process, cleaning the system, restarting the process, loss of production and the eventual cost of damaged equipment. These costs really exist and someone will have to pay them. It depends on the customer whether he will take the risk himself and pay for the possible consequences or would rather pay the distribution company for providing higher power quality, i.e., mitigating the sags in one way or another. In the case where he chooses the latter option, the company should compensate the inconvenience if it is not able to mitigate the sag as promised.

In a Nordic survey [1], a total of 13 000 utility customers were asked for the real cost of sudden interruptions. Industrial customers were also asked to estimate the realistic cost due to a voltage sag (50%, 200 ms). Another two inquiries were launched in Finland in 1995 where households and agricultural customers estimated the cost of a sudden short interruption, which was something that had not been asked in the Nordic survey [15], [16]. Combining the results of the three reports gives the following average event values for the different customer classes (Table IV).

The sag price was available only for industrial customers. For other customer groups the price of a sudden short interruption was used instead. According to [1], the cost of a single sag to an industrial customer is higher than the cost of a sudden interruption lasting one second but lower than the cost of one minute sudden interruption. It was thus assumed that using the interruption cost for the rest of the customer groups would yield sufficiently precise results.

Regarding the industrial, commercial and public customers, an interesting phenomenon was found. Typically, more than 50% of the customers answered that sags and interruptions do not cause them economic losses at all, whereas 1–2% experienced extremely high costs, i.e., € 20–70 000 per event. These figures may be real but there is the risk that they are exaggerated. To ensure that relevant numbers are being used and, most of all, to avoid overestimated figures a kind of peak shaving was done, i.e., all customer reported costs higher than 20 000 euros were taken to be equal to 20 000 euros. These cases made up approximately 1% of the total number of customers. Consequently, the prices obtained for a single voltage sag are shown in Table V.

TABLE V
VALUE USED FOR A SINGLE VOLTAGE SAG IN EACH CUSTOMER CLASS

Customer category	Cost per sag, €
Domestic	1
Agricultural	1
Industrial	1,060
Commercial	170
Public	130

TABLE VI
ANNUAL COST DUE TO VOLTAGE SAGS

	Rural 1	Rural 2	Rural 3	Urban 1	Urban 2
Domestic	45,500	19,805	482,365	71,435	75,075
Agric.	14,250	1,870	44,690	210	210
Industrial	530,000	270,300	8,474,700	1,038,800	519,400
Com.	586,500	245,650	4,216,850	856,800	529,550
Public	214,500	66,300	1,359,150	100,100	95,550
Total ~	1,391,000	604,000	14,578,000	2,067,000	1,220,000
Interruption costs	2,000,000	800,000	4,100,000	500,000	800,000

D. The Annual Sag-Related Costs for the Distribution Companies Being Studied

Multiplying the distribution company customer numbers by the customer category sag prices and the company sag frequency gives the total annual sag cost for each distribution company. By using the figures described above, the following prices are obtained.

In order to provide a suitable reference, the approximate interruption costs [12] are shown in Table VI. Sags of the selected severity seem to cause as expensive problems as the outages, in some cases even more expensive. The sag cost results are also shown in Fig. 5.

As one would expect, the industrial customers are one of the most valuable groups from a financial perspective. Not so obviously, the commercial and public services also seem to have significant value when considering voltage sags. Households and agricultural customers do not have so much significance as far as sags are concerned. The contribution of each customer group to the total cost is shown in Fig. 6 as an average of the five utilities considered in the study.

The costs related to the company referred to as *Rural 3* seem to be rather high. The major reason for this is the high sag frequency of the company, which is due to its large and sag sensitive overhead line network. If the sag frequency were equal to the company labeled *Urban 1*, the costs would be approximately equal for both companies. The *Urban 1* company has an underground cable MV distribution system, which appears to be a good solution from the cost point of view.

Although not all the money shown in Fig. 6 can be realized, a certain number of customers may be willing to pay for avoiding sags and their consequences. The results show that the distribution companies would financially have the most to gain from providing industry and service sector customers with premium power.

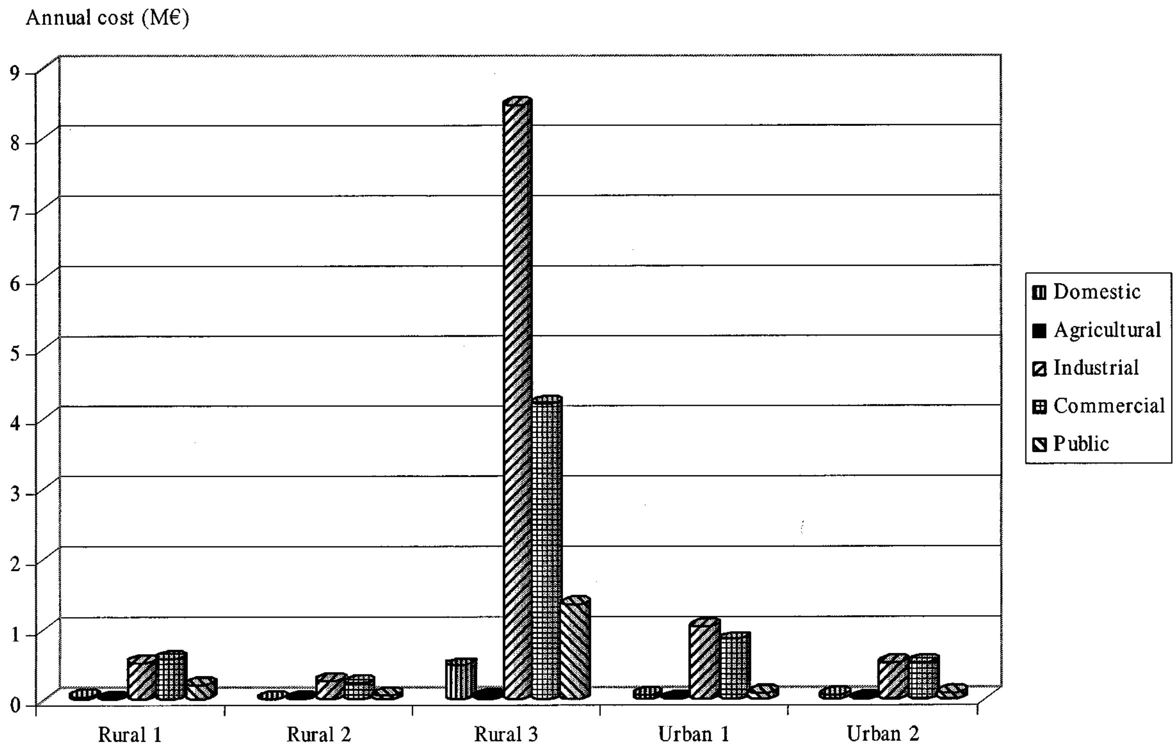

Fig. 5. Annual cost due to voltage sags.

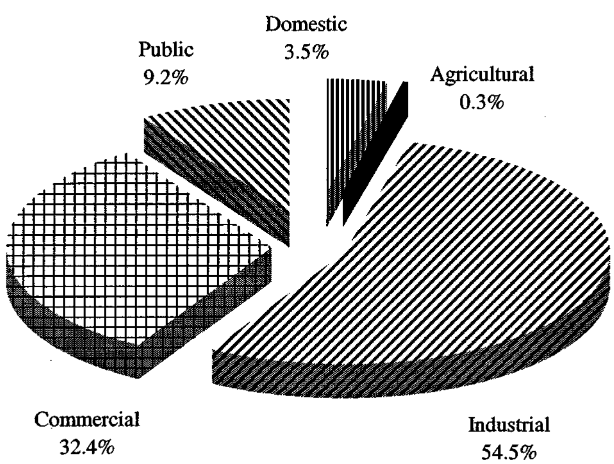

Fig. 6. Cost in terms of each customer groups as an average of all five considered utilities.

From the point of view of the sag mitigation business, the customer's or customer group's sag sensitive load would preferably be located in a small area and heavy enough for reasonable rating and positioning of a mitigation device. This is often the case with big and medium size customers that have high demand. On the contrary, even though a distribution company may have a large number of small size customers, e.g., households, its total load would be spread over a wide area where a lumped protection solution, i.e., a single device, would not be suitable. Using multiple small power conditioners is hardly reasonable, economically or technically.

Industrial, commercial and public sector customers are usually grouped together in industrial parks, shopping centers or office areas. Protecting such areas or a big plant from voltage sags is likely to be both reasonable and cost-effective. Further research is needed in order to ascertain more precisely the characteristics and applications for viable mitigation services, which the utilities or other service providers could then launch.

E. Criticism of the Acquired Results

In addition to inaccuracies in calculating the sag frequency there also exist inexact elements in the estimation of sag-related costs. Using an average to represent highly deviated data does not necessarily give the correct impression of the significance of a single sag to a single customer. On the other hand, data that is more precise is not available. Detailed studies on the issue are thus needed for further refinement.

It would also be advisable to select both the critical voltage and the respective cost on a case by case basis. Depending on the customer, the sag sensitivity of loads may vary a lot.

VI. Conclusions

The frequency and cost of voltage sags experienced by the customers of five Finnish distribution companies were assessed. Only sags having a remaining voltage less than 50% and caused by faults in medium voltage distribution networks were taken into account.

In voltage sag frequency calculations, the method of fault positions was applied. Equations to correct the limitations of the network component reliability data with respect to voltage sags were presented. The voltage sag frequencies were underestimated rather than overestimated and the sag frequencies for $U < 50\%$ showed quite low numbers. Further, the voltage sag frequencies were applied as one input data to voltage sag cost calculations.

Despite the relatively low number of sags that occur, the calculated annual voltage sag-related costs appeared to be reasonably high. Genuine economic benefit could most likely be gained by sag mitigation in the case of industrial as well as commercial and public service sector customers that are located in a compact area and could thus be protected with a lumped solution. Further studies are needed to represent customers' sag-related inconvenience and actual economic losses with greater precision. In addition, a more precise calculation of sag frequencies would give more accuracy in cost evaluation. It is, however, evident that voltage sags are an important power quality issue and have a considerable economic significance that is bound to increase in the years to come.

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