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Overvoltage Protection, Faults and Voltage Sags

P. Heine, M. Lehtonen, and A. Oikarinen

***Abstract*--Distribution transformers in rural networks have to cope with frequent lightning induced overvoltages and thus must be protected using spark gaps or surge arresters. The overvoltage protection type has an influence on the system behaviour and on the interruptions and voltage sags experienced by power system customers. In this paper, measurement results showing the effect of overvoltage protection type on established faults in an unearthed medium voltage overhead line network are presented. Detailed results of fault frequencies and fault types are shown. Further, a probability function is established to describe the influence of overvoltage protection type on voltage sags experienced in the network. This latter aspect is important when limiting the effects of interruptions and voltage sags for sensitive customers.**

***Index Terms*--spark gap, overvoltage, power distribution, power distribution protection, power distribution faults, power quality, surge arrester, voltage sag**

I. INTRODUCTION

LIGHTNING, switching operations and earth faults are typical causes of the overvoltages experienced in medium voltage (MV) networks. Overvoltages can break and damage equipment and are also a health risk for human beings. Thus, they have to be removed quickly and safely from the system. Power distribution transformers in overhead line MV networks are typically protected from overvoltages by either surge arresters or spark gaps. The established practice has been that more valuable, larger transformers are supplied with surge arresters and cheaper, smaller distribution transformers with spark gaps.

Traditionally, MV systems are operated radially and one feeder can supply dozens of distribution transformers. When one spark gap of one distribution transformer ignites, an earth fault occurs in the system and, particularly in unearthed MV networks, the circuit breaker of the faulted feeder has to be opened to remove the fault. On the other hand, in the case of surge arresters, no opening of a circuit breaker is needed.

The opening and closing of a circuit breaker means not only a short interruption, but in weak networks, due to transformer inrush currents, also a short-duration voltage sag. If two adjacent spark gaps ignite at the same time, a short circuit with ground connection occurs. Now a more severe fault and as well as a deep voltage sag are experienced. Thus, the type of overvoltage protection has an influence not only on interruptions but also on voltage sags.

In this paper, the most typical causes of overvoltages and equipment for overvoltage protection on distribution transformers are shortly explained. Measurement results show the influence of overvoltage protection type on real faults in an unearthed MV overhead line network. A probability function is then established to demonstrate the effect of overvoltage protection type on faults and voltage sags.

II. FAULT TYPES AND VOLTAGE SAGS

Faults all over the power system cause sagged voltages that may propagate over long distances. Other causes of voltage sags are, for example, switching operations and high starting currents taken by large motors. Power distribution MV/LV transformers are typically delta/star connected. This means, when considering voltage sags experienced by low-voltage (LV) customers, that the phase-to-phase voltages on the MV side are of interest.

The majority of faults causing sagged voltages at LV customer locations occur in MV networks [1], [2]. During an earth fault in high impedance earthed MV networks, phase-to-phase voltages do not sag. Thus, earth faults in the MV network are not experienced as sagged voltages at the LV customer locations. Although earth faults do not cause sagged voltages, the circuit breaker operations belonging to the fault clearing procedure may, especially in weak networks. Although the minority of faults are short circuits, they are more severe, and the sags caused by short circuits are experienced more widely in the power system.

III. OVERVOLTAGES IN MV NETWORKS

In rural areas supplied by MV overhead lines, typical causes of overvoltages are earth faults, switching operations, and direct and indirect lightning strokes.

A single-phase earth fault is the most typical fault type; in overhead line MV networks, the share of these faults is typically over 80% [1]. The majority of faults are weather related, for example, wind, storms, broken tree branches and trees felled by hard wind, snow, ice, and lightning. An earth fault in a high-impedance earthed network causes an overvoltage, because in an earth fault the neutral point voltage rises and the phase voltages of the sound phases increase. If the fault resistance is $0\,\Omega$, the phase voltage of the faulted phase is zero and the phase voltages of the sound phases reach the value of the phase-to-phase voltages. If, for example, a spark gap strikes over, an earth fault occurs in the system and

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all over the MV network in question an overvoltage is experienced in the healthy two phases.

Lightning causes overvoltages as well, by direct and indirect strokes. A direct lightning stroke causes a travelling wave that propagates from the striking point in both directions. The magnitude of the overvoltage caused by a direct lightning stroke u is half of the characteristic wave impedance Z_w of the feeder times the magnitude of the lightning current i (1) [3].

$$u = \frac{1}{2} Z_w i \qquad (1)$$

The wave impedance of an overhead line feeder is typically 250 - 500 Ω. Thus, for example, a lightning current of 30 kA would cause an overvoltage of u = 3700 - 7500 kV. A direct lightning stroke is a severe fault and will cause most probably a three-phase short circuit.

Indirectly, lightning strokes in the neighbourhood of an MV line cause overvoltages by inducing voltages on the MV line (2) [3].

$$u_{ind} = kiZ_0 \frac{h}{d} = ki \frac{1}{4\pi} \sqrt{\frac{\mu_0}{\varepsilon_0}} \frac{h}{d} \qquad (2)$$

k includes the effect of the speed of the lightning wave in the discharge channel and typically has a value of 1.2-1.3. i is the max lightning current, Z_0 has the dimension of Ω, h is the height of the feeder and d the distance from the feeder to the place of the lightning stroke. For example, the induced overvoltage caused by a lightning stroke having current i = 30 kA at a distance d = 50 m from an MV feeder with a height of h = 5 m is 108 kV. The indirect overvoltages caused by lightning strokes are less in magnitude but more common than overvoltages caused by direct lightning strokes.

IV. OVERVOLTAGE PROTECTION

In rural areas supplied by overhead lines, distribution transformers are typically pole-mounted and one MV feeder can supply tens of distribution transformers. For overvoltage protection, smaller, cheaper transformers are equipped with spark gaps and larger, more expensive transformers with surge arresters. In Finland, the established practice for the selection of overvoltage protection type has been the transformer size; transformers of 200 kVA or smaller have been equipped with spark gaps and larger ones with surge arresters.

A. Spark Gap

A spark gap has one metallic rod connected to a phase conductor and a second rod connected to earth (Fig. 1). A typical placement of a spark gap is across the insulator on the high voltage side of the power distribution transformer. The open air structure has one major disadvantage: a small animal, like a bird or a squirrel, or a tree branch can get in the open air space between the end of the rods and cause the spark gap to ignite.

When a spark gap sparks over, an earth fault enters the system. Especially in unearthed MV networks, the electric arc burning in a spark gap is usually unable to extinguish itself and an opening of a circuit breaker is needed to remove the fault. On the contrary, in compensated networks, it is possible that the arc extinguishes itself before the circuit breaker operation takes place. In addition, when an electric arc is burning in the air, it gets gradually longer, and the air surrounding the electric arc is ionized which makes it in principle possible for an adjacent spark gap to also spark over. In this case, a 2-phase short circuit with ground connection enters on the system and a circuit breaker operation is needed. This case represents a changed fault type: first an earth fault which after some cycles changes to a 2-phase-to-ground short circuit. When a short circuit occurs on the system a circuit breaker operation is always needed. In this case, customers on the faulted feeder experience a short interruption and, in addition, all the customers supplied by the MV network in question experience a short-duration sagged voltage.

B. Surge Arrester

A spark gap is inexpensive but it does not fully protect transformers for very steep-fronted surges. Further, when a spark gap operates, the opening of a circuit breaker is typically needed. These are two important drawbacks which are avoided by the use of surge arresters. Modern surge arresters are metal-oxide arresters without any spark gaps. Their operation is faster and smoother than the operation of spark gaps. No circuit breaker operations are needed and thus no voltage sags are experienced. The drawback of surge arresters is the higher price. In addition, broken arresters can be difficult and laborious to diagnose and locate in the network.

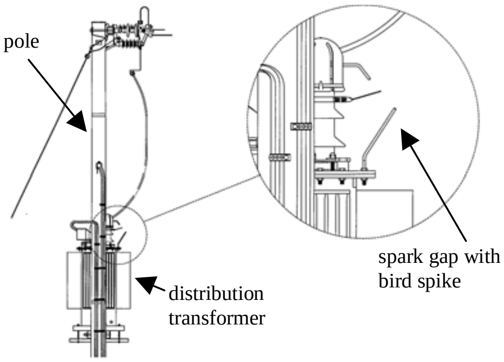

Fig. 1. Pole-mounted distribution transformer with spark gaps.

V. MEASUREMENTS

In this project, the effect of overvoltage protection type on faults was researched by performing measurements at one rural 110/20 kV substation [4]. This substation has an unearthed neutral. An LEM Topas 1000 power quality analyzer was used for the measurements. The measurements included 221 faults where the operation of a circuit breaker was observed. Thus, these faults occurred in the MV network supplied by the MV network in question. The measurements took place over a period of 17 months, from June 2002 to October 2003.

Usually, a feeder has both spark gaps and surge arresters depending on the power distribution transformer ratings. The substation in question has an exceptional feature in this sense; each of the five overhead line feeders has solely either spark gaps or surge arresters. Thus, the feeders can be categorized into two groups: feeders with only spark gaps and feeders with only surge arresters (Table I). The total length and the number of distribution transformers are about the same in these two groups. In addition, the distribution areas supplied by these two feeder categories have very similar geographical and forested / non-forested characteristics.

TABLE I. CATEGORIZATION 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

A. Fault Frequency

Typically in unearthed MV networks, the operation of spark gaps needs a circuit breaker operation to remove the fault from the system. On the contrary, surge arresters operate so quickly and smoothly that no circuit breaker operation is needed. This means that the fault frequency of the feeders with spark gaps should be higher than the fault frequency of feeders with surge arresters. In this research, the fault frequency of feeders with spark gaps was considerably higher (Table II) than in the other feeder category. The fault frequencies in Table II include the whole measurement period of 17 months and all the faults required the operation of a circuit breaker - this means permanent as well as temporary faults cleared by autoreclosure sequences.

B. Faults of Changed Fault Type

In the feeders having only spark gaps, faults that changed from an earth fault to a 2-phase-to-ground short circuit were observed to have an exceptionally high share (Table II). Fig. 2 shows a Topas rms recording as an example of a changed fault. First there is an earth fault (0.1 s - 0.2 s), but after some cycles the fault develops into a 2-phase-to-ground short circuit (0.2 s - 0.3 s). During the earth fault, the neutral voltage rises, the voltage of the faulted phase collapses and the phase voltage of the sound phases reach the phase-to-phase voltage level. There are no significant changes in the currents during an earth fault. The fault type changes at time 0.2 s. During a 2-phase-to-ground short circuit, the neutral voltage has a value of half the phase voltage, two phase voltages are sagged and one is increased. There is no change in the current of the sound phase, but the two faulted phases carry a 2-phase short circuit current.

TABLE II. FAULT CHARACTERISTICS OF FEEDER CATEGORIES.

Overvoltage protection type	Spark gaps	Surge arresters
Fault frequency (1 / 100 km)	192.8	31.4
Changed fault types (1 / 100 km)	19.4	1.0
Share of earth faults (%)	65	44

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In this substation, the time from the beginning of the fault to the opening of the circuit breaker of the faulted feeder is 360 ms for earth faults and 110 ms for short circuits. In such cases where the fault types changes, the average duration of the earth faults was 9.7 cycles, that is 194 ms (Fig. 3), with a variance of 2.3 cycles. The duration of the short circuit was 110 ms in every case. This duration is determined by the settings of the protection. In every observed case, the faulted phase in earth faults was one of the two phases that would take part in the forthcoming 2-phase-to-ground short circuit. Fig. 4 shows the dates and corresponding times of day when the cases involving changed fault types occurred.

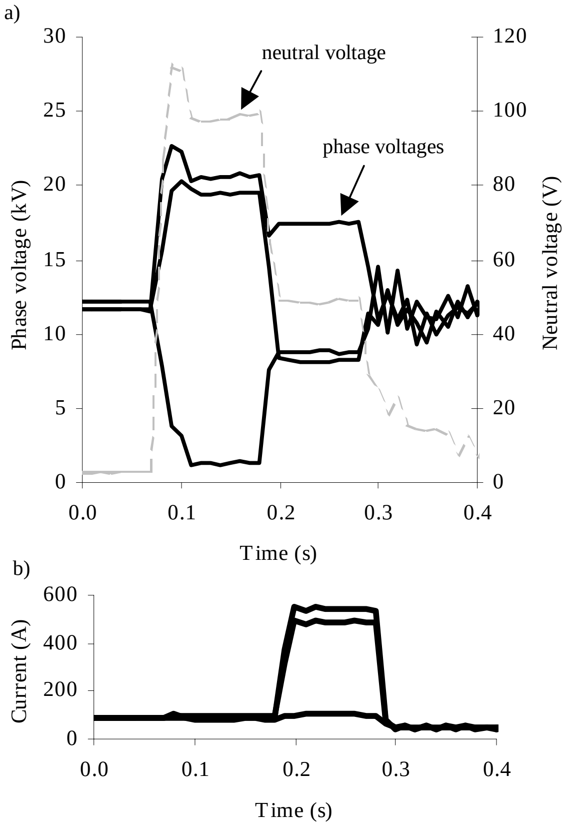

Fig. 2. An earth fault that changed after nine cycles to a 2-phase-to-ground short circuit: a) Phase voltages and neutral voltage, b) Currents.

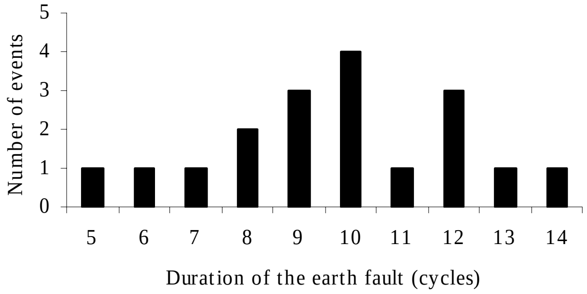

Fig. 3. The distribution of the duration of earth faults before they developed into 2-phase-to-ground short circuits.

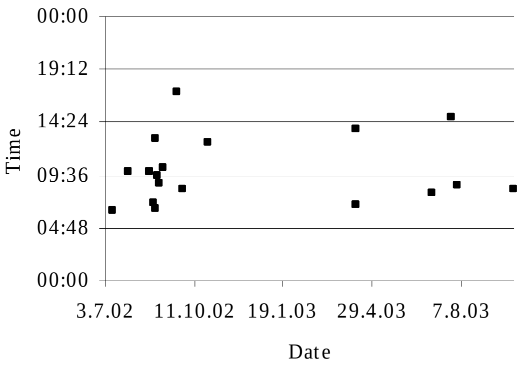

Fig. 4. Dates and times of the cases of changed fault types.

A spark gap must be adjusted so that no sparks occur during earth faults or switching operations, but protection against overvoltages caused by lightning must be adequate. An adjacent spark gap should not operate during an earth fault. In the substation in question, spark gaps of 80 mm and 2 x 40 mm are used. In the Finnish national standard SFS 2646, the wet 1% sparkover voltage values for protective spark gaps are given: for instance 32 kV for spark gap spacing 1 x 80 mm and 42 kV for spark gap spacing 2 x 40 mm, corresponding to the rated frequency voltages [5]. In the measured earth faults, the maximum rms values during the earth fault were about 25 kV and maximum transient voltages 36 kV, respectively. The possible spreading of the electric arc is not seen in the typical high voltage testing of spark gaps as those tests are typically performed as single phase tests. In high voltage laboratories, different circumstances, such as humidity, temperature, dirt, grime, and air pressure, have been observed to affect the operation of spark gaps. Approximately half the measured cases occurred during rainy weather but, on the other hand, in half of the cases the weather was dry.

The weather during each of the changed fault cases was listed. In Finland, during the summer months only a couple of lightning storms are experienced on average. Disturbances caused by lightning typically occur in large numbers during only a few days of the year. No major lightning storms coincide with the dates in Fig. 4. During the measured lightning storms, faults occurred in both feeder groups, particularly short circuits. The number of lightning measurements is so small that no statistical analysis can be performed on the fault data from lightning storms.

Although lightning may not be the main cause of the changed fault types, small animals across the spark gap terminals are likely causes of these faults. The times of day strenghten this as the faults shown in Fig. 4 occur during day light hours. The activity of small animals is highest during the morning and in the afternoon before the darkness. When a small animal causes one spark gap to spark, the sourrounding air is ionized and the electric arc may spread to the neighbouring spark gap.

The problem with these kinds of measurements, performed in the substation, the reasons for the faults are usually unknown. Most of the faults (about 90%) were temporary and none of the observed permanent faults were caused by faults on the power distribution transformer itself.

C. *Voltage Sag Distribution*

Fig. 5 shows the cumulative sag distributions for both feeder categories. In each fault case, the lowest phase-to-phase voltage during the fault before the first tripping of the circuit breaker is used to characterize the sag. The sag influence of earth faults is not seen in Fig. 5 because in earth faults in unearthed networks the phase-to-phase voltages do not drop below 90% of rated voltage. In addition, the short-duration sags caused by the high inrush currents taken by the power distribution transformers when closing the circuit breakers are not shown in Fig. 5. When the fault type is changed from an earth fault to a 2-phase short circuit a minor increase in the sag frequency can be seen. The higher fault frequency of feeders with spark gaps contributes to a higher number of voltage sags compared to the surge arrester case. As shown in Table II, about half the faults in surge arrested feeders are short circuits causing sagged voltages. On the other hand, in spark gapped feeders only a third of the faults were short circuits. Without the changing fault type this share would have been about 25%.

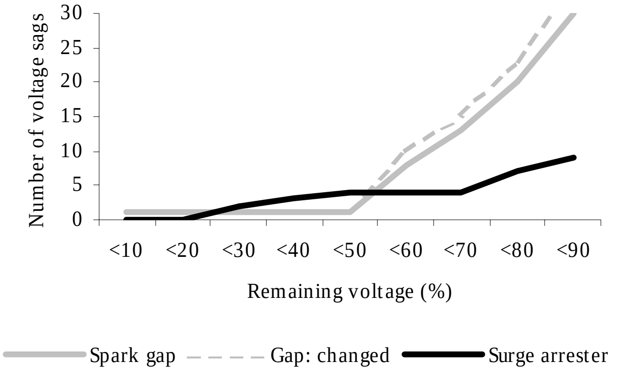

Fig. 5. Cumulative sag distributions for feeder categories consisting of spark gaps and surge arresters.

VI. PROBABILITY

In general, if the statistical distribution of the overvoltages experienced in the system *p(U)* and the probability function of the breakdown voltage of the protective equipment *F(U)* are known, the expected number of sparking events *R* can be calculated [6]. The operation of spark gaps is strongly dependent on the steepness of the overvoltage. The probability distribution for the breakdown of spark gaps can be divided into parts representing the steepness (cause) of the overvoltage.

$$R = \int_{u_{min}}^{u_{max}} p(U)F(U)dU = \sum_{i} \int_{u_{i,min}}^{u_{i,max}} p_i(U)F_i(U)dU \quad (3)$$

where *i* represents different causes of overvoltages, *i=1* for direct lightning strokes, *i=2* indirect lightning strokes, *i=3* switching operations and *i=4* earth faults, etc.

Generally, if the system's overvoltage protection consists of M statistically independent pieces of equipment, then the expected amount of the operations of sparking equipment in the system is

$$F_{i-M}(U) = 1-(1-F_{i-1}(U))^{M} \quad (4)$$

A. *Sags Caused by Lightning*

In Finland, lightning causes about 8% of all permanent faults [7]. A direct lightning stroke is a severe fault and will most probably cause a 3-phase short circuit no matter what the overvoltage protection type is. Generally, it is assumed that at the MV level, induced overvoltages represent an 80% share of the overvoltages caused by lightning. On the other hand, in faults caused by indirect lightning strokes, overvoltage protection has an influence on the fault and fault clearing types. Surge arresters operate without causing a circuit breaker to operate. In spark gaps, the induced overvoltage is travelling similarly in all three phases, most probably causing an immediate breakdown in more than one spark gap, a short circuit, and consequently a circuit breaker operation.

B. *Sags Caused by Switching and Earth Fault*

A spark gap should not be activated during a switching operation or an earth fault in another phase. In the measurements, changed fault types during an earth fault were observed. The idea put forward was that when an electric arc is burning in one spark gap, the surrounding air is ionized and the arc is prone to spreading to the adjacent spark gap causing a 2-phase-to-ground short circuit.

In (4) it is assumed that the sparkover of one device does not have any influence on the operation of the other equipment. Let the probability of one spark gap to spark over be $F_{i-1}(U)$. The probability of a spark gap not to operate is then

$$F_{i-1not}(U) = 1 - F_{i-1}(U) \tag{5}$$

A distribution transformer has three spark gaps, one on each phase. For one transformer during an earth fault, the probability of sparking not to occur in the other two gaps is

$$F_{i-2not}(U) = (1 - F_{i-1}(U))^2 \tag{6}$$

In the substation under study, the feeder group consists 77 distribution transformers equipped with spark gaps and supplied by the substation in question. The expected number of changed fault types in the system is then

$$F_{i-154}(U) = 1 - (1 - F_{i-1}(U))^{154} \tag{7}$$

If it is assumed that the distribution of the maximum phase voltages (rms) during an earth fault follows the normal distribution, $U_{ef\ avg}$ = 24 kV, and s_{ef} = 2.2 kV. In addition, the probability of the sparking characteristics of the spark gaps can be presented with a normal distribution. If assuming wet conditions (U_{avg} = 36 kV, s = 2.2 kV [5], [8]) the probabilities for one and 154 spark gaps can be drawn and are shown in Fig. 6. This example shows the curves of earth fault voltages and withstand level of 154 spark gaps to cut each other.

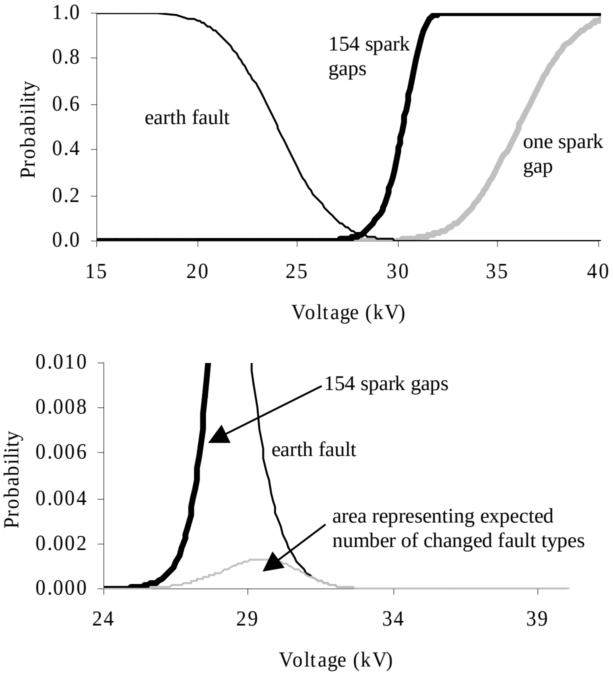

Fig. 6. Probability of short circuits caused by changed fault types on distribution transformers equipped with spark gaps.

The area below the curves and shown in Fig. 6 represents the probability the system to experience a short-circuit fault instead of an earth fault. The probability of a changed fault type is increased when the number of spark gaps in increased. According to these quite strong assumptions, in this example, the changing of a fault type from an earth fault to a short-circuit has a small probability (about 0.4%). Based on the measurements, however, it is suspected that the fault type changing is mainly caused because the electric arc burning in one spark gap is spread to the adjacent spark gap.

C. Probability of Sags Caused by Operation of Overvoltage Protection

The cumulative sag distribution can be written as (8) [1]

$$F(u,t)_k = \sum_{i}^{n} \sum_{ft} (\lambda_{i,ft} \big| u_k \le u, \Delta t_{i,ft} > t) \tag{8}$$

where $\lambda_{i,ft}$ is the fault frequency of fault type *ft* at fault position *i*, u_k the sagged voltage experienced by an LV customer at node *k*, and $\Delta t_{i,ft}$ the sag duration for the fault place and fault type in question.

Because different fault types cause sags with different characteristics, the fault frequencies of each fault type should be determined. Thus, the fault frequency λ_i at a certain fault position includes the fault frequencies of all fault types: single-phase, two-phase, and three-phase faults, with and without earth connections

$$\lambda_i = \sum_{ft} \lambda_{i,ft} = \sum_{ft} \frac{p_{i,ft}}{100} \lambda_i \tag{9}$$

and the share of the various fault types $p_{i,ft}$ will satisfy two properties, (10) and (11)

$$0 \le p_{i,ft} \le 100\% \tag{10}$$

$$\sum_{ft} p_{i,ft} = 100\% \tag{11}$$

In voltage sag studies, short circuits are of most interest. The main interest here is restricted to the faults that occur / are cleared on power distribution transformers. When assuming [7] that lightning represents a share of 10% of all the faults where a circuit breaker operation is needed and that occur on the power distribution transformer, switching 0%, small animals 5% and tree branches 5%, the following probabilities shown in Table III can be used. These probabilities mean that the sag frequency of faults occurring on power distribution transformers with spark gapped feeders is seven times the fault frequency of surge arrested feeders. However, Table III includes only part of the faults that occur on the MV feeders. A considerable share of the faults occurs along the overhead lines.

TABLE III. SAG PROBABILITY CAUSED BY FAULTS OCCURRING ON POWER DISTRIBUTION TRANSFORMERS.

Cause of an overvoltage	Prob. of faults on a transformer (%)			
	Spark gaps		**Surge arresters**	
	earth fault	short circuit	earth fault	short circuit
Lightning (10%)				
- direct 20%	0	2	0	2
- indirect 80%	0	8	0	0
Switching (0%)	0	0	0	0
Earth fault (10%)				
- small animal	2	3	0	0
- tree branch	3	2	0	0
Total, 1	5	**15**	0	**2**
Total, 2	**20**		**2**	

VII. VOLTAGE SAGS AND OVERVOLTAGE PROTECTION

According to performed measurements, feeders with spark gaps have six times higher fault frequency than feeders with surge arresters. In addition, in feeders having spark gaps, cases where the fault type changed from an earth fault to a 2-phase short circuit was observed to occur. A short-circuit fault is more stressful to the system than an earth fault and causes sagged voltages.

Thus, especially when limiting the number of short interruptions in an unearthed network surge arresters instead of spark gaps are preferable. The maximum decrease is achieved if all the transformers are equipped with surge arresters and no spark gaps are used; an operation of any of the spark gaps along the whole feeder length causes a short interruption to all the customers supplied by this feeder. However, if deep sag mitigation is of concern, it is sufficient to focus the main efforts in the neighbourhood of the substation.

VIII. CONCLUSION

In this paper, the influence of overvoltage protection of power distribution transformers on fault frequencies, fault types and voltage sags were presented.

Power quality measurements were performed in one rural substation having an unearthed neutral and supplying five overhead line feeders. The main results of the measurements were:

- Feeders with spark gaps had six times higher fault frequency than the feeders with surge arresters.
- Especially in the feeders having spark gaps, a high number of changed fault types from an earth fault to a 2-phase-to-ground short circuit was observed. This means an increase in the share of short circuits and voltage sags.
- In feeders having spark gaps, the number of voltage sags of magnitude $U_{sag} < 70\%$ was about three times higher than the sag frequency of surge arrested feeders.

Further, detailed analysis of changed fault types was presented. An earth fault changes to a 2-phase short circuit typically within 10 cycles. This means that the prolonging of the delay time of the earth fault protection would not prevent this incident.

The operation of a spark gap causes an earth fault. When one spark gap in the system sparks over, the other spark gaps should not operate during this earth fault. Further, an electronic arc burning in one spark gap should not be able to spread to an adjacent spark gap. Based on the measurements performed here, there is a relatively high possibility that the electric arc of one spark gap does spread to other phases.

If the main power quality improvement is to limit the number of short interruptions, surge arresters should be installed in an unearthed network instead of spark gaps. On the other hand, if the main concern is the inconvenience caused by voltage sags, then the main efforts can be limited to a restricted area in the neighbourhood of the substation.

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X. BIOGRAPHIES

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Arvo Oikarinen graduated in the Vaasa Institute of Technology in 1979. After graduating he worked for two years with the Kajaani Distribution Company and since 1981 with Graninge Kainuu. He works as district manager responsibile for the construction of power distribution networks and power quality issues.