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Hazard Curve Construction for Icing Events of Overhead Power Lines

by

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Contents

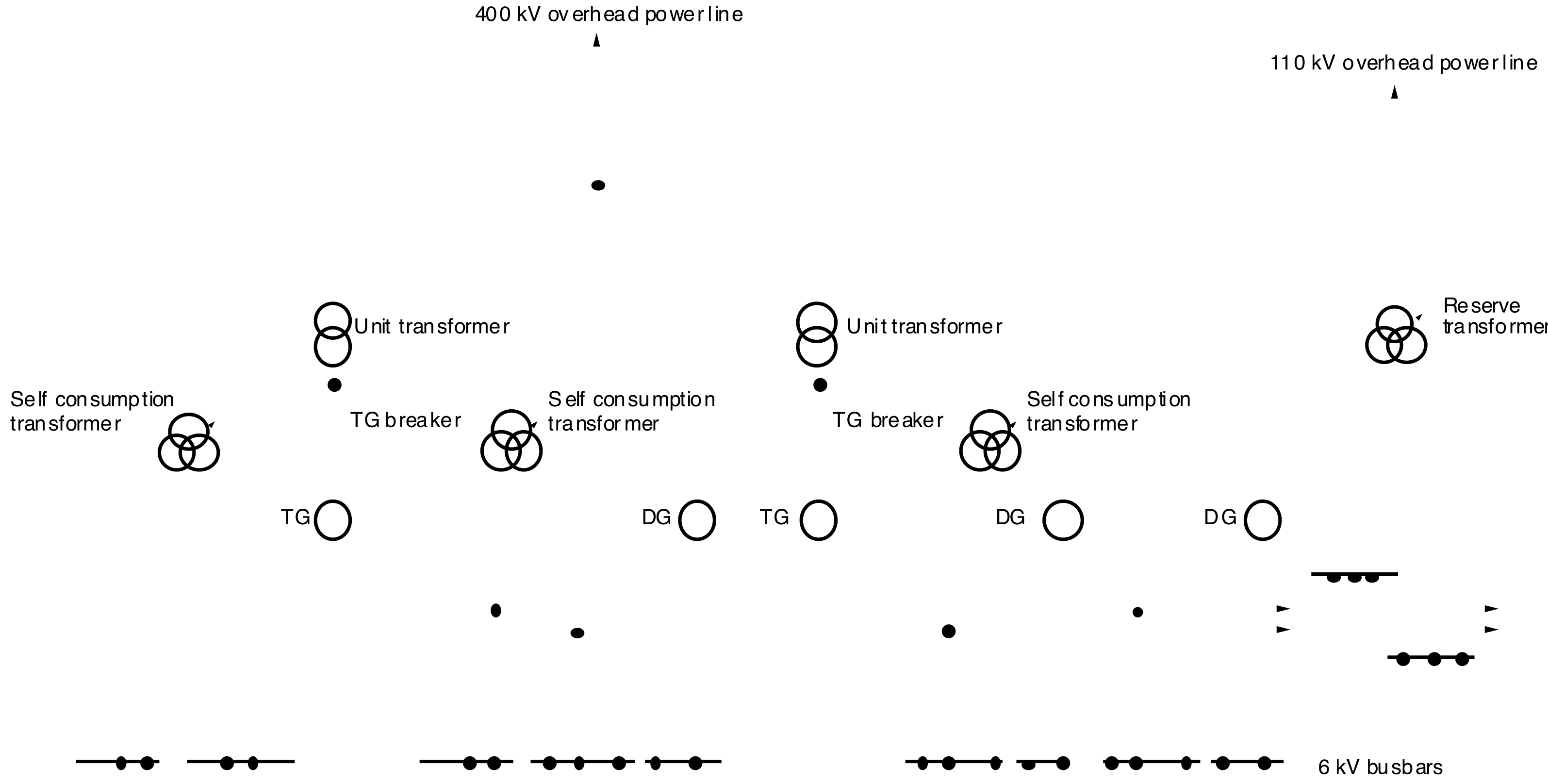
Introduction

- Based on the detailed analyses the following extreme meteorological conditions were included into the non-seismic external event PSA for the Slovak nuclear power plants:
  - extreme wind,
  - tornado,
  - extreme snow,
  - extreme rain,
  - extremely high and extremely low air temperature,
  - icing and
  - lightning.
- External events in the form of extreme weather conditions can occur as single events or as combinations of two or more external events.
- The potentially combined events are two or more external events having a conditional probability of simultaneous occurrence, e.g., strong winds occurring at the same time with icing.

The electrical grid

- The 400 kV overhead power line is used to export electricity to the grid during plant operation and to supply self consumption.
- Given loss of 400 kV line due to external reason the turbogenerators (TG) reduce power to the level of self consumption.
- Reactor trip occurs given loss of the 400 kV line due to internal reason. Then, the self consumption of the plant is supplied from the reserve transformer which is fed from the 110 kV overhead power line from the electrical grid.
- Given simultaneous loss of both 400 kV and 110 kV lines the diesel generators (DG) are being started to supply the 6 kV busbars.

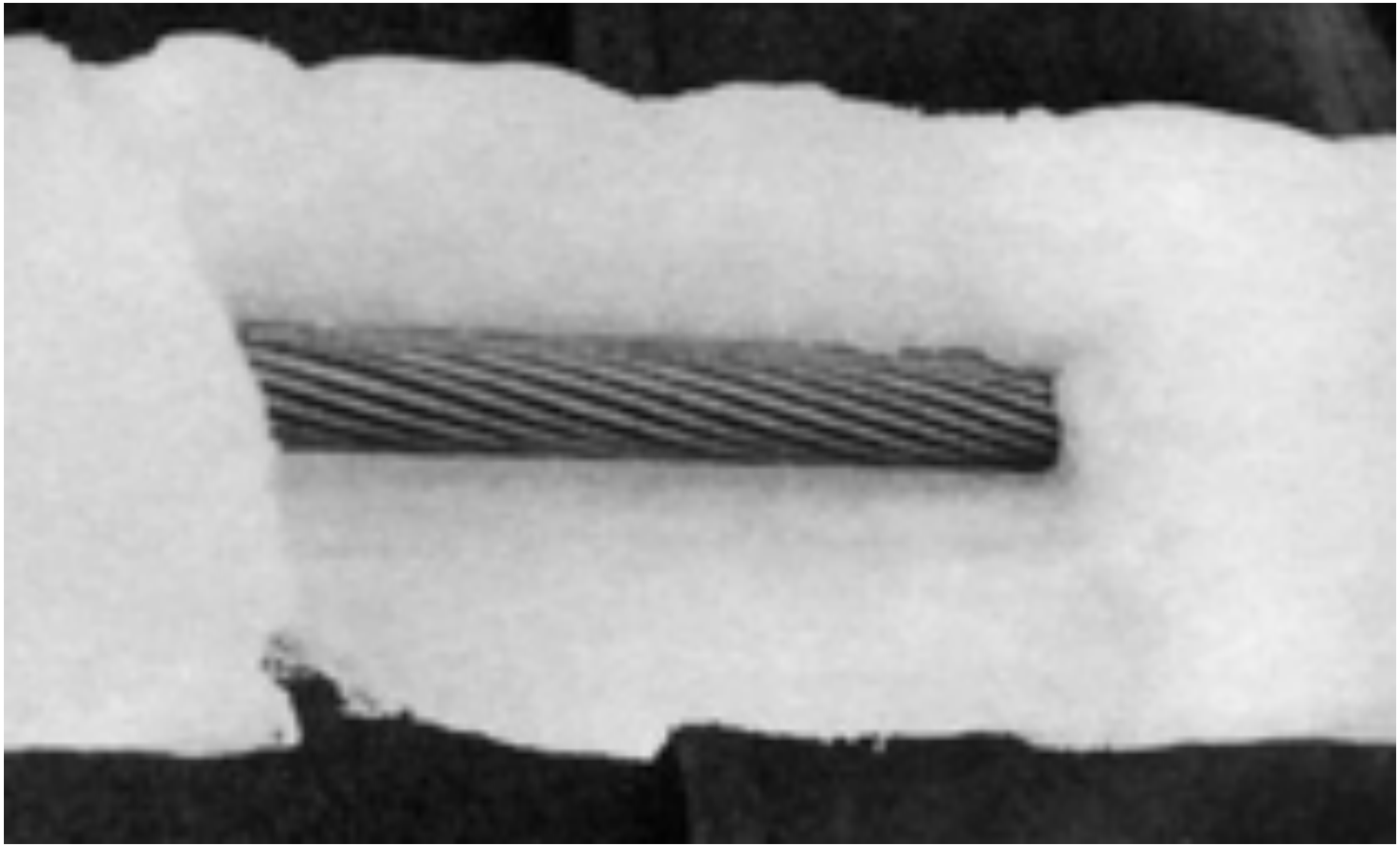
The overhead lines in the self consumption of the plant



Ice loads of the overhead power lines

- The ice load can damage the overhead power lines and cause partial or total loss of offsite power of the plant.
- There are different forms of ice loads of the overhead power lines:
  - Atmospheric icing
  - Glaze due to freezing rain
  - Wet snow
  - Soft and hard rime due to incloud icing

Ice accretion due to freezing rain



Conductor with ice formed in an incloud icing process

Ice observations and measurements

- Field ice data can be obtained through the following activities:
  - Direct measurements of icing thickness or weight of ice samples, taken from observation installations or line conductors. Ice samples fallen on the ground from conductors can be used, if consideration is given to the shape of initial accretion on conductors.
  - Measurements by devices that simulate ice accretion on conductors. Some devices currently used in a few countries consist of simple tube or cable assemblies installed near ground level for ease of observations.
  - Estimation of icing using conductor tension or vertical component of weight at the insulator attachment point.
  - Estimation of icing based on measurements of the conductor tension and sag.

Ice observations and measurements

- Ice loading data are important not only to establish load criteria for design of supports but can also be useful in the planning stages of transmission networks and route selection of a specific line.
- So far other ice load information is not available, measurements lasting for at least 30 years of field observation are necessary to establish a reliable database.
- The observation of extreme ice loads on existing overhead lines provides important information.
- Meteorological models can be used as well to obtain basic information on ice loadings to be expected. The bases for such meteorological models are formed by the temperature, humidity, precipitation rate and wind direction to be expected.

Ice observations and measurements

- SHMI is performing measurement of icing creation on the conductor with length of 1 m and diameter of 30 mm. The thickness of the icing is being measured (mm), then the weight is calculated from it.
- For the purpose of the PSA the measurement for the time period 1996 – 2017 was taken into account.

Data of the maximal icing in mm on the conductor

Winter	Month	Icing [mm]	Winter	Month	Icing [mm]	Winter	Month	Icing [mm]
1995-96	1	9	2003-04	2	4	2011-12	12	4
1996-97	1	14	2004-05	1	3	2012-13	12	4
1997-98	1	2	2005-06	2	13	2013-14	12	1
1998-99	1	26	2006-07	12	12	2014-15	1	1
1999-00	1	10	2007-08	12 - 1	9	2015-16	1	2
2000-01	1	33	2008-09	1	6	2016-17	1	9
2001-02	12	20	2009-10	2	4			
2002-03	1	10	2010-11	12 - 1	15			

Data of the maximal icing load in g/m on the conductor

Winter	Month	Icing [g/m]	Winter	Month	Icing [g/m]	Winter	Month	Icing [g/m]
1995-96	1	439	2003-04	2	181	2011-12	12	181
1996-97	1	732	2004-05	1	134	2012-13	12	181
1997-98	1	88	2005-06	2	671	2013-14	12	43
1998-99	1	1581	2006-07	12	611	2014-15	1	43
1999-00	1	495	2007-08	12 - 1	439	2015-16	1	88
2000-01	1	2169	2008-09	1	280	2016-17	1	439
2001-02	12	1131	2009-10	2	181			
2002-03	1	495	2010-11	12 – 1	795			

Ice observations and measurements

- The observed data were available in mm of icing thickness on the conductor. However, the load of the ice on the conductor should be known in g/m for evaluation the impact of extreme loads.
- Therefore, it was necessary to calculate the weight of icing from the available measurement information on the 1 m long conductor with the diameter of 30 mm.

Icing on the conductor

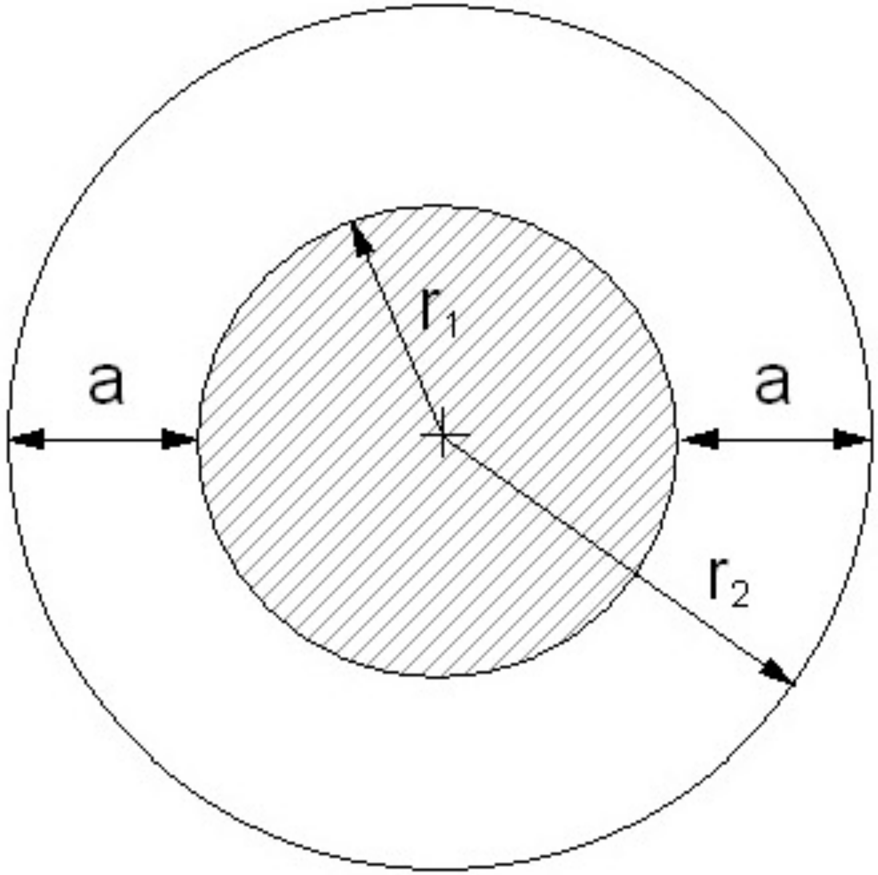
- An example is provided for illustration the weight calculation from the thickness of the icing. The icing is shown on the conductor, where:

a – thickness of icing [mm]

r_1 – radius of the conductor [mm]

r_2 – radius of the conductor with icing [mm]

Icing on the conductor



Icing on the conductor

- The diameter of the line is 30 mm, the radius is r_1 = 15 mm. Thickness of the icing is 33 mm. Such icing was recorded during the winter season 2000 - 2001.
- The thickness of the icing is the sum of two *a* values:

Icing on the conductor

$$33\ mm = a + a$$

Then, it is valid that:

$$a = \frac{33mm}{2} = 16.5mm$$

The values of radii „r_1“ and „r_2“ are applied in calculation, where

$$r_1 = \frac{d_1}{2} = \frac{30\ mm}{2} = 15\ mm\ ,$$

$$r_2 = r_1 + a = 15\ mm + 16.5\ mm = 31.5\ mm$$

Icing on the conductor

In the next step the surface of the electrical line S_1 without icing and with icing S_2 are calculated:

$$S_1 = \pi * r_1^2 = 706.5\ mm^2$$

and

$$S_2 = \pi * r_2^2 = 3115.7\ mm^2$$

Then, the surface S_2 is reduced by the value of S_1 and the surface of the icing ring S is achieved:

$$S = S_2 - S_1 = 2409.2\ mm^2$$

Given that the surface of the icing ring S is available, and the length of the electrical line is $l = 1\ m = 1000\ mm$, the volume of icing can be calculated:

$$V = S * l = 2409.2\ mm^2 * 1000\ mm = 2409200\ mm^3 = 0.0024092\ m^3$$

A conservative value of the icing density is considered $\rho = 900\ kg/m^3$ [1].

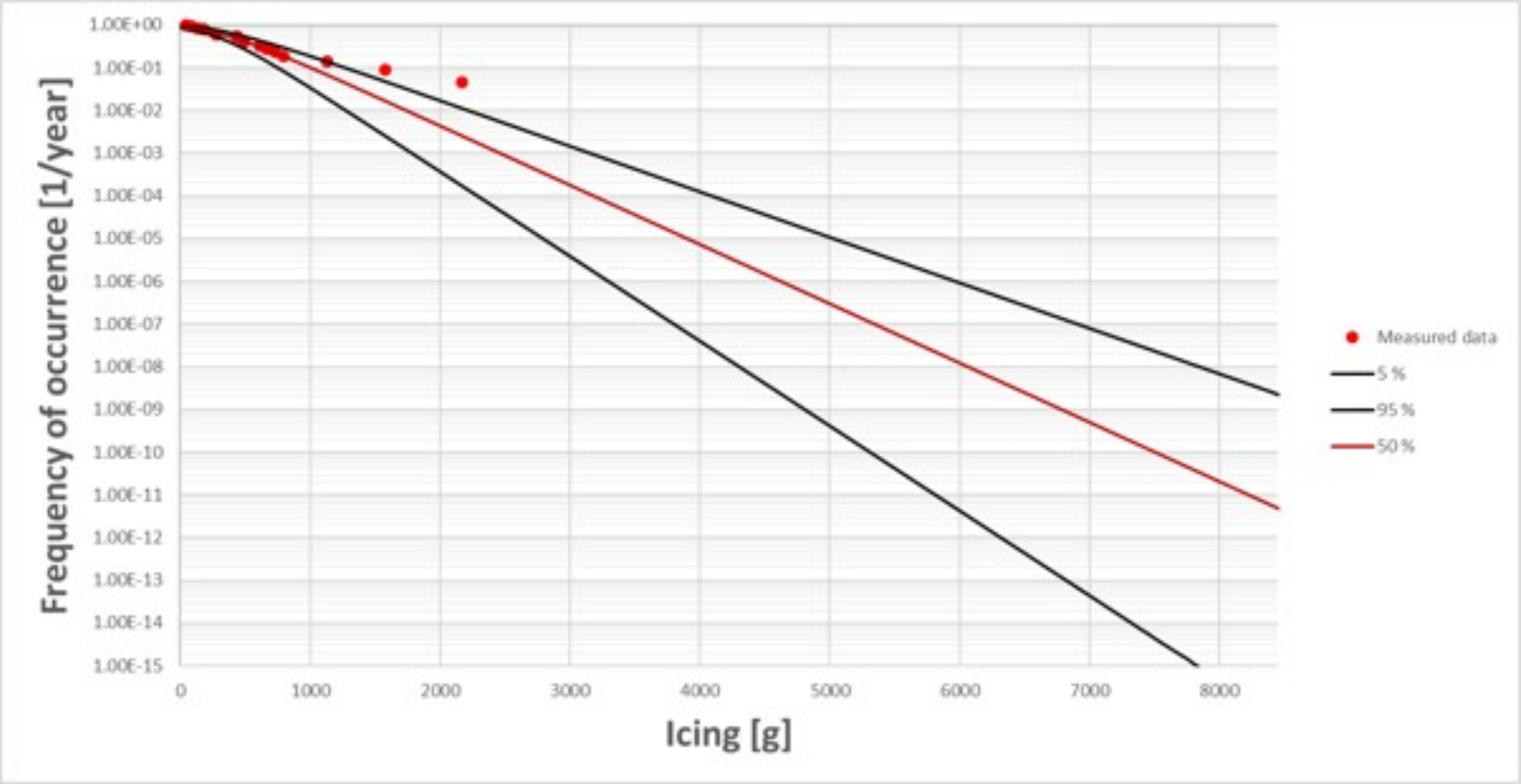
The load of the line with the length of 1 m is:

$$m = V * \rho = 0.0024092\ m^3 * \frac{900\ kg}{m^3} = 2.169\ kg = 2169\ g$$

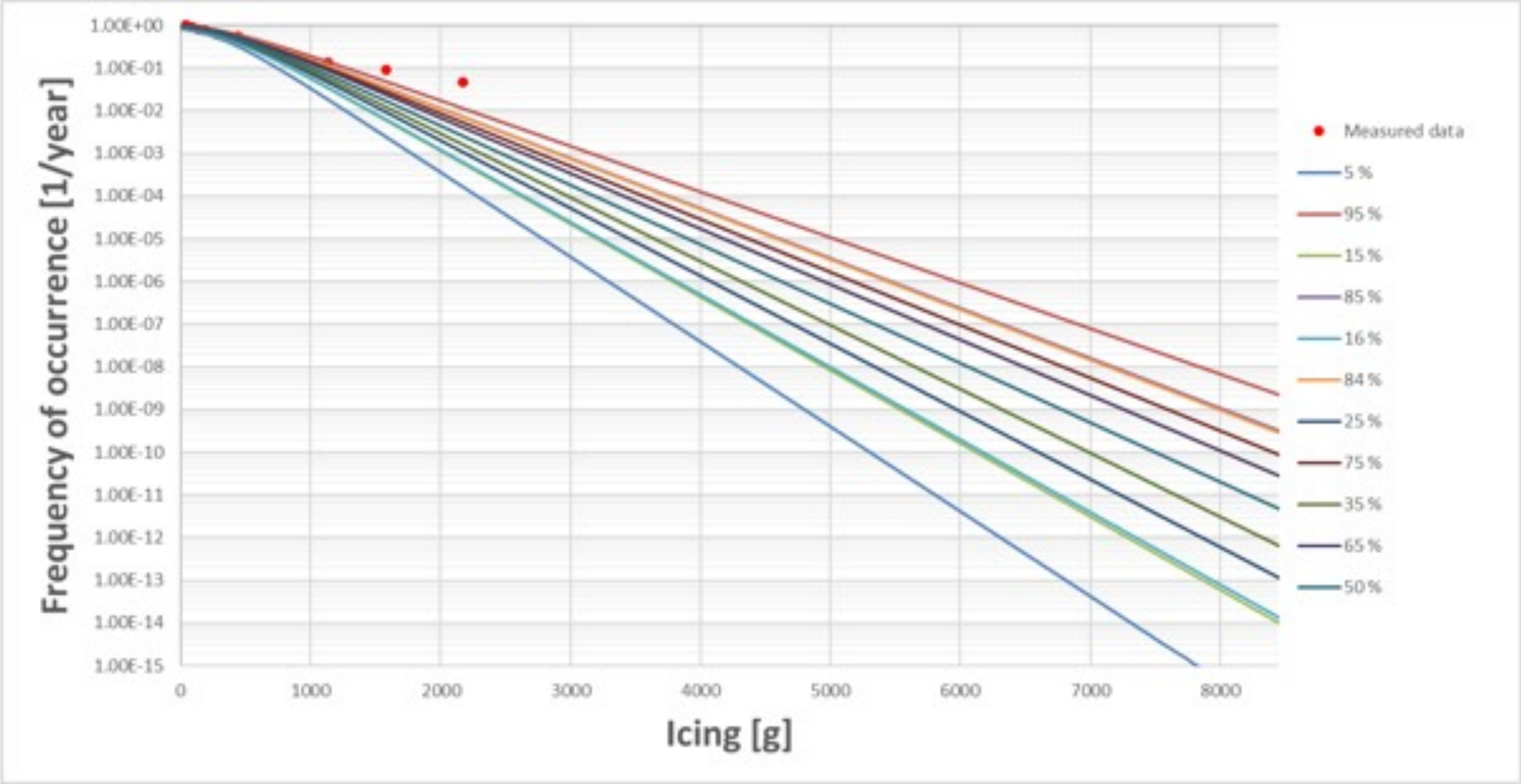
Icing on the conductor

- The hazard curves of icing with different confidence levels are constructed.
- The Gumbel distribution was used to construct the curves.

Hazard curves for icing



Hazard curves for icing



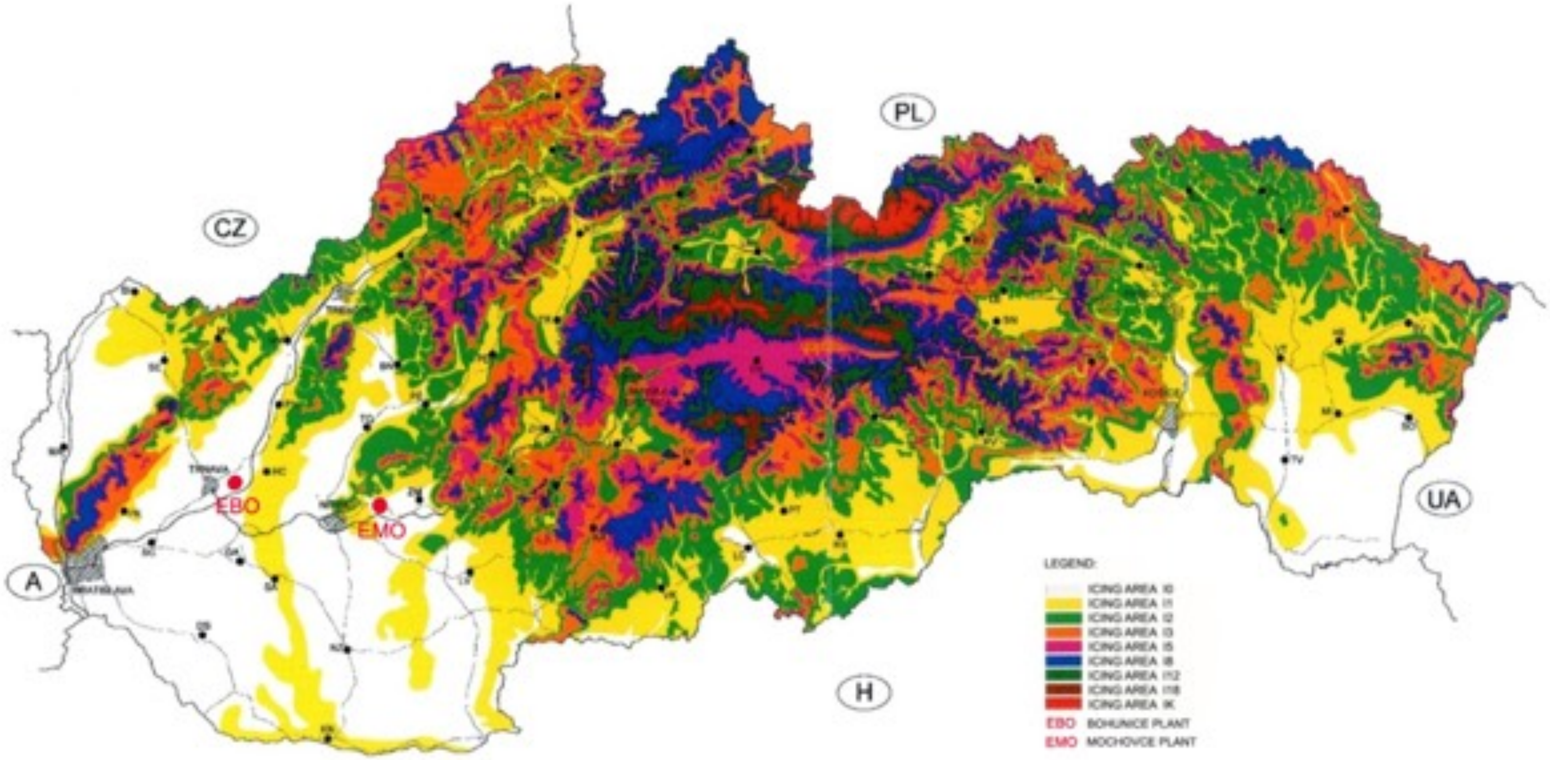
Return period for different confidence levels depending on the icing load

Return period [year]	Confidence levels [g]										
	50%	5 %	95 %	15 %	85 %	16 %	84 %	25 %	75 %	35 %	65 %
5.00E+00	422.02	294.53	549.51	341.69	502.35	344.95	499.10	369.75	474.30	392.16	451.89
1.00E+01	1010.96	745.40	1276.52	843.63	1178.30	850.41	1171.52	902.07	1119.86	948.75	1073.17
1.50E+01	1527.29	1115.21	1939.37	1267.63	1786.94	1278.15	1776.42	1358.31	1696.26	1430.75	1623.82
2.00E+01	1963.05	1423.42	2502.67	1623.02	2303.07	1636.80	2289.30	1741.77	2184.33	1836.63	2089.46
2.50E+01	2466.82	1778.04	3155.60	2032.82	2900.83	2050.40	2883.25	2184.38	2749.27	2305.47	2628.18
5.00E+01	3186.81	2283.42	4090.20	2617.58	3756.04	2640.63	3732.99	2816.37	3557.26	2975.19	3398.44
1.00E+02	3403.51	2435.35	4371.68	2793.47	4013.56	2818.17	3988.86	3006.51	3800.52	3176.71	3630.32
2.00E+02	3906.67	2787.90	5025.45	3201.72	4611.62	3230.27	4583.07	3447.91	4365.44	3644.59	4168.75
5.00E+02	4409.82	3140.24	5679.41	3609.85	5209.80	3642.25	5177.40	3889.22	4930.43	4112.41	4707.23
1.00E+03	4843.21	3443.62	6242.81	3961.32	5725.11	3997.03	5689.39	4269.29	5417.13	4515.35	5171.08
1.00E+04	5346.37	3795.73	6897.00	4369.30	6323.43	4408.87	6283.86	4710.51	5982.22	4983.12	5709.61
1.00E+05	6066.21	4299.37	7833.05	4952.91	7179.51	4998.00	7134.42	5341.70	6790.72	5652.32	6480.11
1.00E+06	6786.06	4802.91	8769.21	5536.46	8035.65	5587.07	7985.04	5972.85	7599.27	6321.49	7250.63
1.00E+07	7505.90	5306.37	9705.44	6119.96	8891.84	6176.09	8835.71	6603.96	8407.85	6990.65	8021.16
1.00E+08	8945.60	6313.15	11578.05	7286.88	10604.33	7354.06	10537.15	7866.14	10025.07	8328.93	9562.28
1.00E+09	8225.75	5809.78	10641.72	6703.43	9748.07	6765.08	9686.42	7235.06	9216.44	7659.79	8791.71

Icing on the conductor

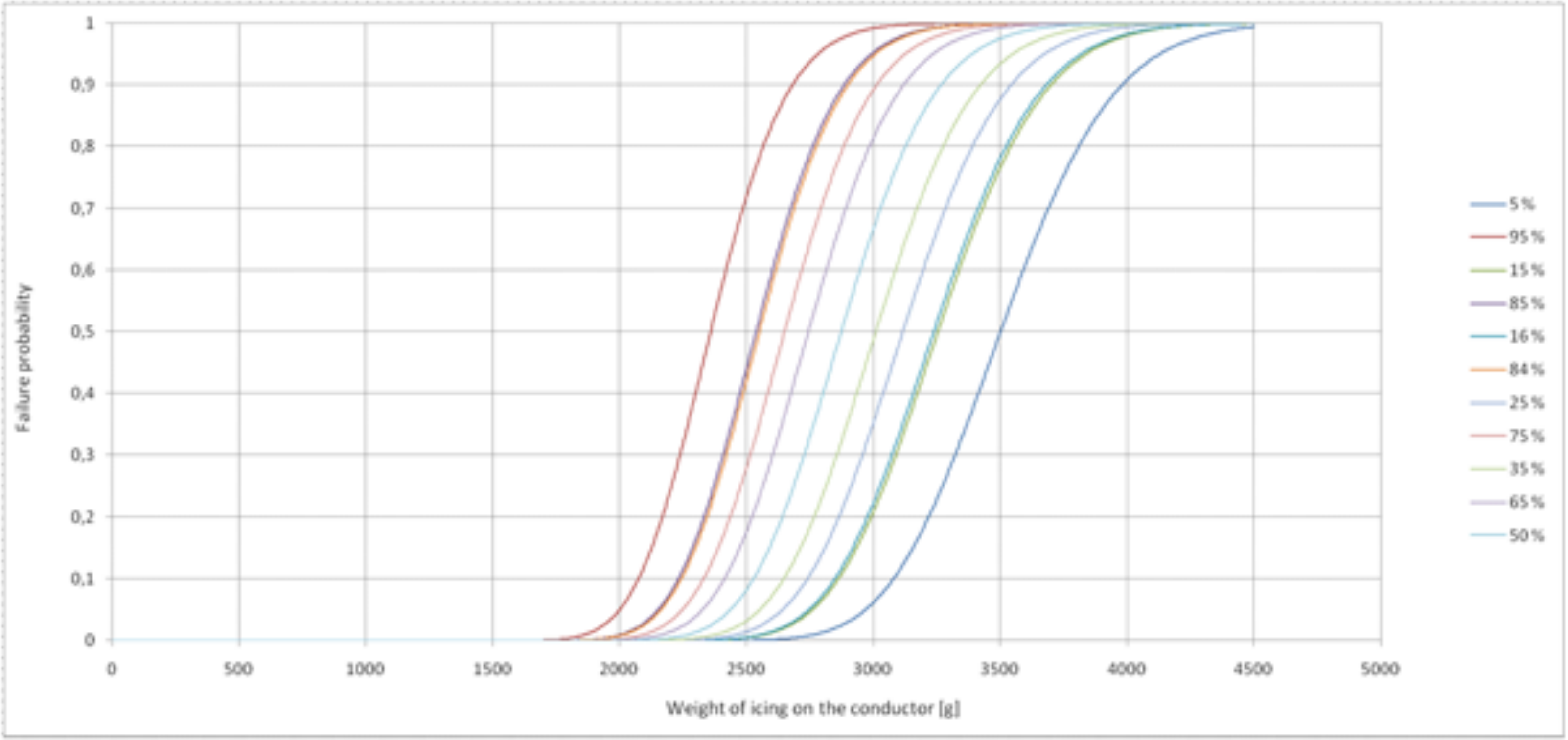
- There are 9 icing areas: I0, I1, I2, I3, I5, I8, I12, I18 and IK.
- The allowed weight of icing on the line (with 30 mm diameter conductor of the line) in the given icing area is specified by the number at the symbol I, e.g., 1 kg/m in area I1, 2 kg/m in area I2 and so on.
- The exception is the area I0, where the allowed weight is 0.5 kg/m.
- In the icing area IK the allowed weight of icing is 18 kg/m.

Map of icing areas in Slovakia



Fragility curves of 400 kV lines

Am	Beta R	Beta U	HCLPF
2875	0,10	0,12	2000



Fragility curves of 400 kV lines

g	5 %	95 %	15 %	85 %	16 %	84 %	25 %	75 %	35 %	65 %	50 %
50	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00	0,0000E+00
100	2,8896E-277	1,2410E-219	4,2611E-266	8,7982E-230	2,4634E-265	1,7205E-230	1,4586E-259	6,2648E-236	2,1168E-254	6,7089E-241	1,3260E-247
150	3,6458E-218	1,7792E-167	2,7925E-208	2,4271E-176	1,3164E-207	5,8203E-177	1,6455E-202	1,0037E-181	5,8559E-198	4,3829E-186	5,6370E-192
200	1,4750E-180	8,5376E-135	1,3862E-171	9,4860E-143	5,6542E-171	2,6290E-143	2,3450E-166	1,3662E-147	3,0790E-162	1,6167E-151	7,8502E-157
300	1,1958E-133	7,9480E-95	5,8470E-126	1,6952E-101	1,9449E-125	5,7607E-102	1,7044E-121	1,4162E-105	5,4923E-118	6,8269E-109	2,1544E-113
400	1,0888E-104	8,6778E-71	6,5431E-98	1,5039E-76	1,8834E-97	5,9051E-77	5,4810E-94	4,3693E-80	6,5224E-91	5,7022E-83	6,7847E-87
500	1,0701E-84	1,3069E-54	1,2660E-78	1,1486E-59	3,2576E-78	5,0449E-60	4,0335E-75	8,7692E-63	2,2174E-72	2,4765E-65	8,2436E-69
600	5,7992E-70	5,4411E-43	1,8196E-64	1,7997E-47	4,2725E-64	8,6615E-48	2,6327E-61	3,0234E-50	7,7040E-59	1,6035E-52	1,2363E-55
700	1,2530E-58	2,7497E-34	1,2810E-53	2,7854E-38	2,7839E-53	1,4482E-38	9,5132E-51	9,1094E-41	1,6341E-48	8,2274E-43	1,2896E-45
800	1,2173E-49	1,4123E-27	4,7142E-45	3,7673E-31	9,5818E-45	2,0941E-31	1,9655E-42	2,1925E-33	2,1290E-40	3,1387E-35	9,0912E-38
900	2,3604E-42	2,7013E-22	3,8853E-38	1,6903E-25	7,4445E-38	9,9653E-26	9,7400E-36	1,6343E-27	7,0275E-34	3,5107E-29	1,7466E-31
1000	2,4215E-36	4,4751E-18	1,8555E-32	5,9947E-21	3,3726E-32	3,7249E-21	2,9523E-30	9,1205E-23	1,4816E-28	2,8149E-24	2,2705E-26
1250	3,4179E-25	1,0403E-10	5,2019E-22	6,9336E-13	8,4579E-22	4,8133E-13	3,1668E-20	2,7450E-14	7,3804E-19	1,8205E-15	4,0733E-17
1500	1,1289E-17	2,9207E-06	4,6093E-15	7,1188E-08	6,8447E-15	5,4058E-08	1,2844E-13	6,1150E-09	1,6044E-12	7,5407E-10	3,8621E-11
1750	1,9857E-12	1,3924E-03	2,6816E-10	9,9356E-05	3,6900E-10	8,1291E-05	3,8762E-09	1,6266E-05	2,8694E-08	3,3661E-06	3,4462E-07
2000	1,0541E-08	4,8939E-02	5,5021E-07	8,5318E-03	7,0919E-07	7,4314E-03	4,5306E-06	2,4037E-03	2,1435E-05	7,7097E-04	1,4223E-04
2250	4,8210E-06	3,1654E-01	1,0997E-04	1,1362E-01	1,3392E-04	1,0422E-01	5,5586E-04	5,0312E-02	1,7864E-03	2,3359E-02	7,1186E-03
2500	3,7388E-04	7,1776E-01	4,1289E-03	4,3884E-01	4,7853E-03	4,1907E-01	1,3657E-02	2,7819E-01	3,1442E-02	1,7483E-01	8,1114E-02
2750	7,7957E-03	9,3691E-01	4,5683E-02	7,8791E-01	5,0725E-02	7,7302E-01	1,0494E-01	6,4240E-01	1,8223E-01	5,0713E-01	3,2833E-01
3000	6,0784E-02	9,9179E-01	2,0664E-01	9,5247E-01	2,2132E-01	9,4727E-01	3,5057E-01	8,9158E-01	4,8533E-01	8,1272E-01	6,6480E-01
3250	2,2729E-01	9,9931E-01	4,9294E-01	9,9324E-01	5,1303E-01	9,9223E-01	6,6153E-01	9,7910E-01	7,7746E-01	9,5433E-01	8,8991E-01
3500	4,9732E-01	9,9996E-01	7,6528E-01	9,9934E-01	7,8046E-01	9,9921E-01	8,7651E-01	9,9725E-01	9,3380E-01	9,9244E-01	9,7541E-01
4000	9,0801E-01	1,0000E+00	9,8024E-01	1,0000E+00	9,8253E-01	1,0000E+00	9,9367E-01	9,9998E-01	9,9774E-01	9,9992E-01	9,9952E-01
4500	9,9390E-01	1,0000E+00	9,9940E-01	1,0000E+00	9,9949E-01	1,0000E+00	9,9988E-01	1,0000E+00	9,9997E-01	1,0000E+00	1,0000E+00

COMBINATIONS OF ICING AND OTHER EXTERNAL EVENTS

- The following combinations of icing and non-seismic external natural events were identified for the plant sites:
  - icing - extreme wind,
  - icing - extreme snow,
  - icing - extremely low air temperature, and
  - icing - extreme wind - extreme snow.

COMBINATIONS OF ICING AND OTHER EXTERNAL EVENTS

- A combination of events is assumed relevant only if the simultaneous occurrence of the events is dependent.
- Given that two rare events occur independently, the combined occurrence is so improbable that the combination can be considered insignificant.
- The qualitative and quantitative assessment is performed for the identified relevant combinations of two events.
- If after a qualitative assessment a combination is still considered relevant, the frequency of the event combination is calculated by using the frequencies of occurrence of the single events.
- These frequencies are estimated using the extreme value theory from the hazard curves and input data of the events for at least 30 years.
- The event with a lower frequency is assumed to be occurred and the conditional probability for the other event to occur is estimated.

COMBINATIONS OF ICING AND OTHER EXTERNAL EVENTS

- The frequency of combination with two events is calculated by multiplication of the lower single event frequency and the conditional probability of the other event.
- The frequency of combination with three events is calculated by multiplication of the lowest single event frequency and the conditional probabilities for the other events.
- The frequency is determined from the hazard curves of the site. The conditional probability of event occurrence is calculated for example according to the occurrence in the different months of the calendar year.

COMBINATIONS OF ICING AND OTHER EXTERNAL EVENTS

- Example for combination frequency calculation:
  - icing - extreme wind = 1.35E-4 x 0.5 = 6.75E-5 /y

Conclusions

- After selection of extreme meteorological events applicable for the plant sites the hazard analysis was performed. The hazard is shown in the form of hazard curves.
- The following tasks will be performed in the next step for icing and its combinations within the PSA of extreme meteorological events:
  - fragility analyses of the overhead lines, effected structures and components,
  - analysis of the plant response,
  - implementation of icing and its combinations into the PSA model, and
  - quantification of the risk due to icing and its combinations and interpretation of the results.

Thank you for your attention !