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RISK ASSESSMENT OF MIDDLE-VOLTAGE OVERHEAD TRANSMISSION LINE FAILURES RESULTING FROM LIGHTNING DISCHARGES

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INTRODUCTION

In the area of electric power economy, and in particular in electricity distribution, we are often faced with the issue of lightning (atmospheric) discharges, or usually termed in a simpler way as lightning strokes. The effect of lightning strokes taking place in the electric power system (EPS) distribution network is sensed either as a transient disturbance or permanent failure. There are several ways of protecting EPS from consequences of this natural phenomenon. There has been a notable progress made in the area of electric power engineering with regard to lightning activity and lightning protection systems. Economic impact on the selection of a particular protection system is considerable. Under market conditions, it is not only the damage caused by lightning strokes that counts. What is particularly important is assurance of a continuous, uninterrupted, consumer supply. A most valuable reference for lightning protection system dimensioning are isokeraunic maps. They give an insight into the frequency of thunderstorm days on a particular location. When planning a lightning protection system, the designer calculates, by using experience formulas, the lightning stroke density rate which serves as a marginal condition for the selection of the appropriate protection level. In April 1998, the Slovenian Centre for Automatic Localisation of Lightning Discharges (SCALAR) was established to register data about lightning events over Slovenia. The first lightning stroke density map has been drawn, too. It replaces approximate assessing of the number of lightning strokes on the surface of one square kilometer. Moreover, in our research addressed in this paper we made use of the most recent map giving information on the lightning stroke density. It served us as a basic comparative criterion for the number of the localised failures obtained with the SCADA system and failure exposure rate for particular middle-voltage (MV) overhead transmission line (OHL) paths.

DESCRIPTION OF THE METHOD

With the method presented in this paper we wanted to determine the relationship between instances of OHL failures obtained from operational logbooks, correlated failures and lightning stroke density rate on the area of our observation. The method is based on a comparison of the number of registered MV OHL faults caused by lightning discharges and the number of localised lightning discharges. The data about the number of the registered MV OHL faults were obtained from operational logbooks. Logbooks are kept in two ways, either classically (by writing down events in operational logbooks) and

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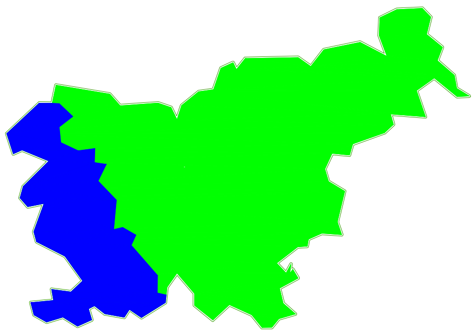
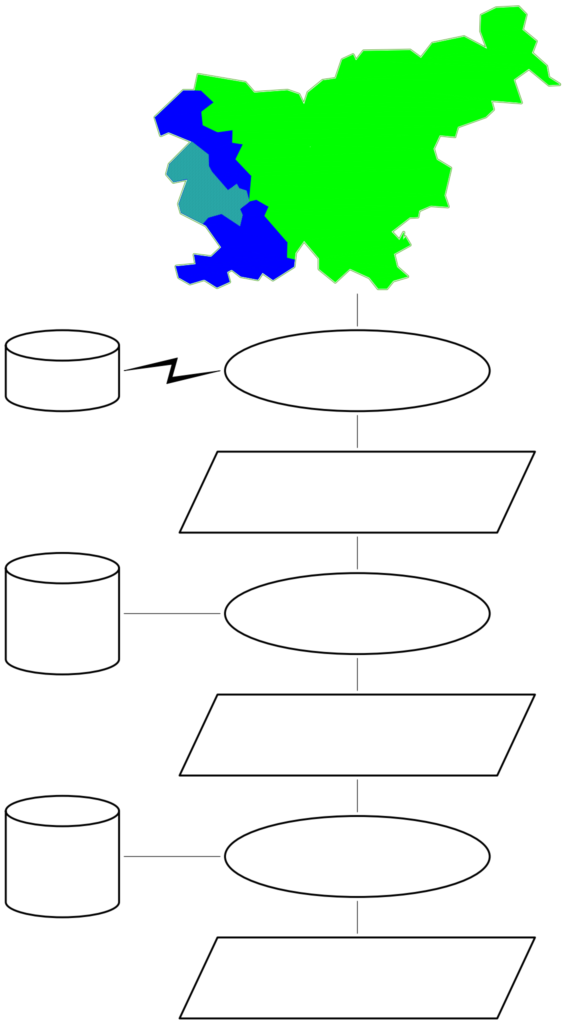
electronically (to allow for statistical and other types of analyses) by using the program “Report about the state in the EPS of the distribution utility Elektro Primorska «.
The number of localised lightning discharges along the feeder path was obtained by filtering the data set of the SCALAR system along the tree structure of the observed feeder and registered events obtained from the archive system named SCADA. The extent of the data geographic profile covered the domain of the distribution utility Elektro Primorska (EP).

FIGURE 1 - Geographic location of the distribution utility Elektro Primorska within Slovenia



The time span of our research lasted from January 1, 2000 until December 31, 2003. By choosing such extent of the time span we wanted to observe the greatest possible number of events of both the SCALAR and the SCADA system.

FIGURE 2 - Lightning stroke correlation process made with the SCADA system



The applied procedure allowing for acquisition of data about the number of registered MV feeder failures took us quite a lot of time. The reason for this was the formulation of the data structure, i.e. entities, which describes the type and the location of the event only in a descriptive way. The same applies to the time tag approximated to a minute. The algorithm for correlation of lightning strokes of the SCALAR system with the registered events from SCADE system (Figure 2) was complex, too.

The most advanced GIS equipment was used for the implementation of the presented process. These were Map and ArcView equipped with macro programs. In the first step, the research scope was limited whereupon data about lightning strokes from the SCALAR system were acquired on the basis of this limitation. Since our analysis was extremely complex, the observed area was divided into four sub-areas in compliance with the organisational structure of EP. In the next step, the corridor around sections of a particular MV feeder was defined. On the basis of this limitation we verified all lightning strokes and equipped them with a code of the involved feeder. In the last step, the time and spatial correlation between lightning stroke data and registered data from the SCADA system was made. The result is a record of all the correlated lightning incidences having triggered a certain event in the SCADA system.

Data about MV OHL faults from operational logbooks

Operational logbooks are kept in the utility remote control centre (RCC) EP. They contain all the events whose consequences are either failure or disconnection of a part of the network. Both cases involve disconnection of the MV network. Such data are also recorded in the program for report writing and further statistical processing. The character of the operational logbook data is of a descriptive nature. This means that the failure location has no geographic and topological tag. The same applies for the time of the disconnection occurrence. It is registered on few minutes precision basis. The description of malfunctioning suggests which type of the fault is involved or explains its origin. For the observed period of time, we filtered 243 disconnections. They were selected from a program set for report writing of EP. The selection was made from 2001 candidates for which it was believed that their disconnection would be the consequence of lightning discharges. After a rough time correlation (the time difference was +/- 5 min) we obtained 118 failures which were based on interdependence between the lightning strokes and network disconnection. We found it impossible to have the remaining 122 disconnections classified with a sufficient level of certitude into the first group of correlated disconnections. The reason for this was the time tag which was approximative. The table below contains data about failures resulting from lightning strokes taking place in the EP EPS, particularly in its subdivision DE Gorica.

TABLE 1 - Events from operational logbooks and reports which are causally connected with lightning strokes

No.	SubStation	Feeder	Feeder description	Cause of the event	DateTime
1.	AJDOV.	OHL RAZDRTO	DV 20 KV RTP AJDOVŠČINA-RAZDRTO	LIGHTNING STROKE	25.06.2000 09:13:00
2.	AJDOV.	OHL VIPAVA	DV 20 kV RTP AJDOVŠČINA – RAZDRTO	OHL FAILURE	28.06.2000 17:53:00
3.	AJDOV.	OHL GORICA	dv 20 KV RTP AJDOVŠČINA-GORICA	OHL FAILURE	07.11.2000 23:59:00
4.	GRGAR	OHL BANJŠICE	DV 10 KV RP GRGAR-SKALNICA	CATHODIC ARRESTER	07.11.2000 22:59:00
5.	VRTOJBA	OHL GORICA - GRADIŠČE	DV 20 KV BILJE 1-ŽIGONI	BROKENDOWN ISOLATOR	08.11.2000 16:43:00
6.	AJDOV.	OHL GORICA	DV 20 KV AJD.-GORICA	THUNDERSTORM	08.11.2000 17:45:00
7.	VRTOJBA	OHL GORICA - GRADIŠčE	DV 20KV RP SELA - KOSTANJEVICA	THUNDERSTORM – GROUND FAULT PROTECTION	17.11.2000 14:53:00
8.	VRTOJBA	OHL VOLČJA DRAGA	DV 20KV RTP VRTOJBA - VOLČJA DRAGA	THUNDERSTORM OVERCURRENT PROTECTION	17.11.2000 14:44:00
9.	VRTOJBA	OHL BILJE 3	DV 20 KV RP BILJE - TP ŠAMPIONKA	THUNDERSTORM – SURGE ARRESTER	17.11.2000 14:44:00
10.	GRGAR	OHL BANJŠICE	DV 10 kV RP GRGAR - BANJŠICE	THUNDERSTORM – SHORT CIRCUIT	08.01.2001 09:19:00
11.	PLAVE	OHL ANHOVO 1	DV 10 KV ANHOVO -KANAL 2	TORN WIRE ON 35 KV OHL OF PLAVE -MOST	28.06.2001 10:16:00

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No.	SubStation	Feeder	Feeder description	Cause of the event	DateTime
12.	AJDOV.	OHL RAZDRTO	TR 1 110/20 KV V RTP AJDOVŠČINA	LIGHTNING STROKE	22.03.2002 13:03:00
13.	VRTOJBA	OHL GORICA-GRADIŠČE	DV 20 KV RP GRADIŠČE-KOMEN	THUNDERSTORM	28.06.2002 15:00:00
14.	GRGAR	OHL SKALNICA	DV 10KV GRGAR SKALNICA	THUNDERSTRORM	24.10.2002 05:06:00
15.	VRTOJBA	OHL GORICA-GRADIŠČE	DV 20KV KOMEN ŠTANJEL	THUNDERSTORM	24.10.2002 04:49:00

Data and events from the SCADA system

The SCADA system records the majority of events affecting EPS. These events are archived to form a collection of which the most important element are the following two tables: the table listing events and the table indicating chronological sequence of events (CSE). The collection is created for each day separately. In our analysis, the most important were the CSE data. As the CSE function is not applied at all the remote control locations, we decided to use for these locations event list data. In both cases, the criterion for data filtering was the disconnection event. Within the span of the observed period, 18479 disconnections were registered in the area of EP. Events from the CSE list are equipped with the time tag on the station computer. This time is coordinated with the GPS hour. Data from the event list are equipped with the time tag after being called in by the master process computer in RCC thus causing the delay of some 15 seconds for the time tag between the event and the archive data. When correlating lightning discharges and registered disconnections from the SCADA system, we separately searched for interdependent data of the CSE tables and the event list. The total number of correlated disconnections detected within the 750 m wide corridor around the topological tree of the station feeder is 682. It is interesting to note that in the correlation time difference as much as two or even three strokes were detected simultaneously for one single disconnection. Table 2 shows some disconnections correlated with lightning strokes. As it can be seen, on June 28, 2002 there were two strokes. It is the last one that satisfies both conditions, i.e. the station and the feeder.

TABLE 2 - Events registered in the scada system and being causally connected with lightning strokes

CSE						Lightning strokes along the feeder topological structure				Conditions		
Station	Bay		DateTime	Time	Event	Station	Bay	Time1	Amp.	DiffTime	Station	BAY
HUBELJ	OHL PREDMEJA	JA03	09.11.2001 04:14:26	04:14:26.059	DISCONNECTION	HUBELJ	JA04	9.11.01 4:14	-10,6	8	YES	NO
GORICA	DV VRTOJBA-GRADIŠČE	JA13	12.11.2001 00:55:52	00:55:52.03	DISCONNECTION	GORICA	JA13	12.11.01 0:55	-26,5	-2	YES	YES
AJDOV.	OHL RAZDRTO	JA05	22.03.2002 13:02:24	13:02:24.601	IDISCONNECTION	AJDOV.	JA05	22.3.02 13:02	127	1	YES	YES
HUBELJ	OHL PREDMEJA	JA03	28.06.2002 15:23:32	15:23:32.971	DISCONNECTION	HUBELJ	JA04	28.6.02 15:23	-24,7	-2	YES	NO
HUBELJ	OHL PREDMEJA	JA03	28.06.2002 15:23:32	15:23:32.971	DISCONNECTION	HUBELJ	JA03	28.6.02 15:23	-19,5	0	YES	YES

Data about lightning discharges of the SCALAR system

The used data about lightning discharges were obtained from the SCALAR system, which has been recording lightning strokes in Slovenia from 1998 onwards. These data are equipped with both time and geographic location. From the SCALAR data set we filtered - within a 750 m wide corridor of the observed feeders having the tree structure – lightning discharges for the period of four years. For geographic information system (GIS) analyses we used the most advanced software. For each lightning stroke we allotted an area of the supply line. In this way we enabled starting the process for having lightning discharges correlated with disconnections of the SCADA system. Table 3 contains some statistic data about lightning discharges having occurred in the observed area.

TABLE 3 -Statistic data about the number of lightning discharges and size of the observed area

Subdivisions of the EP distribut. utility	Surface [km2]	Share of the observed surface covered by EP	Number of lightning strokes recorded in the obsrved period	Flash density per km2/year
GORICA	1.137	26%	30.124	5,3

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Subdivisions of the EP distribut. utility	Surface [km2]	Share of the observed surface covered by EP	Number of lightning strokes recorded in the obsrved period	Flash density per km2/year
KOPER	341	8%	6.307	3,7
SEŽANA	1.552	36%	28.950	3,7
TOLMIN	1.313	30%	32.907	5,0
EP	**4.342**	**100%**	**93.260**	**4,4**

APPLICABILITY OF THE PRESENTED FAILURE RISK ASSESSMENT METHOD

The method was tested on the entire territory covered by the EP distribution utility for the period from January 1, 2000 till December 31, 2003. As the number of events, and consequently archive files, was extremely great (365 files annually), we limited our investigation on 80 files per year. We decided to focus on days with more than three lightning strokes!

Description of the investigated part of EPS covered by the EP distribution utility

The area of our observation encompasses 20 substations, 41 distribution stations and 2543 transformer stations. Table 4 presents data about the transmission line length for the entire area, for each voltage level and each type of the power transmission line (either overhead or underground).

TABLE 4 - Data about OHL length for the area covered by the EP distribution utility

MV Network (length in km)	Subdivisio DE Gorica	Subdivision DE Koper	Subdivision DE Sežana	Subdivision DE Tolmin	TOTAL
35 kV OHL	55,6	25,2	84,4	7,4	172,6
20 kV OHL	502,5	216,8	500,6	464,1	1.684,0
10 kV OHL	130,6	24,6	76,6	20,5	252,2
TOTAL OHL	**688,6**	**266,6**	**661,7**	**492,0**	**2.108,8**
35 kV UGL	0,8	2,6	2,3	0,4	6,1
20 kV UGL	118,3	147,0	145,0	85,4	495,7
10 kV UGL	4,8	5,2	13,5	2,1	25,6
TOTAL UGL	**124,0**	**154,8**	**160,8**	**87,8**	**527,4**
TOTAL	**812,5**	**421,4**	**822,5**	**579,8**	**2.636,2**

Our investigation was limited to feeders exposed to lightning discharges.

RESULTS

Table 5 displays data for one distribution unit of the observed feeders. Data are given for the OHL part of the feeder, average density per feeder length, and number of correlated failures per feeder. Figures 3 and 4 show the lightning stroke density rate per transmission line length and correlated lightning strokes along the lightning stroke density profile of the OHL path.

TABLE 5 - Data about impacting factors per individual feeders

Station	Un [kV]	Bay name	Length [km]	Average density [n/km2/year]	Number of events	Number of failures [n/year /100 km]
VRTOJBA	20	OHL GORICA-GRADI.	157,3	4,37	22	0,47
AJDOV.	20	OHL GORICA	34,8	4,114	12	1,15
HUBELJ	20	OHL PREDMEJA	17	4,891	10	1,96
AJDOV.	20	OHL RAZDRTO	28,4	3,557	9	1,06
VRTOJBA	20	OHL BILJE 3	23,4	4,615	8	1,14
HUBELJ	20	OHL LOKAVEC	16	3,816	4	0,83
VRTOJBA	20	OHL VOLČJA DRAGA	12	4,498	4	1,11
ČRNI VRH	20	OHL MRZLI LOG	14,9	4,352	3	0,67
GORICA	20	OHL AJDOVŠČINA	27,4	4,11	2	0,24
AJDOV.	20	OHL PLANINA	6,3	4,245	1	0,53
AJDOV.	20	OHL VIPAVA	10,9	3,385	1	0,31
ČRNI VRH	20	OHL LOME	6,1	3,503	1	0,55
ČRNI VRH	20	OHL ZADLOG	11,7	3,936	1	0,28
GORICA	20	OHL VRTOJBA-GRADi.	8,3	4,584	1	0,40
GORICA	20	UGL SOLKAN	2,5	4,744	1	1,33

Station	Un [kV]	Bay name	Length [km]	Average density [n/km2/year]	Number of events	Number of failures [n/year /100 km]
VRTOJBA	20	OHL MIREN	4,4	4,484	1	0,76
GRGAR	10	OHL BANJŠICE	23,1	6,269	9	1,30
GRGAR	10	OHL ČEPOVAN	43,7	6,005	9	0,69
GRGAR	10	OHL TRNOVO	11,8	5,553	4	1,13
PLAVE	10	OHL ANHOVO 1	51,7	5,79	4	0,26
PLAVE	10	OHL DOBLAR	19,6	5,209	3	0,51
GRGAR	10	OHL SKALNICA	2,3	6,093	2	2,90
PLAVE	10	OHL BRDA	21,1	5,689	2	0,32
PLAVE	10	OHL DOBROVO	21,8	5,378	2	0,31
GORICA	10	OHL GRGAR	9,7	5,514	1	0,34
DOBROVO	10	OHL DOBROVO	5,1	5,292	0	0,00

The correlated events were classified into two groups with regard to their rated voltage. For each group we searched for linear approximation between the lightning stroke density as an independent variable and the number of failures per year and. 100 km of the OHL length. For the linear approximation of the below form

$$y = kx + n \qquad (1)$$

the parameter n = 0 was assumed. This means that the number of failures at density 0 equals 0. Value k was found with the least square method. The result for the 10 kV network was k = 3.35 and for the 20 kV network k = 2.39. In practice, the two results mean that for the density of one lightning stroke/km2/year over the length of 100 km of the 10 kV OHL 3.35 failures/year can be expected; for the 20 kV OHL this value is 2.39 failures/year. When the density is five lightning strokes/km2/year, the number of failures linearly increases for the same factor k.
Diagrams 1 and 2 show interdependence between the number of failures and average lightning stroke density for 10 in 20 kV voltage levels.

DIAGRAM 1 - Number of failures per 100 km as a function of the lightning stroke density for the 10 kV OHL

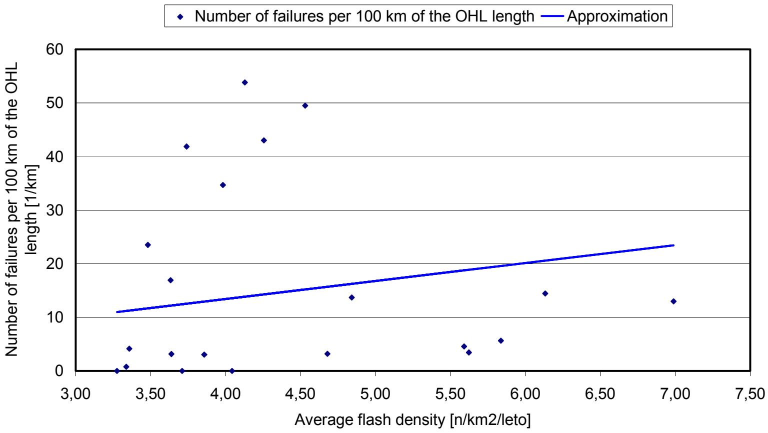
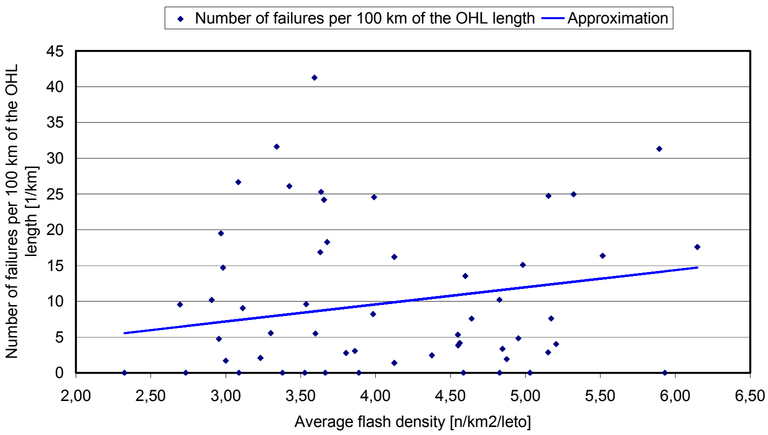


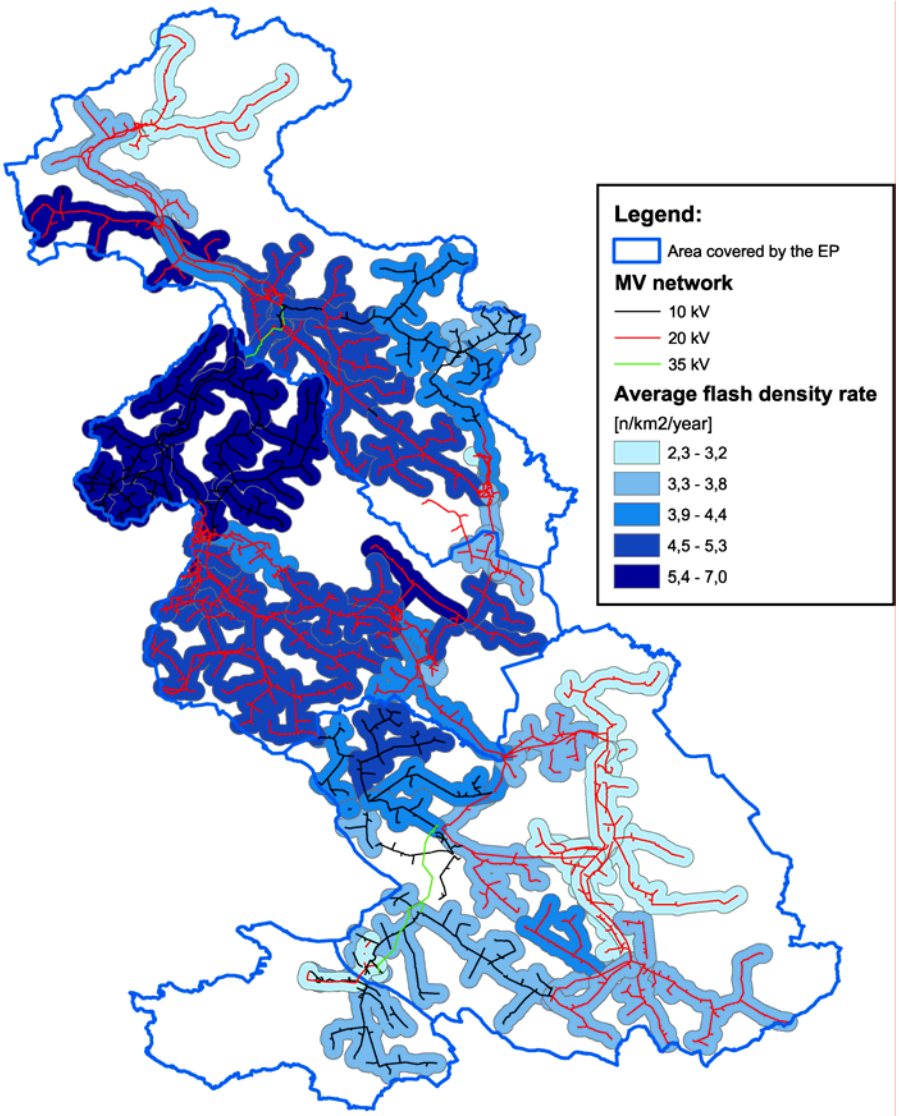
DIAGRAM 2 - Number of failures per 100 km as a function of the lightning stroke density for the 20 kV OHL



The following are the conclusions that can be drawn from the above results:

1. As the statistical pattern is small - it concerns only one distribution utility for the period of four years – the degree of the result dispersion is very high.
2. The lightning stroke density rate for the observed area is high (over three lightning strokes /km2/year) and very high (over five lightning strokes /km2/year – see Figure 3). This means that no relevant assessment can be made for the areas of low and medium lightning stroke density rates (below three lightning strokes /km2/year).
3. By using the least square methods, it is possible to calculate k from the obtained results. k is positive (see Equation 1). This means that in areas where the lightning stroke density rate is higher, the number of failures is higher, too. The same can to a certain degree be established also from Figure 4.
4. A quantitative assessment is made of the number of failures that may be statistically expected for a certain lightning stroke density rate for the 10 and 20 kV voltage network.

FIGURE 3 - Average flash density rate along a supply feeder path



CONCLUSION

The method described in this paper enables assessment of the number of failures of MV OHL per line length as a function of the lightning stroke density rate registered along the line path. The analysis was based on the data from operational logbooks of a distribution unit for which the lightning stroke density rate has been on average estimated as high and very high. Irrespective of the facts that the

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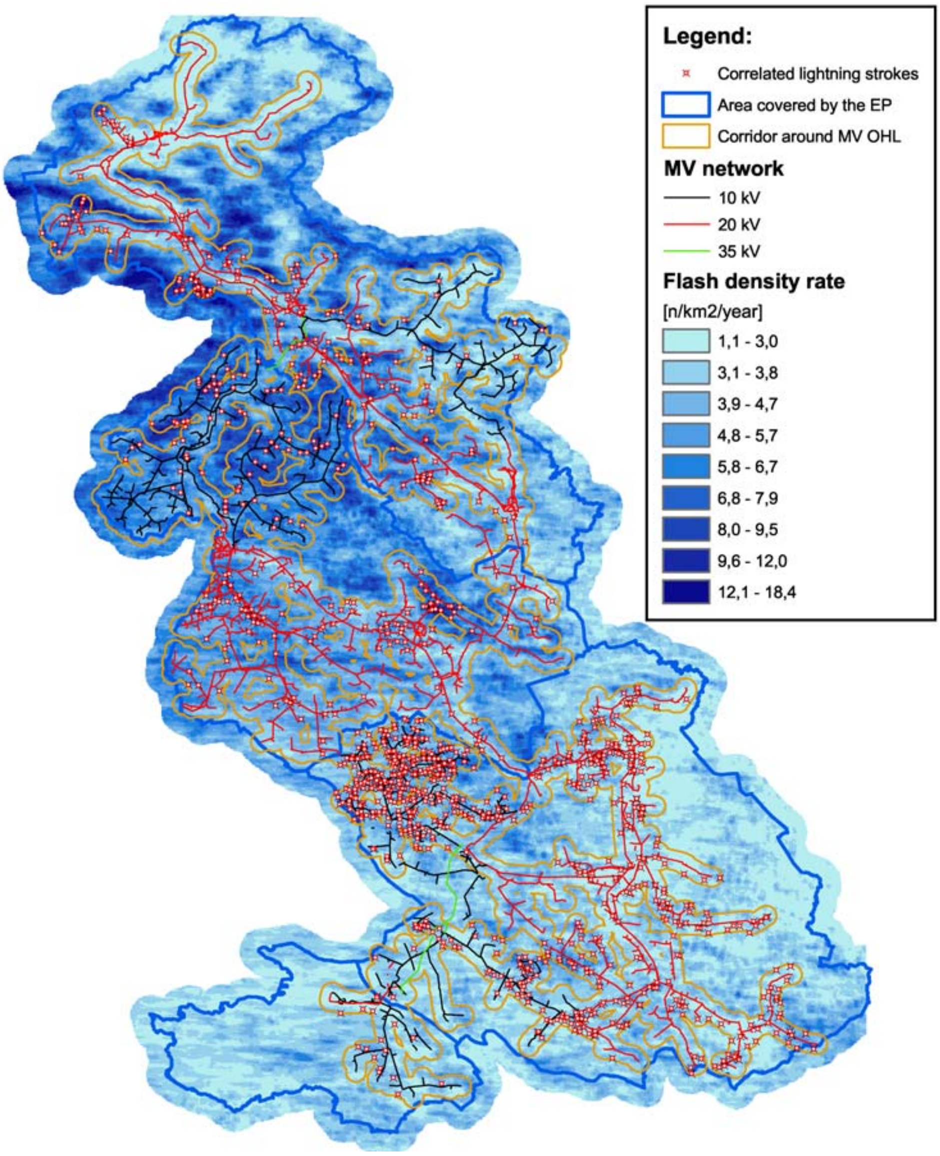
analysis covered a rather short period of time, i.e. four years, and involved only one distribution utility - which makes the value of its statistical results quite low - the results indicate that the correlation between the number of OHL failures and lightning stroke density rate is solid. The conclusion of the performed analysis is that operational logbooks are a most valuable source of information. If kept consistently and precisely, they allow for quality statistical analyses. To simplify future analyses, it would be very helpful to ensure, with a new software version, a regular intake of failure causes in order to minimise incorrectness when interpreting events and make searching of data in various files easier. To optimise results obtained with this method, future analyses should address also those areas for which we know that the lightning stroke density rates are lower than the ones dealt with in this paper (Suha krajina, Prekmurje, Dravsko polje). Observation of the operational period should be extended to minimally five years, which is also the period for which data from the SCALAR system are available. Notwithstanding, results obtained with this method provide for solid basis for the first quantitative assessment of probable MV network failures.

FIGURE 4 - Correlated lightning strokes along the lightning stroke density profile



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