Oil Shale, 2013, Vol. 30, No. 2S, pp. 225–243
doi: 10.3176/oil.2013.2S.04
ISSN 0208-189X

CAUSES OF INDEFINITE FAULTS IN ESTONIAN 110 kV OVERHEAD POWER GRID

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Abstract. *The study considers causes of indefinite faults in the 110 kV overhead power grid in Estonia. The number of indefinite faults (flashovers on overhead line insulators) has increased significantly in the last years, causing a lot of problems to the transmission system operator (TSO). The study claims wildlife, more specifically migrating birds white storks, to be responsible for most of the indefinite faults in the power grid (excremental contamination).*

Keywords: *indefinite faults, insulator flashovers, contamination, bird streamers, White Stork.*

1. Introduction

The transmission system operator (TSO) of Estonian electrical power grid, Elering AS, has encountered a problem with indefinite faults in the grid (flashovers on overhead line insulators). As the number of such faults has considerably increased in the last years, TSO started to seek actively the cause of faults in order to eliminate the problem and maintain the high reliability of the power grid. Eliminating flashovers or minimizing their number is important to any TSO, since every such incident may result in a breakdown or malfunction of the electrical equipment of TSO and its clients, which in turn may lead to financial loss for both. The aim of the current study is to find out possible causes of faults in the Estonian power grid.

To this effect, TSO collected data about indefinite faults from 2005 to 2009 and started, in cooperation with Tallinn University of Technology, to analyze in more detail their possible causes.

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2. Registration of faults

Determination of the exact location of a fault is complicated because the devices used by TSO to register rapid changes of power line characteristics, in the present case flashovers, are inaccurate. This may be explained by that the location of a fault in the power line is calculated using parameters such as voltage, current and resistance. Faults in the lines are not caused by direct (metallic) short circuits. Instead, electric arc short circuits occur induced by insulator flashovers. These insulator flashovers induced electric arc short circuits can have resistance that may change to a great extent, and we presume this circumstance to account for the inaccuracies of the measuring equipment.

Finding the right place is complicated since the line protection switches off too fast to enable traces to be observed from distance. Imprints on wires left by the electric arc can only be seen, being on the same level or higher than the line wire. Imprints can be detected only in fair weather by using high sensitivity optical devices (binoculars, telescopes, digital cameras).

However, the data collected is accurate enough to make statistics and approximately locate the faults. An important component for data processing is the time of occurrence of faults.

2.1. Registered faults

During the years 2005–2009 TSO registered a total of 797 faults in 110 kV overhead lines in Estonia. The distribution of faults by origin is shown in Figure 1. The reclosure of a circuit breaker after an indefinite fault was successful in 99% of cases. This means that 99% of indefinite faults were transient type faults indicating insulation failure (insulator flashovers). All indefinite faults were of phase to earth type. The distribution of faults between phases was rather even (A0 ca 30%, B0 ca 40%, C0 ca 30%).

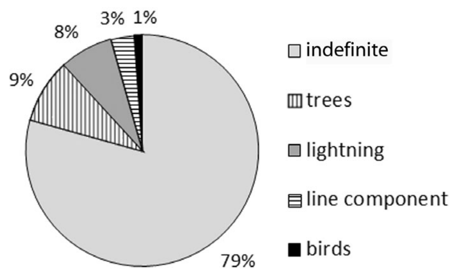

Fig. 1. Distribution of faults in the entire 110 kV overhead power line grid by origin, 2005–2009, %.

3. Time of occurrence of indefinite faults

Yearly differences in the number of faults are considerable (Fig. 2). For example, in the years 2005 and 2008, the number of faults was 1.5 times higher than in 2006, 2007 or 2009. The average yearly number of faults is approximately 125.

The monthly numbers of faults also differ quite significantly (Fig. 3). From September to the end of March there are almost no faults. From April to the end of May some increase of faults may be observed. From June to the end of August there is a rapid and continuous growth of the number of faults; approximately 85% of all indefinite faults occur during those three summer months.

The hourly numbers of faults during a 24 h period also differ significantly (Fig. 4). So, from 6 a.m. until 8 p.m. almost no faults are registered. From

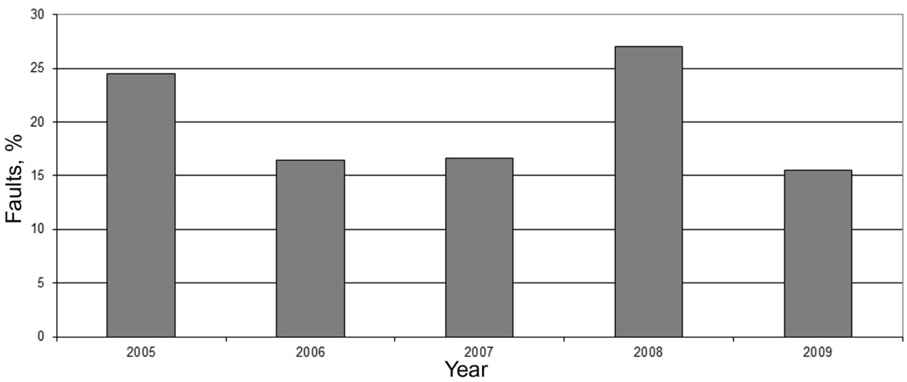

Fig. 2. Yearly indefinite faults in the entire 110 kV overhead power line grid, 2005–2009.

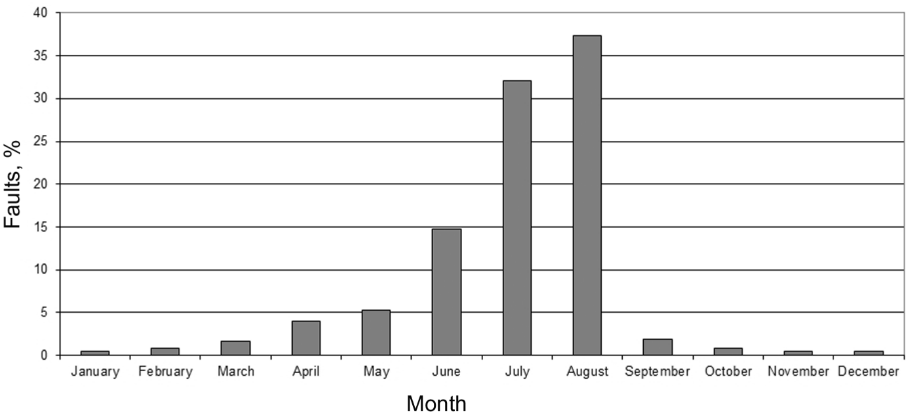

Fig. 3. Monthly indefinite faults in the entire 110 kV overhead power line grid, 2005–2009.

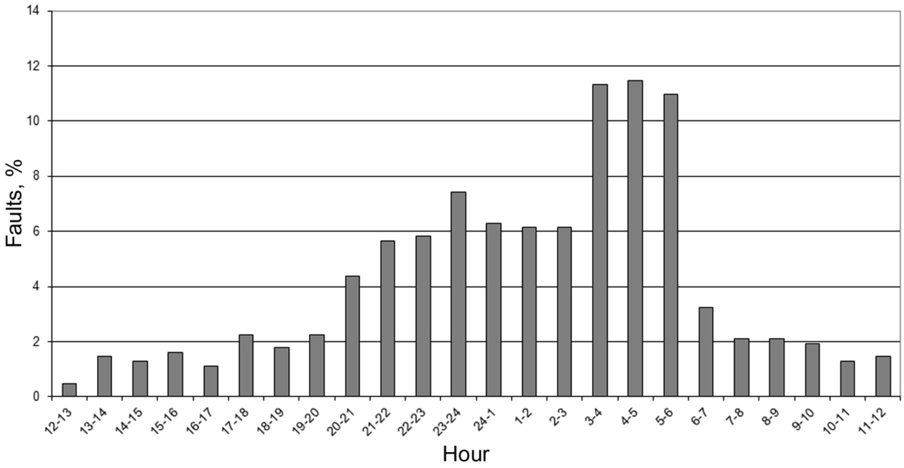

Fig. 4. Hourly indefinite faults in the entire 110 kV overhead power line grid, 2005–2009.

8 p.m. onwards the number of faults increases considerably and continuously until midnight, remaining thereafter almost constant until 3 a.m. (during those seven hours almost 40% of all faults occur). After 3 a.m. there is a rapid rise of the number of faults again until 6 a.m., these three hours account for about 35% of all faults. From 8 p.m. to 6 a.m., i.e. during the 10 h at night, about 75% of all indefinite faults within the 24 h occur.

4. Location of indefinite faults

The total length of overhead power lines in southern and northern Estonia is almost equal (50:50), but the majority of faults (two thirds) occur in South Estonia, while North Estonia accounts for one third. The geographical distribution of indefinite faults in Estonia is shown in Figure 5. On the basis of this figure it is difficult to visually evaluate the distribution of faults between North and South Estonia as “hot spots”, i.e. places with multiple faults, cannot be differentiated because all faults are marked with same-sized dots.

As mentioned above, the yearly number of faults averages approximately 125. The total length of overhead lines of the Estonian 110 kV power grid is 3415 km, which means that there is on average one indefinite fault per 27.5 km of overhead line a year.

The tolerable number of flashovers per line kilometer a year varies considerably depending on the importance and location of the transmission line. A typical global number of insulation failure-caused faults is one fault per 15–300 km of line a year [1]. For most European countries, the rate of about one flashover per 150 km of line a year is generally tolerable [2]. So, according to European standards the insulation failure-caused fault rate in the Estonian 110 kV power grid is too high.

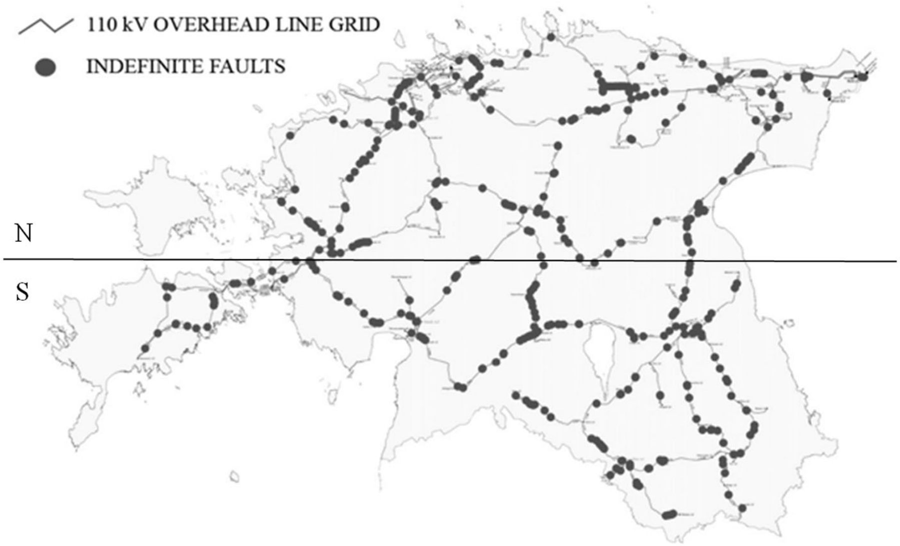

Fig. 5. Geographical distribution of indefinite faults, 2005–2009.

Table 1 lists seven most problematic lines in Estonia, which all have experienced at least 20 faults or more during 5 years. Names of the lines, whose glass insulators were replaced with composite insulators, are printed in boldface, while the respective year can be traced by the number of faults printed similarly.

However, as seen in Table 1, the changeover from glass insulators to composite insulators, which do not get contaminated easily and which at least in the beginning of their lifecycle should tolerate better all kinds of contamination, has not yielded the expected results. This is indicative of that flashovers are caused not by traditional, type a contamination [3], but more likely by type b contamination [3] because insulators get contaminated very fast.

Statistics show that faults are not distributed evenly along the whole line span. On the contrary, they tend to concentrate on certain line segments (towers). This is seen from Tables 2 and 3 which present data about faults

Table 1. Yearly indefinite faults in lines

	Line	2005	2006	2007	2008	2009	Total
1	L106A/B/D	6	2	8	20	11	47
2	**L060/061**	9	0	**6**	**11**	**8**	34
3	L157/158	6	5	6	9	6	32
4	L017	8	2	8	2	6	26
5	**L187**	11	9	**0**	**2**	**0**	22
6	L058	1	0	0	18	2	21
7	**L189**	4	7	5	**3**	**2**	21

Table 2. Indefinite faults in line L106A/B/D

Faults, pcs	47	Same place, pcs	Distance, km	Probable tower, no
Line				
L106A/B/D		25	77.6	57
		6	3.8	17
		6	2.0	9
		2	47.7	115
		2	45.3	121
		2	30.8	137
		2	18.7	85
		2	8.0	36

Table 3. Indefinite faults in line L060/061

Faults, pcs	34	Same place, pcs	Distance, km	Probable tower, no
Line				
L060/061		13	4.5	23
		7	8.6	42
		3	16.1	13A
		2	24.8	83
		2	11.0	52
		2	6.7	33
		2	2.6	15
		2	0.9	6
		1	21.1	67

in two most problematic lines in Estonia, as well as from Figure 5. The tables contain information on faults that have occurred alongside (up to 2 km). Combining data like that minimizes substantially the number of locations with faults, and spotlights the most problematic line segments (towers). From Tables 2 and 3 it can be seen that there are two or three places in the line where the concentration of faults is the highest.

Indefinite faults, which occurred, were phase to ground transient by type (99% of events). When merging the locations of faults, the fact that the latter occurred in different phases is irrelevant. This is because the faults are distributed between phases almost evenly and the sequence of phases may not be the same throughout the whole length of the lines (transposition in order to assure the electrical symmetry of phases in respect to each other, land or neighbouring systems). Tables 2 and 3 also show the distance from the beginning of the line to the location of a fault.

5. Correlation between the occurrence of indefinite faults and the time of sunrise and sunset

A certain correlation can be found between the occurrence of indefinite faults and the time of sunrise and sunset (Fig. 6). This correlation can be estimated by drawing, for example, so-called ±1.5 hour corridors around the lines, which show the time of sunset and sunrise [4]. This may be done in order to estimate the number of faults occurring in or out of these corridors. The corridors themselves constitute relatively small surface areas in the time/month graph (Fig. 6). Dividing the number of faults by the percentage of a particular surface area will yield a relative ratio which can be used to evaluate the rate of correlation. The higher the ratio is, the closer the correlation is.

As seen from Table 4, the number of faults is the highest at sunrise, while at sunset the respective figure is more than two times lower.

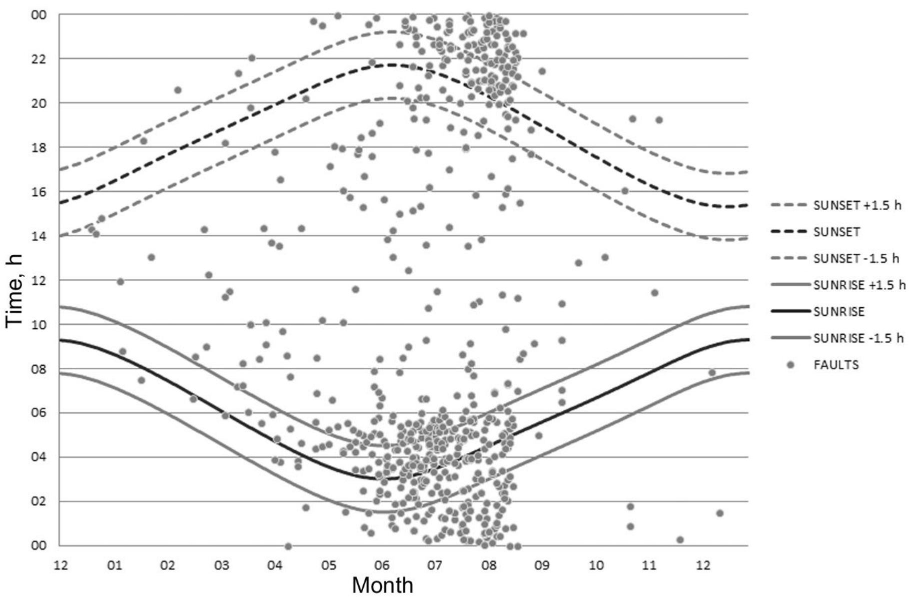

Fig. 6. Correlation between the occurrence of indefinite faults in the entire 110 kV overhead power line grid and the time of sunrise and sunset, 2005–2009.

Table 4. Correlation between the number of indefinite faults and the time of sunrise and sunset

	Surface area, %	Faults, %	Faults, pcs	Faults/surface area, pcs/%
Day	39	21	133	**3**
Night	35	28	174	**5**
Sunset ±1.5 h	13	17	109	**8**
Sunrise ±1.5 h	13	34	216	**17**

6. Connection between the occurrence of indefinite faults and atmospheric conditions (intensity of fog/dew, air temperature, relative humidity, rainfall)

Comparison showed no direct correlation between the occurrence of indefinite faults and average hourly, weekly and monthly values of relative humidity and air temperature and number of rainfalls in Estonia. However, it can be stated that the majority of failures occur at sunrise when the relative humidity and intensity of fog/dew are the highest. Exceptionally, one can find a correlation between the yearly number of indefinite faults (Fig. 2) and hourly average number of rainfalls in summer months per year (Fig. 7). However, further data collection will be needed to build up longer time series in order to confirm this.

The correlation remains poor even if only one power line has been taken under observation, for example, when finding a relationship between the number of indefinite faults in line L106A/B/D and data of the nearest, Pärnu weather station.

As seen in Figure 8, most of these indefinite faults have a different ‘signature’.

8 faults out of 14 can be described as typical flashovers of polluted insulators when after sunrise the intensity of fog/dew is the highest. Because of the thermal inertia of insulators their temperature is lower than that of the ambient air when the sun rises. This causes an intensive condensation of air humidity on the insulators [1]. The wetted layer of pollution then leads to a flashover.

2 faults out of 14 can be characterized as flashovers of polluted insulators in heavy rain when the relative humidity is near 100%.

4 faults out of 14 cannot be associated with atmospheric conditions, especially with fog/dew, rainfall, relative air humidity. These faults happened when there was neither rainfall nor fog/dew, and the relative humidity was

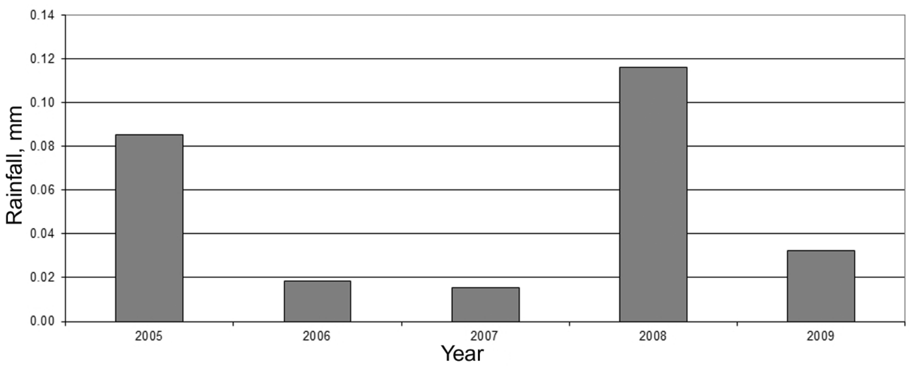

Fig. 7. Hourly average number of rainfalls per year (April–September) (average of 17 weather stations).

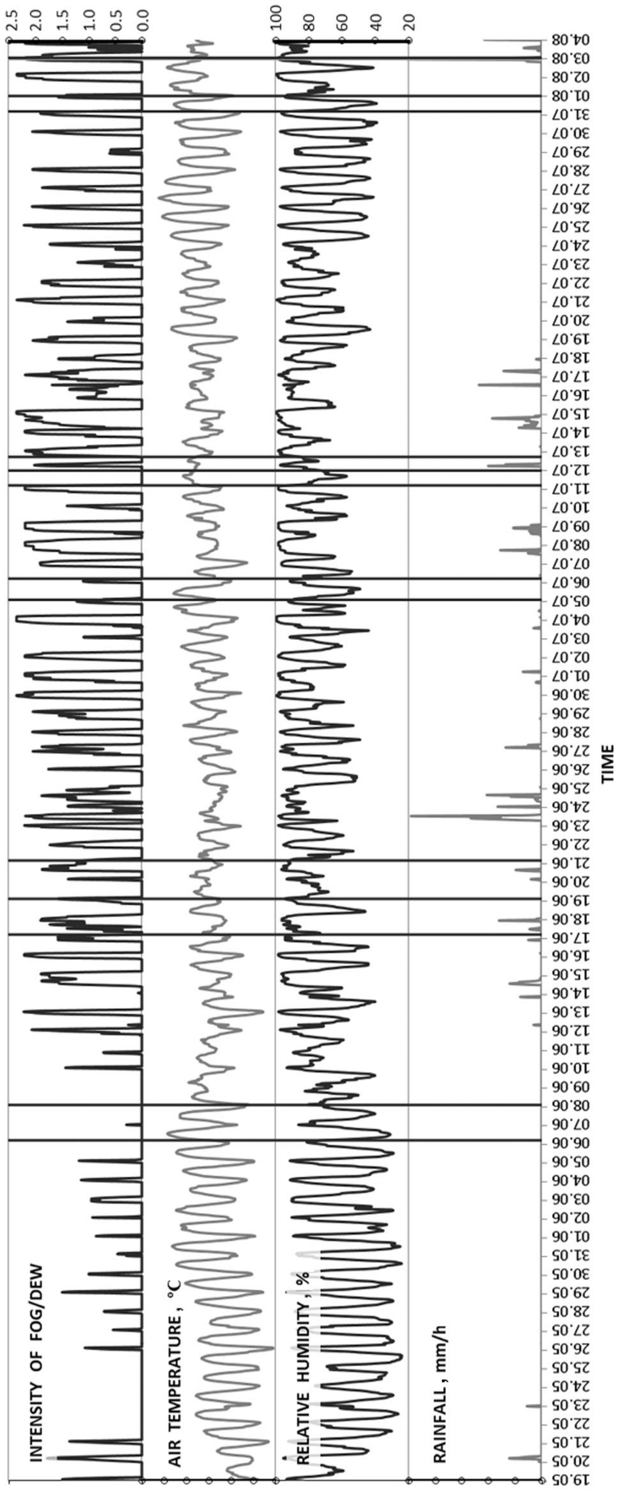

Fig. 8. Correlation between the occurrence of indefinite faults in line L106A/B/D and data of Pärnu weather station, 19 June–4 August 2008.

substantially lower than its daily peak. This indicates clearly that "traditional" pollution leading to insulator flashover was not the case here. It is transient-type pollution because the pollution causing a flashover occurs very fast and after the incident the auto-reclosure of the circuit breaker is successful in 99% of cases. It may be assumed that these "fast polluters" are large birds, more precisely, their excrement streamers.

On the basis of Figure 8 it can be said that there is no direct link between the occurrence of indefinite faults and atmospheric conditions. This poor correlation may be explained by different atmospheric conditions in a weather station and the location of faults (local microclimate) on the one hand, and the presence of fast polluters causing flashovers (large birds, type b contamination [3]) on the other.

7. Influence of air pollution (industry, agriculture) on the occurrence of faults

The impact of air pollution on the occurrence of faults is evaluated indirectly since the measurement of air pollution (content of different volatile particles in one air volume measure) was not carried out. For evaluation the so-called exclusion method was used.

Air pollution (type a pollution) is caused by a number of factors, but mainly by [1–3]:

1. industry (dust, ash, waste gas, chemical compounds);
2. agriculture (erosion, fertilizers, disinfestation, pollen);
3. transportation (exhausts, abrasion of tires/roads).

As industry and transportation are quite constant sources of contamination all the year round, they cannot be considered responsible for the growth of faults in summer. This is also supported by fault statistics. So, in big cities, where most industries have been concentrated and where there is no agricultural activity, the number of indefinite faults is quite insignificant.

Therefore the main additional source of air pollution during the summer months could be agricultural activities. The major sources of contamination could be spring sowing, autumn gathering, soil erosion caused by warm weather, and the pollen carried to the insulators by the wind.

The best time for spring sowing depends on weather conditions as well as on crop species, but it is mostly the end of April or beginning of May. Autumn gathering falls mainly on the end of August and September. Thus, the continuous rise of the number of indefinite faults between June and August is difficult to explain (Fig. 3).

Pollen spreads mostly in the beginning of spring (April–May) [5] when most trees and/or plants blossom, after which its concentration in the air decreases again. Hence, the continuous rise of the number of faults from June to August cannot be accounted for by pollen pollution (Fig. 3).

The role of soil erosion in severely polluting insulators, ending with a flashover, is considered to be modest if the soil does not contain any additives such as fertilizers, salts, poisons, etc. This is due to that the resistance of layers of such pollution on the insulator is usually relatively high and rain and strong wind have good cleaning capabilities with respect to this type of pollution [1, 6].

Soil erosion occurs mainly in dry, warm and moderately windy weather. The longer the dry and windy weather stays, the higher the impact of soil erosion pollution on the insulator is. This means that the period during which the insulator is subjected to contamination is longer before weather becomes wet or windy enough. Then either the insulator is self-cleaned by rain and strong wind or there will be contamination flashover caused by mist/dew or moisture condense making the pollution layer to conduct electricity. Usually it takes months and years, not days or weeks, to build up a pollution layer that is capable of causing flashovers [1, 6].

On the basis of Figure 8 and assuming that the weather station's data describe the meteorological conditions at actual failure sites correctly, it seems that there were no long dry periods without rainfall (max 12 days) during the period under examination. Two first faults occurred when there was neither fog/dew nor rainfall, and the third, fourth and fifth faults occurred several hours after rainfall when the intensity of fog/dew was substantially lower than the daily peak. So, soil erosion contamination cannot be considered responsible for the continuous rise of the number of faults from June to August.

8. Influence of the living nature (birds)

An American energy company, Florida Power and Light Company (FPL), carried out a study from 1988 to 1992 into causes of indefinite faults in 138, 230 and 500 kV overhead lines in Florida, and considered measures to prevent the faults. The study concluded that most indefinite faults were caused by the excrements of large birds. Those excrements can cause flashovers by either severely contaminating insulator surfaces or short-circuiting the insulators with excrement streamers (the highly conductive excrement stream of a large bird seating on the traverse causes a short circuit between the traverse and the conductor), or the concurrence of these two. Different root causes of faults (lightning, bird excrements and contamination) and their chronological division during a 24 h period were also determined (Fig. 9) [7].

As seen in Figure 9, birds-caused faults have a certain so-called signature. The number of faults rises quickly mostly after sunset, showing some decrease after midnight. At sunrise there is again a rapid increase of faults, after which this figure drops close to zero, remaining at this level practically the whole day.

Even though birds can excrete excrements almost all the time, there is some regularity in the so-called mass behavior of large birds while in flocks.

The peak of excrement excretion at sunset may be interpreted as the last supper of the day, meaning the last excretion of excrements before the night sleep. The peak at sunrise may be explained by that more birds excrete excrements right after the awakening and before daily activities [8].

In Figure 10 it can be seen that there is a strong correlation between the 24h time profiles of birds-caused indefinite faults in Estonia and Florida.

The graph of the time of occurrence of bird excrements caused faults in Estonia and Florida (Fig. 10) shows that the peaks of faults in the evenings and mornings are flatter in case of Estonia and these are also closer in

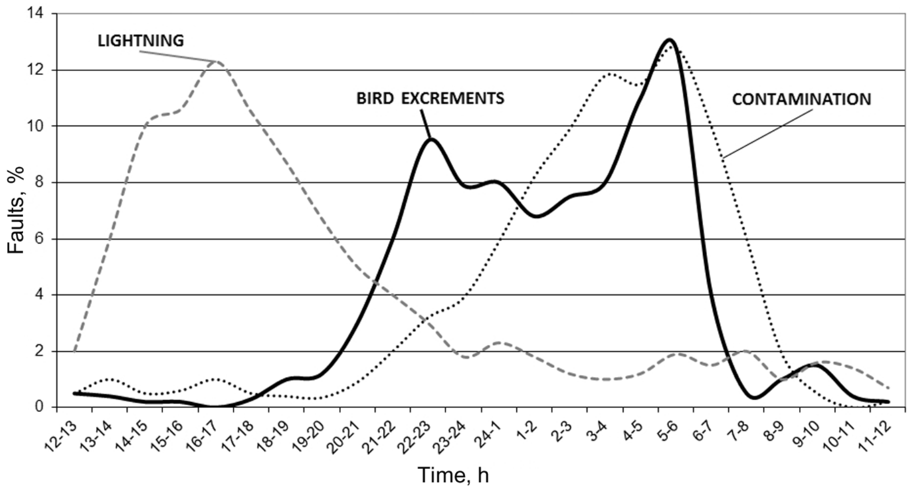

Fig. 9. Hourly faults in 138, 230 and 500 kV overhead power line grids in Florida, USA, 1988–1992, % [7].

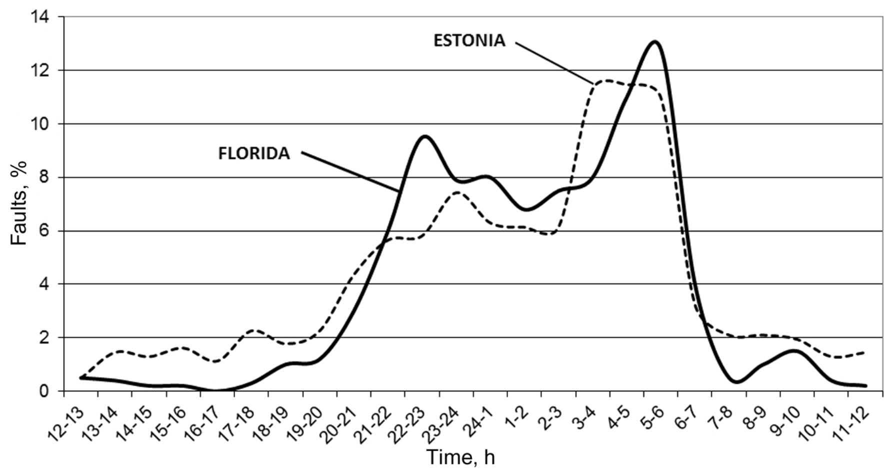

Fig. 10. Bird excrements caused faults in the overhead power line grid in Florida [7] and Estonia.

timeline. This can be explained by the different longitudes and latitudes at which Estonia and Florida are situated. Florida is much closer to the equator than Estonia and is roughly at the same latitude as Israel. The length of the day in Florida varies maximum 4 h, its minimum length in winter is 10 h, in summer 14 h. But in Estonia, this difference is 12.5 h, the minimum length of the day in winter being 6 h vs 18.5 h in summer. In Estonia, the time interval between the peaks of faults in the evenings and mornings in summer is shorter since at this time of the year, when most faults occur (Fig. 3), nights are here shorter than in Florida. Also, the flatness of peaks in Estonia's case can be explained by the fact that the time of sunrise and sunset varies here significantly (Fig. 6). During three summer months, June, July and August, this variation is about two hours for both, as well as during "white nights" there is the glow of sun on the horizon almost all night long.

A presumption that birds are the main cause of faults is supported by observations made by the system operator, as well as by random visual observation of towers carried out by the authors of this study. So, birds can easily be sighted standing or nesting on tower arms or at the top of the tower (Fig. 16). One can find bird excrements on insulators which have suffered from recent flashovers, as well as around those towers, on the towers, tower arms and phase conductors – near where they anchor on the insulators (Figs. 11 and 12). The system operator has got information from people living close to the places with frequent faults about the presence of single white storks or flocks of the birds at the time of occurrence of faults.

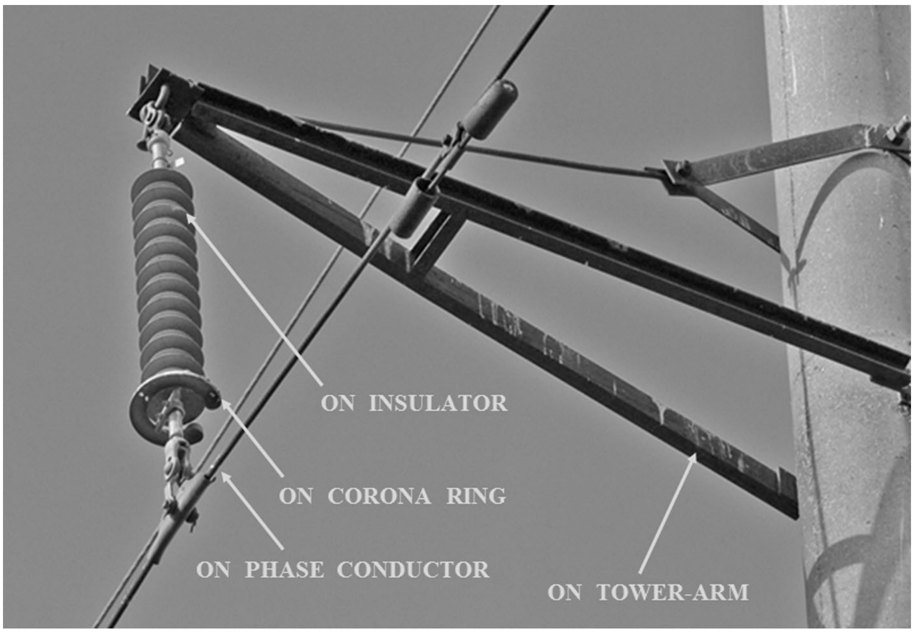

Fig. 11. Bird excrement imprints on the composite insulator, corona ring, phase conductor and tower arm (L060, M22).

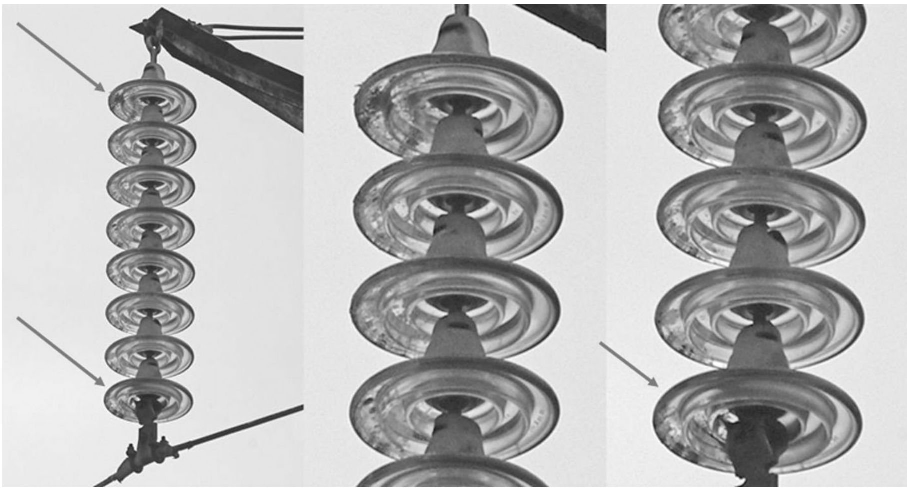

Fig. 12. Bird excrement imprints on glass insulator string (L178) (photo by V. Milt).

8.1. Migrating birds (the White Stork)

The main causers of indefinite faults are most probably large migrating birds who come to breed in Estonia during the summer. This is obvious from Figure 3 which shows that most faults occur in the summer (from April to August). In Estonia, this bird is most probably the White Stork (*Ciconia ciconia*) since it is the largest migrating bird who breeds in Estonia and whose population has risen rapidly in the last decades (ca up to 5000 pairs) (Fig. 13). A White Stork's body weight is 3.2 to 4.0 kg, body length 1.00–1.15 m and wingspan ca 2 m. The birds prefer to build their nest in a solid footing in high trees, overhead telephone and power line poles/towers, chimneys, etc. Therefore the storks choosing a place for nest (Fig. 14) prefer more and more (already 70%) poles/towers of overhead lines which offer such a solid base for the nest. Also, the birds like to guard and stalk their catch from high up from either the top of the tree, or pole or tower of the overhead line [9].

The White Stork arrives in Estonia to nest and breed in the middle of April and leaves either in the last weeks of August or in the beginning of September. This time interval coincides almost 100% with the time when the number of faults rises rapidly (Fig. 3).

The increase of the monthly number of faults during this period may be accounted for by the nesting habits of storks. So, in the beginning of the nesting period the couples prefer privacy in order to mate and breed. White storks breed in open farmland areas with access to marshy wetlands, building a stick nest in trees, on buildings or special platforms, and often nest close to human habitation. It feeds on fish, frogs and insects but also eats small reptiles, rodents and smaller birds. They have a strong attachment to their nest site.

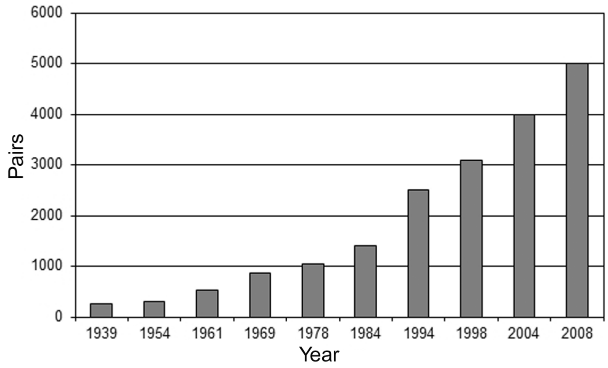

Fig. 13. White storks breeding in Estonia [10].

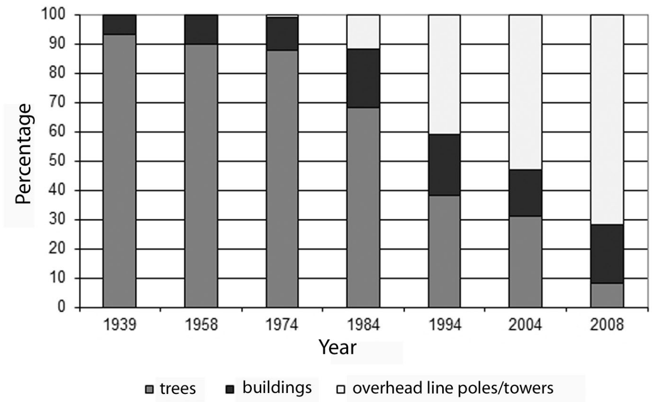

Fig. 14. Nesting sites of white storks in Estonia [10].

The female bird usually lays 3–5 eggs, more rarely up to seven. The parents share incubation duties for 33–34 days after what they have to feed usually 2–3 young chicks. This means an additional need for food, causing also the increase of the quantity of excrements leading to the rise of faults in June. Young chicks will become fully fledged within approximately 60 days, which means a twofold increase of population of flying birds by the months of July and August on an average. In August, all the birds are preparing for migration, couples and small colonies flock together and form small groups and bigger flocks. These flocks can comprise easily over 100 birds that would all like to find the best place to have an overview, for example, of a pole or tower of an overhead line. This circumstance is expectedly another cause of the increase of faults in the month of August [10].

In Estonia, the population of the White Stork is growing rapidly. The density of population is much higher in South Estonia than in North Estonia, reaching 25 pairs per 100 km^2 [10]. This pattern comes also forward in

Figure 5, knowing that two thirds of faults occur in South Estonia and one third in North Estonia.

The association of the White Stork with indefinite faults can be illustrated by the results of a study made in Israel [11, 12]. In Beit-Shean valley, there was also a problem with indefinite faults in the 161 kV overhead power line grid. Fault rate increased rapidly when the Black Stork (*Ciconia nigra*), a close relative to the White Stork, arrived in the valley to winter there (ca 400 pairs) (Fig. 15). From these and other collected data Israeli researchers concluded that black storks are the main causers of indefinite faults.

Figure 15 shows monthly insulation failures caused by wintering black storks in Israel and by breeding white storks in Estonia. In this figure one can easily identify the migrating stork's four basic life cycles (wintering, migration, breeding and migration again) per year.

As mentioned above, the presumption that mainly white storks are responsible for the line faults in Estonia is also supported by the line observations made by TSO and the authors of this study (Fig. 16).

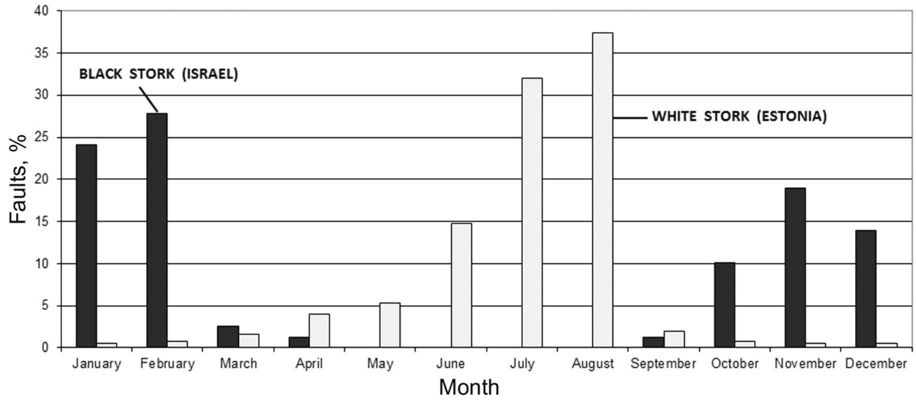

Fig. 15. Monthly distribution of faults caused by wintering black storks in the 161 kV overhead power line grid in Beit-Shean valley of Israel, 2003–2005 [11–12], and by breeding white storks in the entire 110 kV overhead power line grid in Estonia, 2005–2009.

9. Conclusions

In conclusion, it may be stated that most indefinite faults in the overhead power grid in Estonia are in high probability caused by the wildlife, more specifically migrating birds white storks, because their population, nesting time, nesting places and behaviour match the results of observations and fault statistics.

Fig. 16. White storks' nests on overhead power line tower arms (photo by R. Oidram).

The main root cause of faults is most likely bird excrements (a 3–4 kg bird is able to produce on average 60 g/d, while this amount may vary from 20 to 140 g [13]) [3, 7, 11–16].

Laboratory test results about bird excrement contaminated insulators can be found from a continuing work "Main bird excrement contamination type causing insulator flashovers in 110 kV overhead power lines in Estonia [17]".

Acknowledgment

The authors gratefully acknowledge the financial support from and supply of initial data by Elering AS. Väino Milt, expert on HV power lines at Elering AS, is specifically thanked for pleasant cooperation.

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Received October 22, 2012