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Measured Faults during Lightning Storms

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***Abstract*—Lightning storms may only last some hours, but the number of faults during these storms can represent a considerable share of the annual disturbances. In this paper, six identified lightning storms were the main interest. In general, single-phase earth faults are the most typical fault type. However, in the lightning storms we researched, short circuits represented the majority of faults. The majority of faults, both during lightning storms and in normal conditions, are cleared by high-speed autoreclosure. In addition, it was observed that during lightning storms coincident faults and fault types that develop into another fault type before the opening of the circuit breaker occurred repeatedly. When observing the influence of overvoltage protection type on faults, the results encourage the use of surge arresters.**

***Index Terms*—fault, lightning, overvoltage, power distribution, power quality, spark gap, surge arrester, voltage sag**

I. INTRODUCTION

In rural medium voltage power distribution networks, the cause of disturbances is typically weather related, like thunder, snow and ice, and trees felled by snow, wind and storms [1]. Lightning strokes usually occur in large numbers during only a few days of the year in the summer months. During lightning storms, in addition to lightning strokes, rain, strong wind, falling trees and tree branches cause disturbances.

Generally, the most common fault type is the single-phase earth fault [1]. However, during lightning storms, short circuits may represent a considerably higher share of the experienced faults. Short circuits are stressful and severe faults, causing, in addition to interruptions, sagged voltages.

In this paper, six lightning storms and in particular, the fault types and fault clearing sequences during these storms are the main interest. In addition, the influence of overvoltage protection on the measured faults is observed. The measurements were performed at two 110/20 kV substations in the middle part of Finland. The substations supply rural areas with overhead lines and use autoreclosure.

II. CAUSES OF FAULTS

In areas supplied by overhead lines, an autoreclosure sequence is commonly used to clear temporary faults. In these areas, the share of permanent faults is typically less than 10% [1], [2]. In Finland, on average, about 70% of permanent faults in rural MV (medium voltage) networks are caused by weather conditions such as thunder, snow, icing, storm, hard wind and fallen trees [1]. However, the cause of the majority of faults remains unknown when they are cleared automatically by autoreclosure arrangements. Typically, no statistics of the causes of temporary faults is available.

A. Lightning

Lightning causes overvoltages by both direct and indirect strokes. A direct lightning stroke is a severe fault causing exceptionally high overvoltages. Induced overvoltages caused by indirect lightning strokes are lower in magnitude but are more common (80%) than direct lightning strokes [3].

An MV feeder typically supplies tens of distribution transformers. Transformers are protected against overvoltages caused by lightning with either spark gaps or surge arresters [4]. Generally, smaller and cheaper distribution transformers are equipped with spark gaps, and more expensive, larger distribution transformers with surge arresters.

1) Direct Lightning Stroke

When a lightning stroke hits a feeder it causes a travelling wave that propagates from the striking point in both directions. The magnitude of the overvoltage u is half of the characteristic wave impedance Z_w of the feeder times the magnitude of the lightning current i (1), [3].

$$u = \frac{1}{2} Z_w i \tag{1}$$

The wave impedance of an overhead line feeder is typically 250 - 500 Ω. Thus, for example, a lightning current of 50 kA would cause an overvoltage of u = 6250 - 12500 kV. A direct lightning stroke causes extremly high overvoltages and is thus a severe fault. It will most probably cause a 3-phase short circuit regardless of the overvoltage protection type in use. An opening of a circuit breaker is needed to remove the resultant 3-phase short circuit.

2) Indirect Lightning Stroke

Indirectly, lightning strokes in the neighbourhood of an MV line cause overvoltages by inducing voltages on the MV line (2), [3]. The induced overvoltages u_{ind} are proportional to the magnitude of the lightning current i and the height of the feeder h, and further, are inversely proportional to the distance d between the feeder and the location where the lightning stroke hits the ground. The induced overvoltage can be calculated using (2)

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

where 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. Z_0 is measured in ohms (Ω). For example, the induced overvoltage caused by a lightning stroke having current i = 50 kA at a distance d = 50 m from an MV feeder with a height of h = 5 m is u_{ind} = 180 kV. An indirect lightning stroke causes overvoltages that are typically considerably lower in magnitude than direct lightning strokes.

When an overvoltage induced by an indirect lightning stroke is propagating on the feeder and reaches the first distribution transformer, the spark gaps or surge arresters protecting the distribution transformer will operate and prevent the overvoltage from affecting the transformer and the rest of the network. Depending on the number of operating, parallel spark gaps, a single-phase earth fault (one spark gap), a 2-phase-to-ground (two neighbouring spark gaps) or a 3-phase-to-ground short circuit (three neighbouring spark gaps) occurs on the system (Fig. 1). Typically, an opening of a circuit breaker on the faulted feeder is needed to remove this fault. In addition to the interruption, short circuits will always cause sagged voltages to be experienced in the whole substation area. However, in ungrounded or compensated neutral systems, a single-phase earth fault does not normally cause sagged voltages for low-voltage customers. When a surge arrester operates no circuit breaker operation is needed. Thus, in the case of indirect lightning strokes and induced overvoltages, the fault type and the possible need of a circuit breaker operation depend on the overvoltage protection type (Fig. 1).

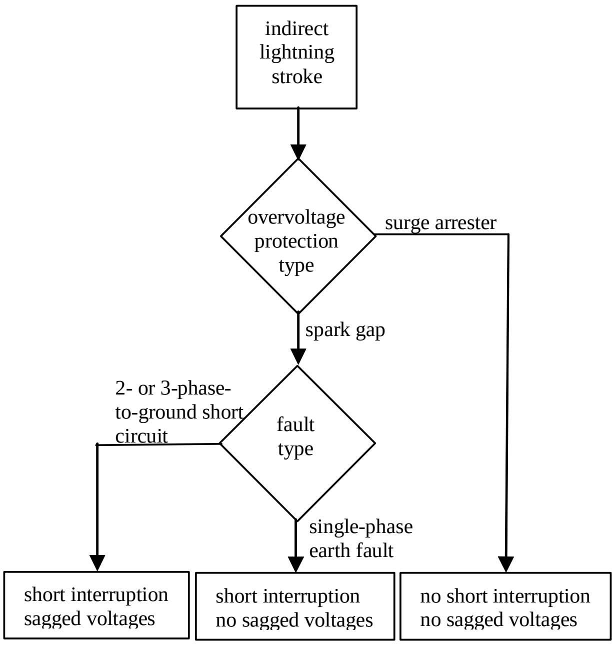

Fig. 1. The power quality effects caused by an indirect lightning stroke.

III. MEASUREMENTS

A. *Measurement Arrangements*

This paper represents one part of a long-term measurement project [2], [5]. Detailed results of measured faults during identified lightning storms are presented. The measurements were performed at two 110/20 kV substations located in the middle part of Finland (Table I). The distance between these two substations is about 250 km. In these areas, the winter months with snow typically last from November until March. Both the substations supply rural, forested areas with only radially operated MV overhead lines. The MV feeder construction includes wooden poles with ungrounded crossarms. The overhead lines have no lightning or ground wires protecting the lines. In the neighbourhood of the substations, the MV feeders leaving the substations follow the same feeder corridor for a couple of kilometers but further away from the substation each feeder supplies separate distribution areas. As is typical in Finnish overhead line networks, an autoreclosure sequence is used for protection purposes to clear temporary faults.

Substation A is unearthed and Substation B has a compensated neutral. The distribution transformers are pole-mounted. Substation A has an exceptional feature in the sense of distribution transformers: three of the feeders from Substation A supply transformers equipped with spark gaps while the other two feeders have transformers protected by externally gapped metal-oxide surge arresters. Substation B has only spark gaps for overvoltage protection.

TABLE I
SUBSTATION DATA

	Substation A	Substation B
Number of MV feeders	5	5
Total MV feeder length (km)	200	749
Total number of MV/LV transformers	159	488

The faults that occurred in the MV network supplied by the substation in question are categorized according to the fault type (single phase earth fault / 2-phase short circuit / 2-phase-to-ground short circuit / 3-phase short circuit / 3-phase-to-ground short circuit), the fault clearing sequence (fault cleared by high-speed autoreclosure / fault cleared by time-delayed autoreclosure / permanent fault) and the faulted feeder.

B. *Identified Lightning Storms*

In Finland, lightning mostly occurs in short bursts during the summer months from May to August. On average, only a couple of lightning storms are experienced during one summer. In this measurement project, the time periods when lightning storms passed the distribution areas were identified and listed. Fig. 2 presents the monthly distribution of faults measured at the 110/20 kV substations during the year 2004. The higher number of faults during the summer months are mainly caused by lightning storms.

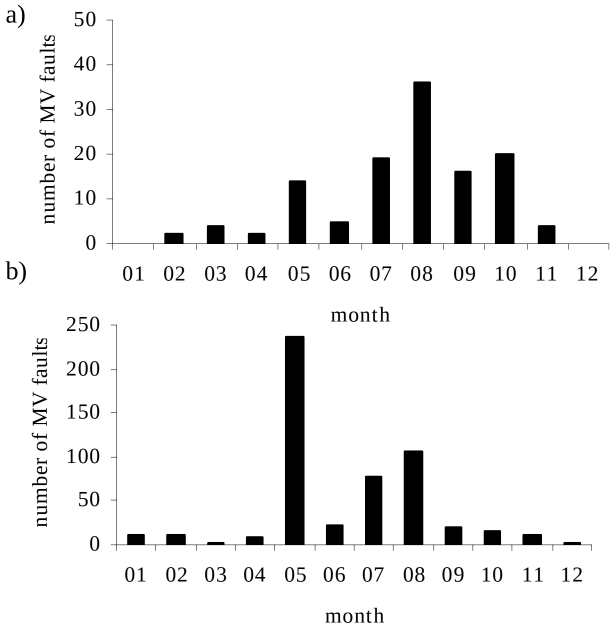

Fig. 2. The monthly distribution of MV faults that triggered circuit breaker operation during the year 2004, a) Substation A, b) Substation B.

The region around Substation area A did not experience any especially severe lightning storms during the measurement period. Table II presents the main results of the worst two lightning storms measured at Substation A during the years 2002-2004. Storm 1, 20.8.2004, included altogether 13 faults where a circuit breaker operation was needed and Storm 2, 21.8.2004, caused 10 faults. These two storms together lasted only seven hours but represented two thirds of the MV faults that occurred in August 2004.

Contrary to Substation A, the geographical area around Substation B seems to be more vulnerable to lightning storms. The worst reported lightning storm at Substation B included 196 faults within 12 hours (Table II). Storm 3 was, however, an exceptionally long and severe lightning storm in Finland. This storm represented 85% of all circuit breaker operations in May 2004. Storm 4 can also be considered to be a quite strong lightning storm but Storms 5 and 6 were less severe.

C. Fault Types and Fault Clearing Sequences

Generally, it is supposed that the majority of faults are single-phase earth faults [2]. However, during each observed lightning storm the majority of lightning faults were short circuits (Table II, Fig. 3). During the observed lightning storms the share of short circuits was 61% at Substation A and 87% at Substation B.

In general in overhead line networks that have autoreclosure, the majority of faults are cleared by high-speed autoreclosure. This was also the situation during the observed lightning storms (Table II, Fig. 4). When considering the extreme nature of lightning storms (hard wind, rain, falling tree branches and trees, lightning strokes), permanent faults were surprisingly rare. Storm 2 and Storm 3 each included one permanent MV fault. The causes of these permanent MV faults were a fallen tree on the MV feeder and a broken MV/LV transformer that had seen hit by a lightning stroke. During Storm 3, several permanent faults on the LV side were also reported. In addition to MV faults with circuit breaker operations, a considerable number of transient MV faults were analyzed. Here a transient fault means a fault that clears itself before a circuit breaker is opened at the substation. The measured transient faults were single-phase earth faults.

D. Coincident Faults

Especially during lightning storms, coincident faults can occur. Here, a coincident fault means that two or more faults occur at the same time on different feeders. Within these measurement arrangements, the fault clearing sequence of these coincident faults can be determined, but the fault type of each single fault belonging to coincident faults can usually not be.

During the measured lightning storms, the coincident faults typically caused very low remaining phase-to-phase voltages on the substation busbar. For the first couple of kilometers the MV feeders leaving the 110/20 kV substation follow the same feeder corridor through the forested areas and are even mounted on the same pole construction. In these feeder sections near the substation, coincident short circuit faults on several feeders are possible. The nearer the substation the short circuit fault occurs the lower the remaining voltages on the substation busbar will be. For example at Substation A, the coincident faults caused the remaining phase-to-phase voltages to sag to 75% - 47% - 68% and 43% - 45% - 56% in Storm 1 and 59% - 59% - 59% and 25% - 28% - 26% in Storm 2.

E. Faults of Changed Fault Type

Faults where the fault type develops into another fault type before the circuit breaker at the substation opened to clear the fault have been observed to occur. However, the lightning storms at Substation A included no such case. On the contrary, at Substation B this phenomenon did take place. Different observed cases of developing fault types are reported in Table II. Fig. 5 presents a case where a single-phase earth fault develops into a 2-phase-to-ground short circuit and Fig. 6 shows a 2-phase-to-ground short circuit developing into a 3-phase-to-ground short circuit.

F. Lightning Faults and Overvoltage Protection

Direct lightning strokes most probably cause a 3-phase short circuit no matter what kind of overvoltage protection is employed. These faults can occur anywhere along the feeder length. On the other hand, faults caused by induced overvoltages take place on distribution transformers where the overvoltage protection equipment is located. Within these measurement arrangements, the operation of a surge arrester remains unnoticed, because it causes no triggering of measurements on the substation busbar. On the contrary, when a spark gap operates, a fault (a single-phase earth fault, a 2- or a 3-phase-to-ground short circuit) occurs and the subsequent event is recorded (Fig. 1).

The distribution transformers supplied by the three feeders from Substation A and all the feeders from Substation B have only spark gaps for overvoltage protection. When assuming, during lightning storms, that the majority of faults are caused by induced overvoltages and occur on distribution transformers it means that not only one, but usually two or three spark gaps are activated at the same time causing typically, not a single-phase earth fault, but a 2- or 3-phase-to-ground short circuit. The measurements strengthen this assumption. Multi-phase short circuits without ground connection can be caused by direct lightning strokes occurring anywhere along the feeders.

At Substation A, only two of the 23 lightning faults occurred in those feeders having surge arresters for overvoltage protection. Thus, during the lightning storms, the fault frequency of surge arrested feeders was only 9% of the fault frequency of spark gapped feeders. This is also a lower fault frequency than has been reported for long-term fault frequencies. In [5], the fault frequency of surge arrested feeders was reported to be 16% of the fault frequency of spark gapped feeders. These new results from lightning storms strengthen the motivation to use surge arresters for overvoltage protection.

IV. CONCLUSIONS

Faults that occur during a small number of lighting storms in the summer months may represent a considerable share of annual faults. In this paper, detailed results of the faults that occurred during six lightning storms were presented. The measurements were performed at two substations supplying rural areas with only overhead lines and autoreclosure in use.

TABLE II
MV FAULT DATA FROM THE IDENTIFIED LIGHTNING STORMS

	Substation A		**Substation B**			
	Storm 1	**Storm 2**	**Storm 3**	**Storm 4**	**Storm 5**	**Storm 6**
Date	**20.8.2004**	**21.8.2004**	**6.5.2004**	**6.7.2004**	**7.8.2004**	**8.8.2004**
Started	**5:50**	**15:40**	**1:50**	**11:30**	**14:20**	**12:40**
Duration	**3h 20min**	**3h 50min**	**12h 30min**	**3h 30min**	**4h 20min**	**3h 50min**
MV faults with circuit breaker operation	**13**	**10**	**196**	**64**	**18**	**25**
- single-phase earth faults	2	3	28	2	0	0
- 2-phase short circuits	0	0	0	0	0	1
- 2-phase-to-ground short circuits	5	1	50	14	4	6
- 3-phase short circuits	0	0	41	23	11	15
- 3-phase-to-ground short circuits	1	1	27	10	3	3
- coincident circuit breaker operations	5	5	50	15	0	0
MV faults with circuit breaker operation	**13**	**10**	**196**	**64**	**18**	**25**
- cleared by high-speed autoreclosure	10	5	169	57	18	25
- cleared by time-delayed autoreclosure	3	4	26	7	0	0
- permanent	0	1	1	0	0	0
MV faults with changed fault type	**0**	**0**	**18**	**4**	**2**	**0**
- single-phase earth fault → 2-phase-to-ground short circuit	0	0	7	1	1	0
- single-phase earth fault → 3-phase-to-ground short circuit	0	0	3	0	0	0
- 2-phase-to-ground short circuit → 3-phase-to-ground short circuit	0	0	3	1	0	0
- 2-phase-to-ground short circuit → 3-phase short circuit	0	0	5	1	1	0
- 3-phase short circuit → 3-phase-to-ground short circuit	0	0	0	1	0	0

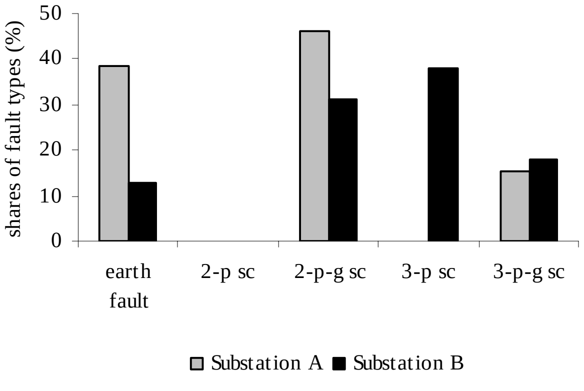

Fig. 3. The shares of fault types for MV faults that triggered circuit breaker operation during lightning storms at Substation A and Substation B.

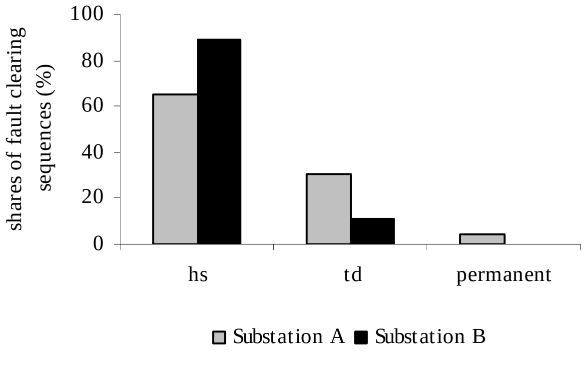

Fig. 4. The shares of fault clearing sequences for MV faults that triggered circuit breaker operation during lightning storms at Substation A and Substation B.

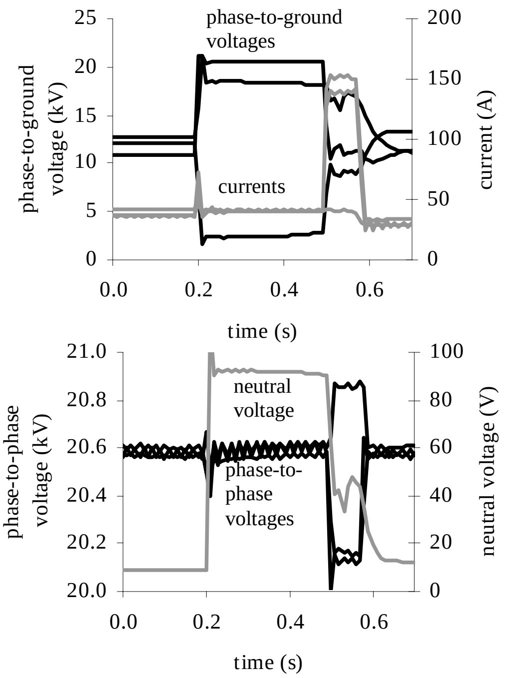

Fig. 5. A single-phase earth fault that develops into a 2-phase-to-ground short circuit within 14 cycles.

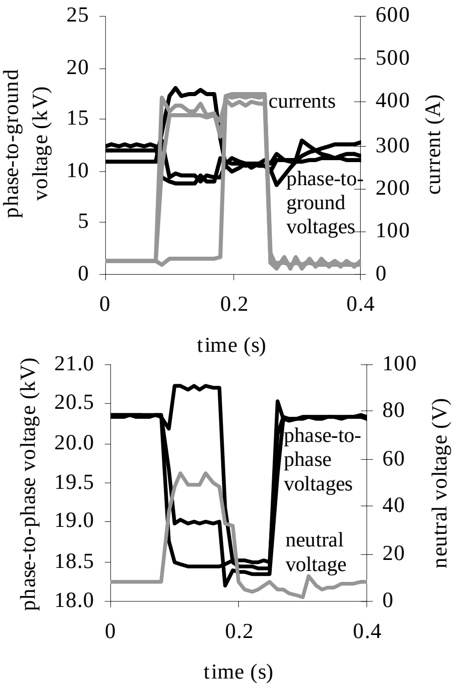

Fig. 6. A 2-phase-to-ground short circuit that develops into a 3-phase short circuit within 4 cycles.

The numbers of faults experienced at these two substations were quite different. The supply area of Substation B seemed to be more vulnerable to faults and lightning storms than Substation A. At both substations, coincident faults seemed to be typical events during lightning storms. In addition, fault types that developed into another fault type took place repeatedly at Substation B.

Generally, most faults are cleared by high-speed autoreclosure and this was also true in lightning storms. During the lightning storms, short circuits represented the majority of faults. This means that in addition to short interruptions experienced along the faulted feeders, sagged voltages occurred in the whole substation area. The overvoltage protection type seemed to also have an influence on the faults experienced during lightning storms. By using surge arresters instead of spark gaps the fault and sag frequency can be reduced.

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VI. 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 responsible for the construction of power distribution networks and power quality issues.