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Disturbances of the Normal Operation of Kosovo Power System Regarding Atmospheric Discharges

B. Prebreza, I. Krasniqi, G. Kabashi, G. Pula, N. Avdiu

***Abstract*—**This paper discusses aspects of outages in the electric transmission network in the Kosovo Power System caused by the atmospheric discharges.

Frequency and location of the atmospheric discharges in Kosovo territory will be provided by a lightning location system ALARM (Automated Lightning Alert and Risk Management) and from the data from the Meteorological Department in Prishtina International Airport. These data will be used to make comparisons with the actual outages registered in the Kosovo Power System from the Kosovo Transmission, systems and market operator (KOSTT) during a specific time period.

The lines with the worst performance determined, regarding the atmospheric discharges, will be choose for further discussions in terms of over voltages caused by the direct or indirect lightning strokes.

Recommendations for protection in terms of insulator coordination and surge arresters will be given at the end and in this stage dynamic simulation will take part.

***Keywords*—**Atmospheric discharges, dynamic simulations, Kosovo Power System, surge arresters.

I. Introduction

GENERATION of the electric charges in the atmosphere is due to wind updrafts and downdrafts, that contribute to charge separation. This process separates negative charges at the bottom of the cloud, and positive charges at the top of the cloud. Because the ground is positively charged, when the amount of the negative charges at the bottom grows enough, the potential difference between cloud and ground grows as well, and this process continues until air breakdown occurs.

When the sufficient charge has been separated by a storm, the intense local electric fields will eventually cause an atmospheric discharge (lightning) to occur. Lightning is a transient electrical discharge, which may occur within clouds, between clouds or between the cloud and the ground.

The most lightning currents are of negative polarity, especially in the south hemisphere.

The leading interruptions and failures in the electric power systems are caused by the atmospheric discharges [1].

B.Prebreza is with the Electrical and Computer Engineering Department, University of Prishtina, st. “Bregu i diellit”, n.n. Prishtina, Kosovo (corresponding author; phone: +37744110576; e-mail: bprebreza@hotmail.com).

I. Krasniqi, G. Kabashi, G. Pula and N. Avdiu are with the Electrical and Computer Engineering Department, University of Prishtina, st. “Bregu i diellit”, n.n. Prishtina, Kosovo (e-mail: isuf.krasniqi@yahoo.com; gazmend.kabashi@kostt.com; gazmend.pula@gmail.com; nysret.avdiu@gmail.com).

A. Ground Flash Density

We will define Ground flash density, GFD or Ng as the number of lightning flashes striking ground per km^2 and per year. In case that there are no available data from the lightning location systems we can determine the GFD as a function of TD (Thunder Days or keraunic level) or TH (Thunder Hours). In the Kosovo territory there is available only one system for localization of thunderstorms, called ALARM (Automated Lightning Alert and Risk Management) system and it is located in the Prishtina International Airport, and it gives the location and the frequency of the atmospheric discharges with an easy to use display of approaching and overhead lightning threats. This system shows cloud to ground and cloud to cloud lightning activity in three ranges and in directional Octans, cloud lightning counts and displays data within a 30 nautical miles (56 km) radius around the location.

For our purpose we can use the expressions for determining the ground flash density, respectively [1]:

$$N_g = 0.04 \cdot TD^{1.25} \; flashes \; / \, km^2 \, / \; year \qquad (1)$$

$$N_g = 0.05 \cdot TH^{1.1} \; flashes \; / \, km^2 \, / \; year \qquad (2)$$

B. Kosovo Meteorological Characteristics for Period 2003-2009

Here are presented the meteorological phenomena occurred in Prishtina International Airport, where ALARM system is located, regards the weather, winds, showers and precipitations, and thunderstorms for period 2003-2009.

Data used here are taken from the Meteorological Station in Prishtina International Airport with the latitude φ=42° 34’ 26” North and longitude λ =21° 02’ 28” East. The Prishtina International Airport lies along Kosovo valley that stretches north-south position, which helps the wind channeling effect and gives it orientation from north to south and vice versa. The Airport and Kosovo valley is surrounded by mountains, forests and hills. The Albanic Mountains are the highest mountains in Kosovo with height of the top around 2017 m.

In Figs. 1-3 are presented the wind roses for period 2003-2007 and for years 2008 and 2009.

Wind rose is the method of graphically presenting the wind conditions, direction and speed over a period of time at a specific location.

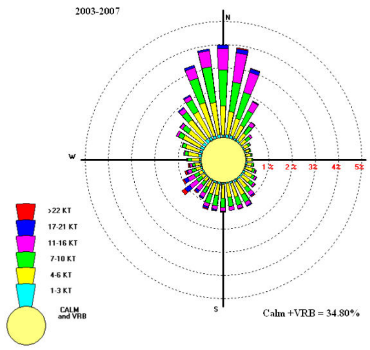

Fig. 1 Wind rose for year period 2003-2007

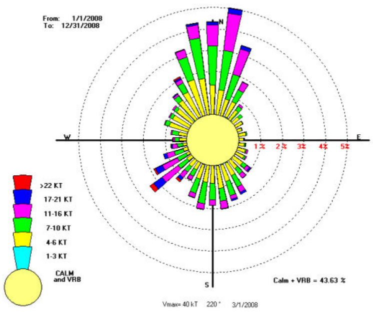

Fig. 2 Wind rose for year 2008

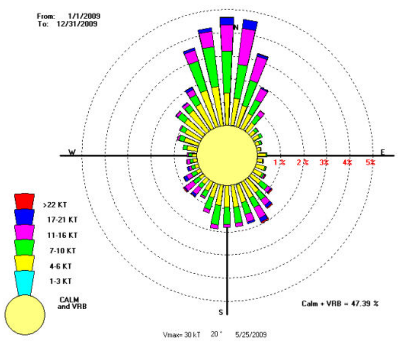

Fig. 3 Wind rose for year 2009

Analyzing the wind roses we can see that the higher percentage of wind is from the north-west direction (Polar maritime air mass). Strong winds can affect power system as well, especially during stormy weather with atmospheric discharges.

Table I and Fig. 4 shows the average number of days with thunderstorms for period 2003-2009. There is an average of 30 days with thunderstorms for the years 2003-2009, although for the first three years this number is lower.

This increase of days with thunderstorms is associated with the increase of number of days with convective precipitations (showers) compared with the number of days with dynamic precipitations in the continental regions. The same situation is indicated also in some other neighbor stations in region.

TABLE I
AVERAGE NUMBER OF DAYS WITH THUNDERSTORMS FOR PERIOD 2003-2009

Year/ Month	1	2	3	4	5	6	7	8	9	10	11	12	Total:
2003	1	0	0	0	3	3	4	4	0	2	1	0	18
2004	0	2	0	2	3	9	2	6	0	1	0	0	25
2005	0	0	0	3	4	3	6	6	4	1	1	0	28
2006	0	0	0	4	1	8	11	6	1	1	0	0	32
2007	2	0	0	2	10	9	0	2	4	0	1	0	30
2008	0	0	1	0	6	11	7	4	6	1	0	2	38
2009	0	0	1	1	13	10	7	7	2	0	0	1	42
Av:	0.4	0.3	0.3	1.7	5.7	7.6	6.1	5	2.4	0.9	0.4	0.4	30.3

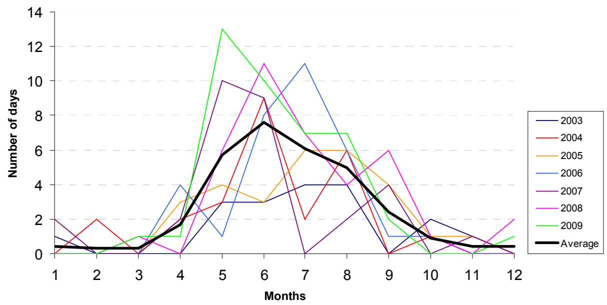

Fig. 4 Average number of days with thunderstorms for period 2003-2009

It is indicated that number of days with thunderstorms and thundershowers in the last years is greater.

Lightnings mostly occur on summer days when the ambient temperature is high and the air is humid [6], as indicated in the Table I.

Months November to March shows the minimum number of days with thunderstorms. In these months there is only one or two days with thunder associated with rain showers or snow showers.

It should be recognized that the incidence of lightning is statistical and it can vary significantly from year to year and from season to season.

Average amount of precipitation (l/m^2) for period 2003-2009 is shown in Table II:

TABLE II
AVERAGE AMOUNT OF TOTAL PRECIPITATIONS FOR PERIOD 2003-2009

Years:	2003	2004	2005	2006	2007	2008	2009	Average amount of total precipitations in l/m^2
Total Prec.:	618	761	645	680	613	596	640	650

Average number of showers for period 2003-2009 is shown in Fig. 5 and Table III.

TABLE III
AVERAGE NUMBER OF DAYS WITH SHOWERS FOR PERIOD 2003-2009

Year/ Month	1	2	3	4	5	6	7	8	9	10	11	12	Total:
2003	0	3	2	4	5	4	5	4	2	5	2	2	38
2004	4	5	6	8	10	11	3	5	1	2	2	1	58
2005	0	1	3	5	6	2	4	5	5	2	2	1	36
2006	0	1	4	4	2	9	9	6	1	2	2	0	40
2007	3	1	2	3	12	7	1	4	4	1	4	2	44
2008	0	0	5	4	7	11	9	3	5	1	2	4	51
2009	0	0	4	4	13	9	6	7	2	0	0	2	47
Av:	1	1.6	3.7	4.6	7.9	7.6	5.3	4.9	2.9	1.9	2	1.7	44.9

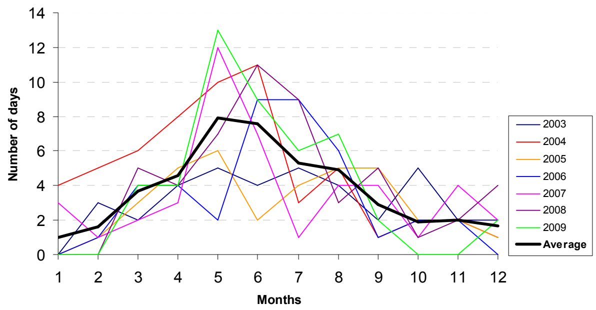

Fig. 5 Average number of days with showers for period 2003-2009

C. Outages of the Kosovo Power System for Period 2007-2009 Regarding the Atmospheric Discharges

Electric power transmission enables transfer of electrical energy, from generating power plants to substations located near to population centers. Transmission lines, when interconnected with each other, become high voltage transmission networks.

Electricity in Kosovo is transmitted with high voltages (110 kV or above) to reduce the energy lost in long distance transmission. Power is transmitted through overhead power lines, because of lower cost and smaller operational limitations compared with underground power transmission.

In Table IV is shown the length of the high voltage transmission lines for Kosovo Power system.

TABLE IV
LENGTH OF THE HIGH VOLTAGE TRANSMISSION LINES IN KOSOVO POWER SYSTEM

Transmission lines	length [km]
110 kV	631.2
220 kV	353.8
400 kV	182.8

Thunderstorm data are used to make comparisons with the outages of the Kosovo power transmission system from the atmospheric discharges, for the period 2007-2009. Outage data are taken from KOSST and these outages are shown in Table V.

TABLE V
AVERAGE OF OUTAGES IN KOSOVO POWER SYSTEM REGARDING THE ATMOSPHERIC DISCHARGES FOR PERIOD 2007-2009

Element Outages/ Years	2007	2008	2009	Average
Transmission lines 110 kV	42	61	58	53.7
Transmission lines 220 kV	2	5	0	2.3
Transmission lines 400 kV	1	1	3	1.7
Transformer 110 kV	12	31	13	18.7
Transformer 220 kV	2	9	3	4.7

It is essential to reduce the number of outages and attain the continuity of electric supply. Therefore, it is necessary to make a special attention towards the protection of transmission lines and power equipment from the main causes of overvoltages in electric power systems, namely lightning overvoltages and switching overvoltages [5].

The GFD level is an important parameter to consider for the design of electric power system.

According to (1) and Table I we can find the GFD for Kosovo for years 2003-2009 and it is shown in Table VI.

TABLE VI
GROUND FLASH DENSITY FOR KOSOVO

Years	Ground flash density (flashes/km^2/year)
2003	1.5
2004	2.2
2005	2.6
2006	3.0
2007	2.8
2008	3.8
2009	4.3
Average	2.8

The low incidence of lightning does not necessarily mean an absence of lightning - related problems. Power lines, are prone to failures even when the GFD levels are low, especially when they pass through high hills or mountains [1]. For Kosovo the average GFD for 2003-2009 is 2.8.

Lightning is a leading cause of failures in transmission system in the Kosovo power system and an estimated of 30% of all power outages are lightning related on annual average.

II. ENERGY CAPABILITY, LINE DISCHARGE CLASS AND PROTECTION MARGINS OF SURGE ARRESTERS

Surge arresters offers protection against atmospheric over voltages and also against switching over voltages.

The connection of the surge arresters is always in parallel with the equipment which will be protected.

There is a large variety of standard arresters regarding protection levels and energy capability.

From the manufacturer, we can get the "Guaranteed protective data" which shows the range of U_r and maximum continuous operating voltages U_c (see Table VII).

Different systems have different fault - clearance time. Generally it is under 1 s, for effectively earthed systems, but it can vary depending on system (Table VIII).

TABLE VII
GUARANTEED PROTECTIVE DATA

Max System Voltage	Rated voltage	Max. continuous operating voltage As per IEC	As per ANSI/IEEE	Temporary overvoltage capability		Max. residual voltage with current wave 8/20µs	
U_m	U_r	U_c	MCOV	1 s	10 s	10 kA	20 kA
kV_{rms}	kV_{rms}	kV_{rms}	kV_{rms}	kV_{rms}	kV_{rms}	kV_{peak}	kV_{peak}
145	108	86	86.0	124	118	254	280
	120	92	98.0	138	132	282	311
	132	92	106	151	145	311	342
	138	92	111	158	151	325	357
	144	92	115	165	158	339	373
	150	92	121	172	165	353	388
	162	92	131	186	178	381	419
	168	92	131	193	184	395	435

TABLE VIII
MINIMUM VALUE OF THE ARRESTER RATED VOLTAGE U_R

System earthing	Fault duration	System Voltage U_m (kV)	Min. rated Voltage U_r (kV)
Effective	≤ 1 s	≤ 100	≥ 0.8 x U_m
Effective	≤ 1 s	≥ 123	≥ 0.72 x U_m
Non-effective	≤ 10 s	≤ 170	≥ 0.91 x U_m ≥ 0.93 x U_m (EXLIM T)
Non-effective	≤ 2 h	≤ 170	≥ 1.11 x U_m
Non-effective	> 2 h	≤ 170	≥ 1.25 x U_m

The IEC gives classification of the arresters by their nominal discharge current and for 10kA and 20kA arresters, it is done by the energy capability.

In Table IX is shown the energy capability for different surge arresters made by ABB [2].

TABLE IX
ENERGY CAPABILITY OF ABB ARRESTERS

Arrester type	Line discharge class	Energy capability (2 impulses) kJ/kV (U_r)	Normal application range (U_m)
EXLIM R	2	5.0	≤ 170 kV
PEXLIM R	2	5.1	≤ 170 kV
EXLIM Q	2	7.8	170-420 kV
PEXLIM Q	2	7.8	170-420 kV
EXLIM P	2	10.8	362-550 kV
PEXLIM P	2	12	362-550 kV
HS PEXLIM P	2	10.5	362-550 kV
EXLIM T	2	15.4	420-800 kV
HS PEXLIM T	2	15.4	420-800 kV

We will consider the lightning impulse protection level (U_{pl}) at 10kA for maximum system voltage $U_m \leq 362$kV and at 20kA for higher voltages, for purposes of insulation co-ordination (see Table X).

TABLE X
U_{PL} AND U_{PS} RATIOS FOR ABB ARRESTERS

Arrester type	Nom. discharge current (I_n)	U_{pl}/U_r at 10 kA_p	U_{pl}/U_r at 20 kA_p	U_{ps}/U_r
EXLIM R	10	2.590		2.060 at 0.5 kA_p
PEXLIM R	10	2.590		2.060 at 0.5 kA_p
EXLIM Q	10	2.350		1.981 at 1.0 kA_p
PEXLIM Q	10	2.350		1.981 at 1.0 kA_p
EXLIM P	20	2.275	2.5	2.020 at 2.0 kA_p
PEXLIM P	20	2.275	2.5	2.020 at 2.0 kA_p
HS PEXLIM P	20	2.275	2.5	2.020 at 2.0 kA_p
EXLIM T	20	2.200	2.4	1.976 at 2.0 kA_p

Protection margins are defined as follows:

Margin for lightning impulses = $((U_{wl}/U_{pl})-1)$x100, where U_{wl} is the external insulation withstand of the equipment against lightning impulses.

Margin for switching impulses = $((U_{ws}/U_{ps})-1)$ x100, where U_{ws} is the external insulation withstand of the equipment for switching impulses.

Margins are normally excellent due to the low U_{pl}, U_{ps} and also that most equipment at present have a high U_{wl} and U_{ws}. However, depending on the electrical distance between the arrester and the protected equipment, the U_{pl} margin is reduced and thus arresters fail to protect equipment that is not in the close vicinity of the arresters (i.e. within their protection zone). It is recommended that the protection margins should be of the order of 20% or more to account for uncertainties and possible reduction in the withstand values of the protected equipment with age [2].

III. MODELING OF THE METAL-OXIDE ARRESTERS

The model is based on IEEE recommendations and it is dependent from frequency. This proposed model is shown in Fig. 6.

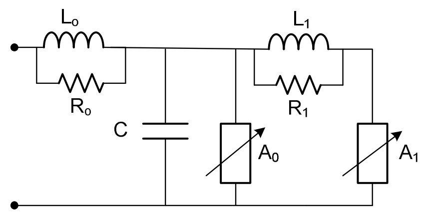

Fig. 6 IEEE frequency-dependent model

For low frequency surges the filter impedance is too low, and in this case A_0 and A_1 are practically connected in parallel.

For high frequency surges the impedance of the filter increases, and it causes a current distribution between the two non-linear resistances. Because of L_1 effect, the current through A_0 increases when the front decreases [7].

Parameters L_0, R_0, L_1, R_1 and C of the surge arrester were obtained using the IEEE model and experimental results:

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$$L_1 = 15\frac{d}{n}[\mu H] \quad (3)$$

$$R_1 = 65\frac{d}{n}[\Omega] \quad (4)$$

$$L_0 = 0.2\frac{d}{n}[\mu H] \quad (5)$$

$$R_0 = 20\frac{d}{n}[\Omega] \quad (6)$$

$$C = \frac{100n}{d}[pF] \quad (7)$$

where: d is the estimated height of the ZnO arrester in meters and n is the number of parallel columns.

The non-linear V-I characteristic is obtained from two non-linear resistors A_0 and A_1, which are separated by an R-L filter (R_1 and L_1).

V-I characteristics for the non-linear resistances will be obtained from the Table XI and it will be used for Matlab metal-oxide (ZnO) surge arrester simulations.

IV. Dynamic Simulation of Surge Arresters

We will choose voltage level 110kV for computer analysis of line surge arresters with Matlab [8], because these lines have the worst performance determined, regarding the atmospheric discharges in Kosovo power system.

The surge arresters for voltage level 110kV can be with maximum voltage of U_m=145kV (see Table VII), and based on catalog of ABB surge arresters, the nominal voltage for arresters for direct system of grounding (see Table VIII), is as follows: U_{r0}=0.72 x U_m=0.72 x 145=104.4kV

From the Table VII, we will choose arrester with nominal voltage U_r=108kV.

According to Table IX, the best option for 145kV is arrester of class 2, Type PEXLIM R. This arrester has an U_{pl}/U_r=2.59(see Table X), and it means U_{pl}=280kV at 10kA. With U_{wl}=550kV this arrester with provide protection margin M_{rl}=(550/280-1)x100=96%.

TABLE XI
V-I Characteristics of the Non-Linear Resistances A_0 and A_1

A_0 I [kA]	A_0 V [p.u.]	A_1 I [kA]	A_1 V [p.u]
0.01	1.3	0.01	1.1
0.1	1.37	0.1	1.17
1	1.56	1	1.36
2	1.6	2	1.4
4	1.66	4	1.26
6	1.76	6	1.56
9	1.81	9	1.61
10	1.84	10	1.84
20	2.06	20	1.86
40	2.35	40	2.15
50	2.5	50	2.3

If the selected arrester type does not give the desired protection margins, the selection should be changed to an arrester of a higher line discharge class, which automatically leads to lower U_{pl}. In cases that margin is insufficient, we would choose the class 3 arrester, with the same rated voltage 108kV [2].

The height of this arrester from the catalog is d=1.236m, parameter n will be choosing equal to 1, and we obtain:

$$L_1 = 15\frac{d}{n} = 18.54[\mu H] \quad (8)$$

$$R_1 = 65\frac{d}{n} = 80.34[\Omega] \quad (9)$$

$$L_0 = 0.2\frac{d}{n} = 0.2472[\mu H] \quad (10)$$

$$R_0 = 20\frac{d}{n} = 20.47[\Omega] \quad (11)$$

$$C = \frac{100n}{d} = 80.9061[pF] \quad (12)$$

Lightning currents differ in amplitude and shape. The majority of the clouds to ground lightning strokes vary from kilo amperes to several tenths of kilo amperes [3].

For testing of the ZnO surge arresters in laboratory is used current generator of different shapes. Based on IEEE recommendations arresters should be tested for discharge currents of 10kA and 20kA with impulsive waveform 8/20μs/μs [4].

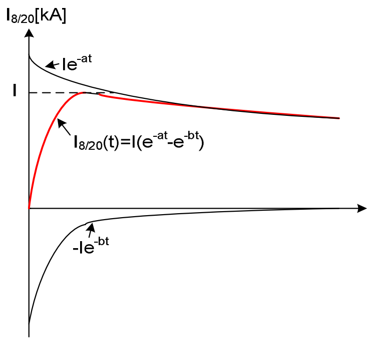

Fig. 7 The exponential form of current impulse caused from the atmospheric discharges

The function which represents the discharge current with waveform 8/20μs/μs is given by expression:

$$I_{20/80}(t) = 4 \cdot I(e^{-86600 \cdot t} - e^{-173200 \cdot t}) \quad (13)$$

Earthed arrester will be directly linked to the end of the current generator.

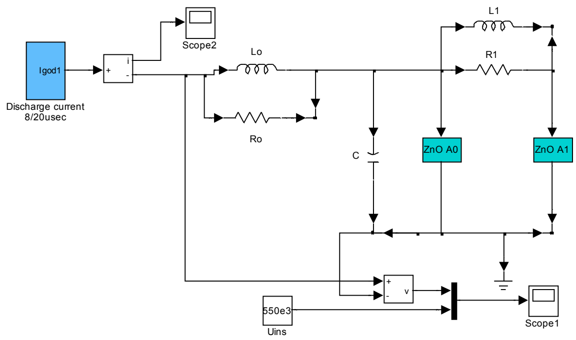

Fig. 8 Simulation model for performance analyzing of ZnO arresters

The simulation is done for discharge currents 10kA and 20kA. The following figures show the respective results simulated with Matlab:

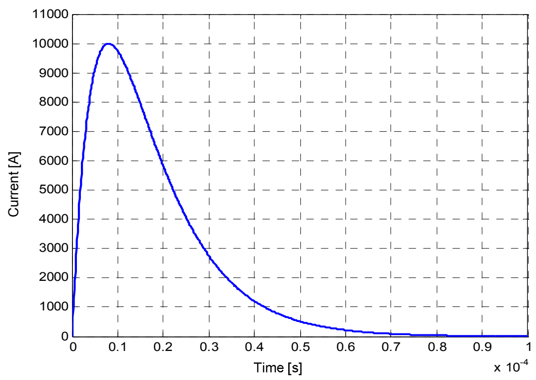

Fig. 9 Discharge current 10kA with impulsive form 8/20µs/µs

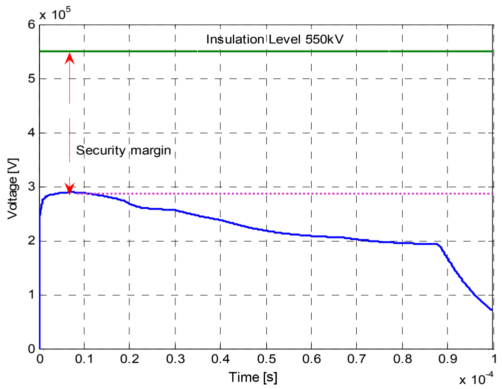

Fig. 10 Residual voltage for the discharge current 10kA with impulsive form 8/20µs/µs (U_r=280kV)

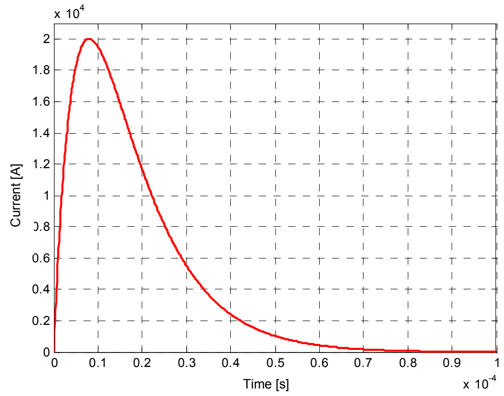

Fig. 11 Discharge current 20kA with impulsive form 8/20µs/µs

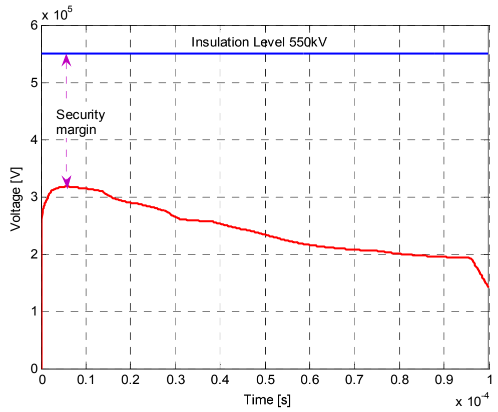

Fig. 12 Residual voltage for the discharge current 20kA with impulsive form 8/20µs/µs (U_r=315kV)

Simulation results show that the residual voltage is almost identically with the residual voltage which is guaranteed by the manufacturer. The differences between the external insulation withstand and the residual voltage defines the arresters protection margin.

V. Conclusion

An accurate model of metal-oxide distribution surge arrester is presented. It is based on the IEEE frequency-dependent model.

Because the Kosovo GFD is increasing, it means that the number of strikes to the transmission network is increasing also.

Thus it is recommended the use of metal-oxide (ZnO) arresters in Kosovo power system, also for line fields, because they will increase the efficiency and will enable normal function for the power transmission system.

Choosing the right protection is essential for power systems regarding the atmospheric discharges.

ACKNOWLEDGMENT

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