EE 5220 - Lecture 35 Wed Apr 3, 2024

Topics for Today:

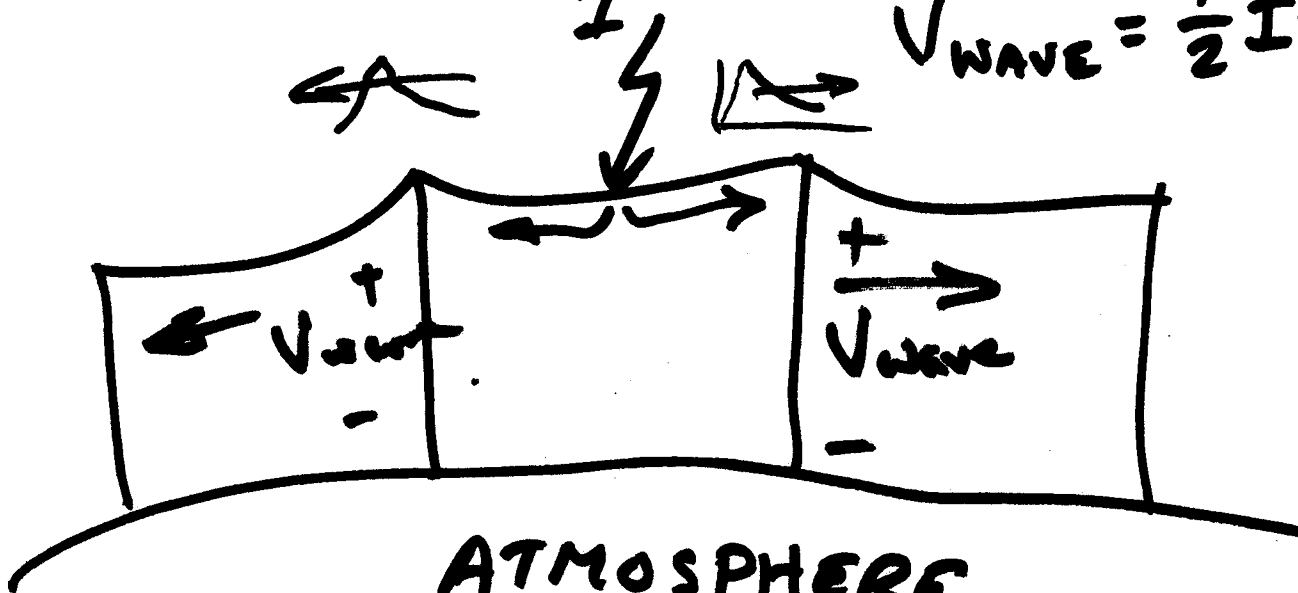
- Course Info:
  - Web page: https://pages.mtu.edu/~bamork/ee5220/
  - Book, references, syllabus, more are on web page.
  - Software - Matlab. ATP/EMTP [License - www.emtp.org] ATP tutorials posted on our course web page
  - EE5220-L@mtu.edu (participation = min half letter grade)

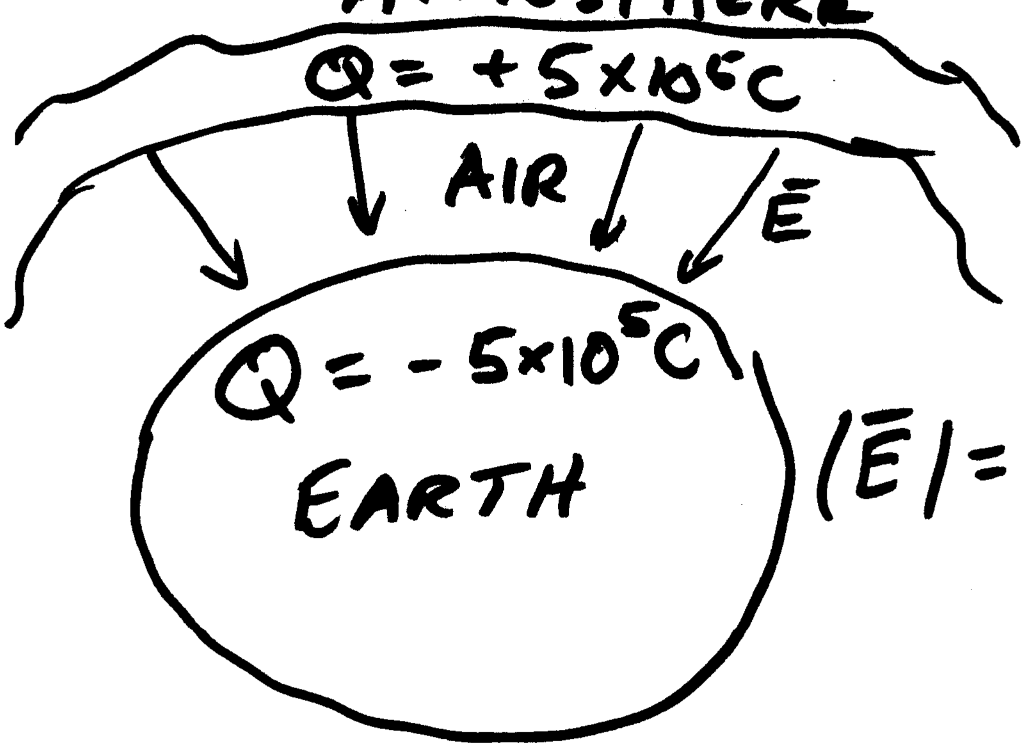
- Term Project - Journal paper analysis - completed by 9am Mon Apr 8th
- ATP - Statistical switches (refer also to lecture 34 notes)
- View the Lightning (Raging Planet) video
- Lightning - Ch.14
  - Basic characteristics
  - Statistical approach
- Transient overvoltages due to lightning - Chapters 15.
  - Breakdown characteristics
  - Probabilistic approach

Lightning - Ch. 14

KV	
230	- Causes 26% of Outages
345	- " 65% " "

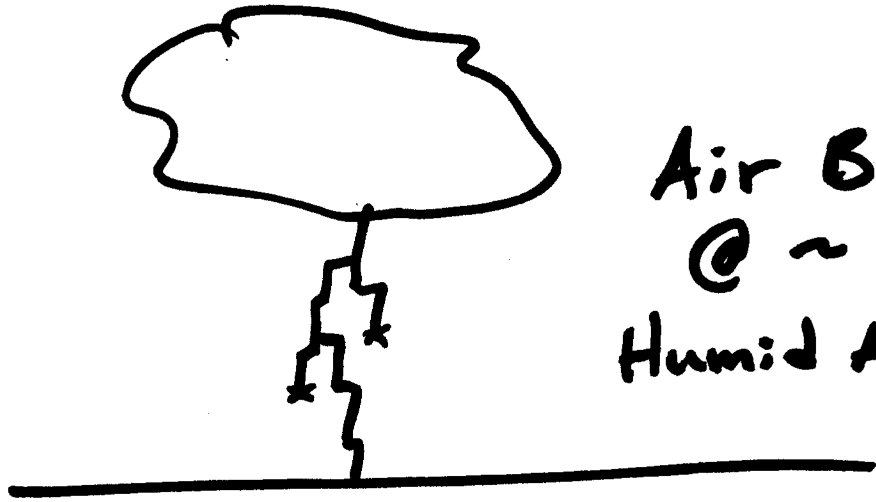
$V_{WAVE} = \frac{1}{2} I Z_c$





$|\bar{E}| = 0.13 \frac{KV}{M}$

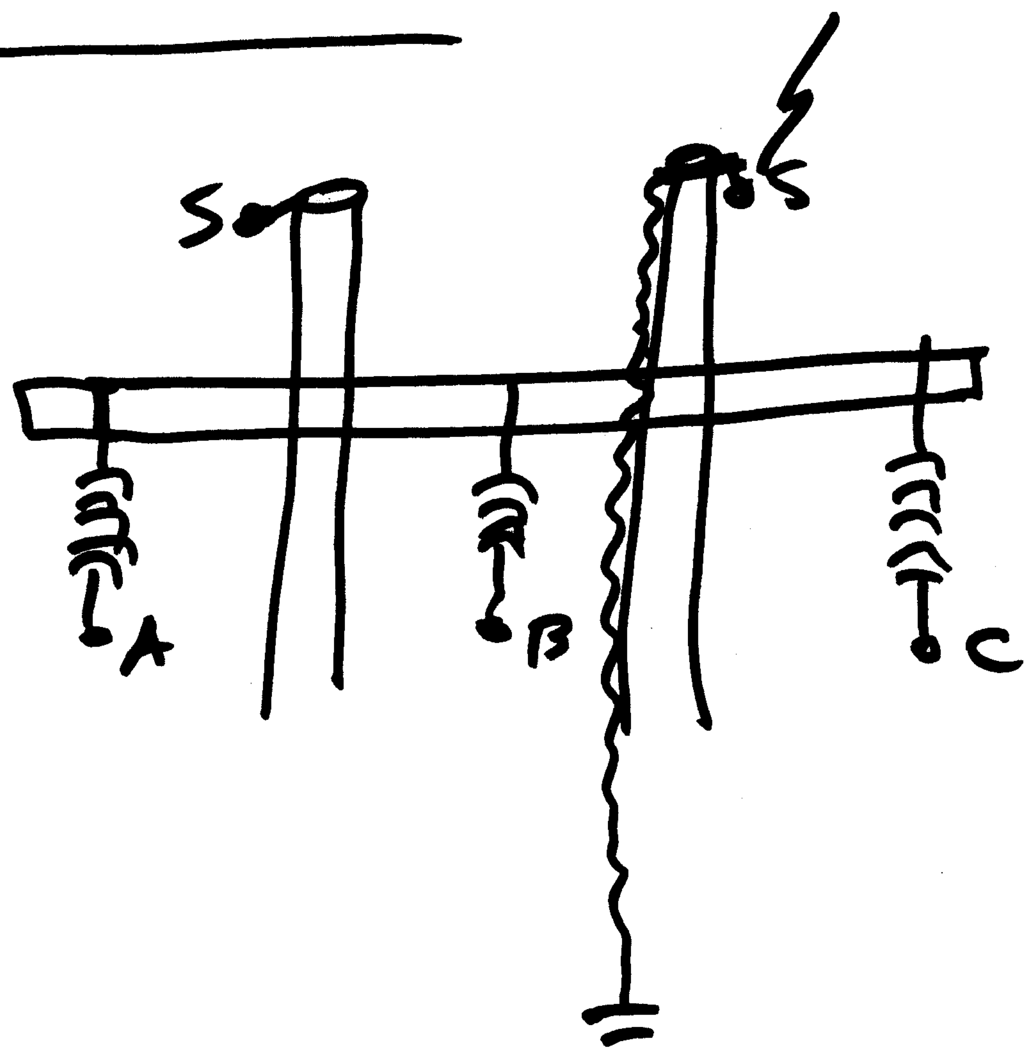
See p. 466 - How Lightning develops.



Air Breakdown @ ~ 30 kV/cm

Humid Air: ~10 kV/cm

See Isokeraunic Map, p. 473



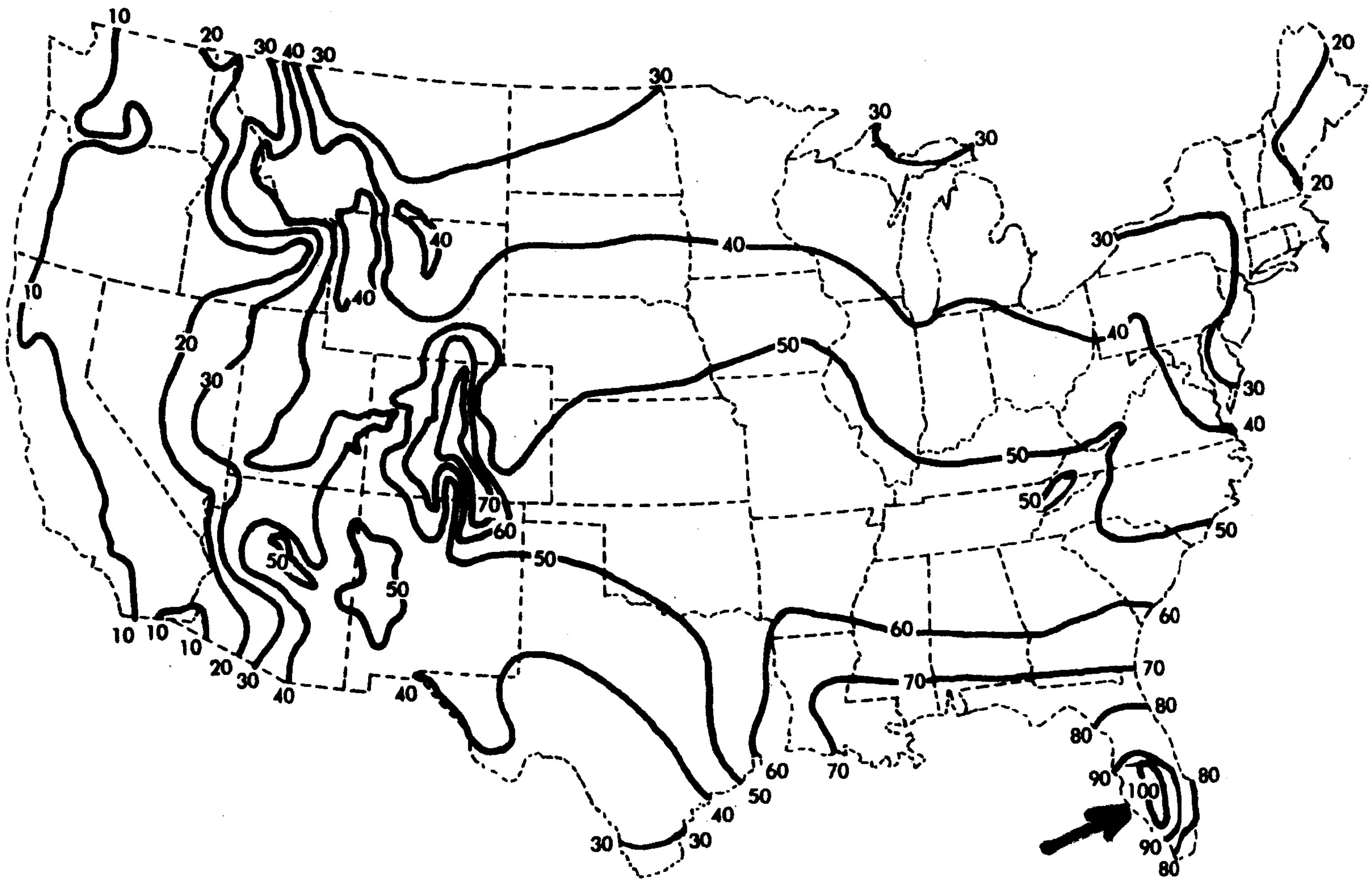
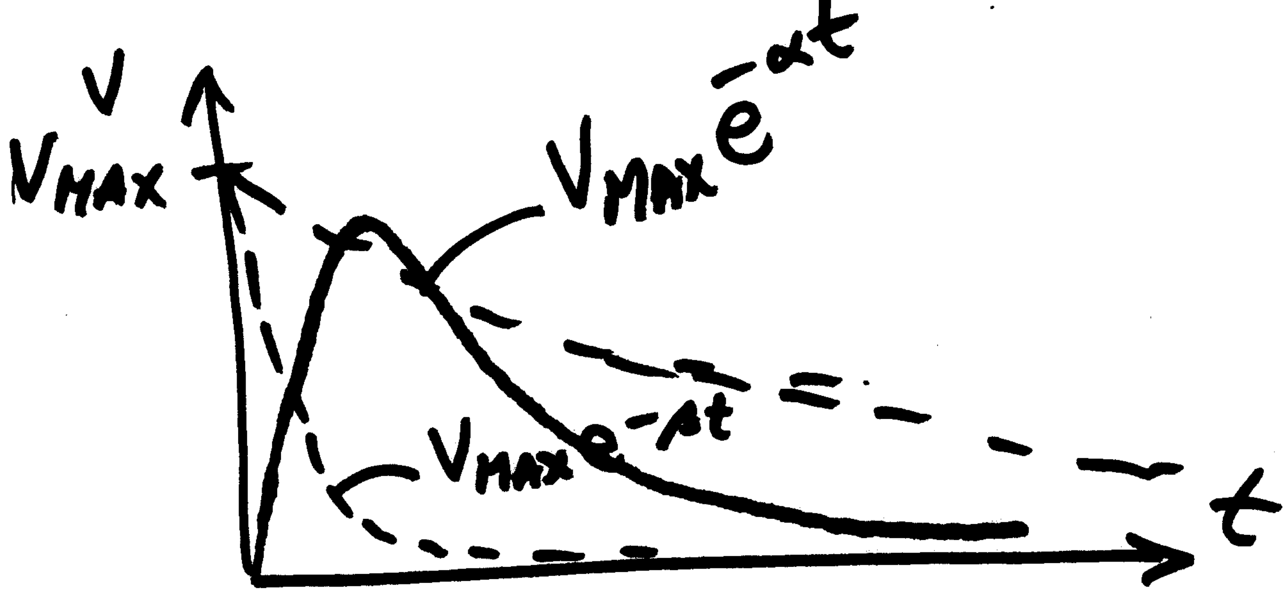


Fig. 14.6. Isokeraunic map showing mean annual days of thunderstorm activity within the continental United States, [21].

which is defined as the number of days per year on which thunder is heard at

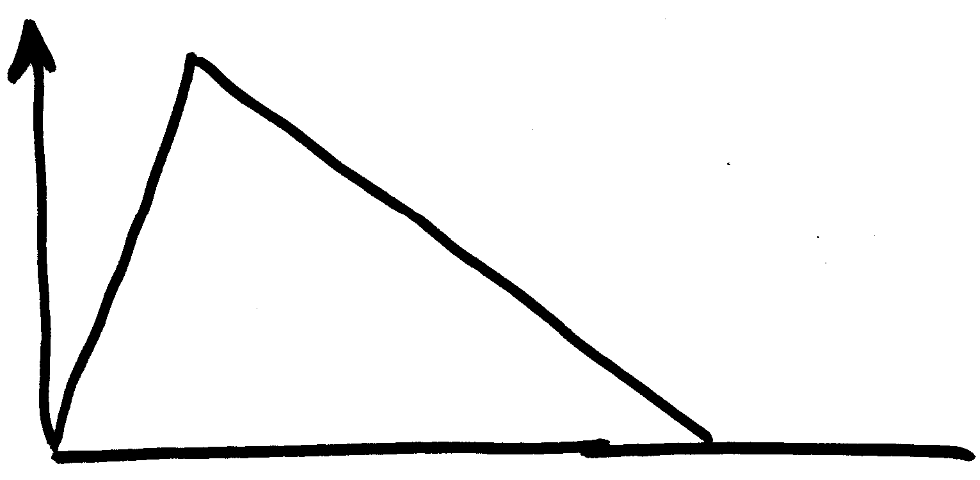
Waveshapes:

- "Double Exponential"

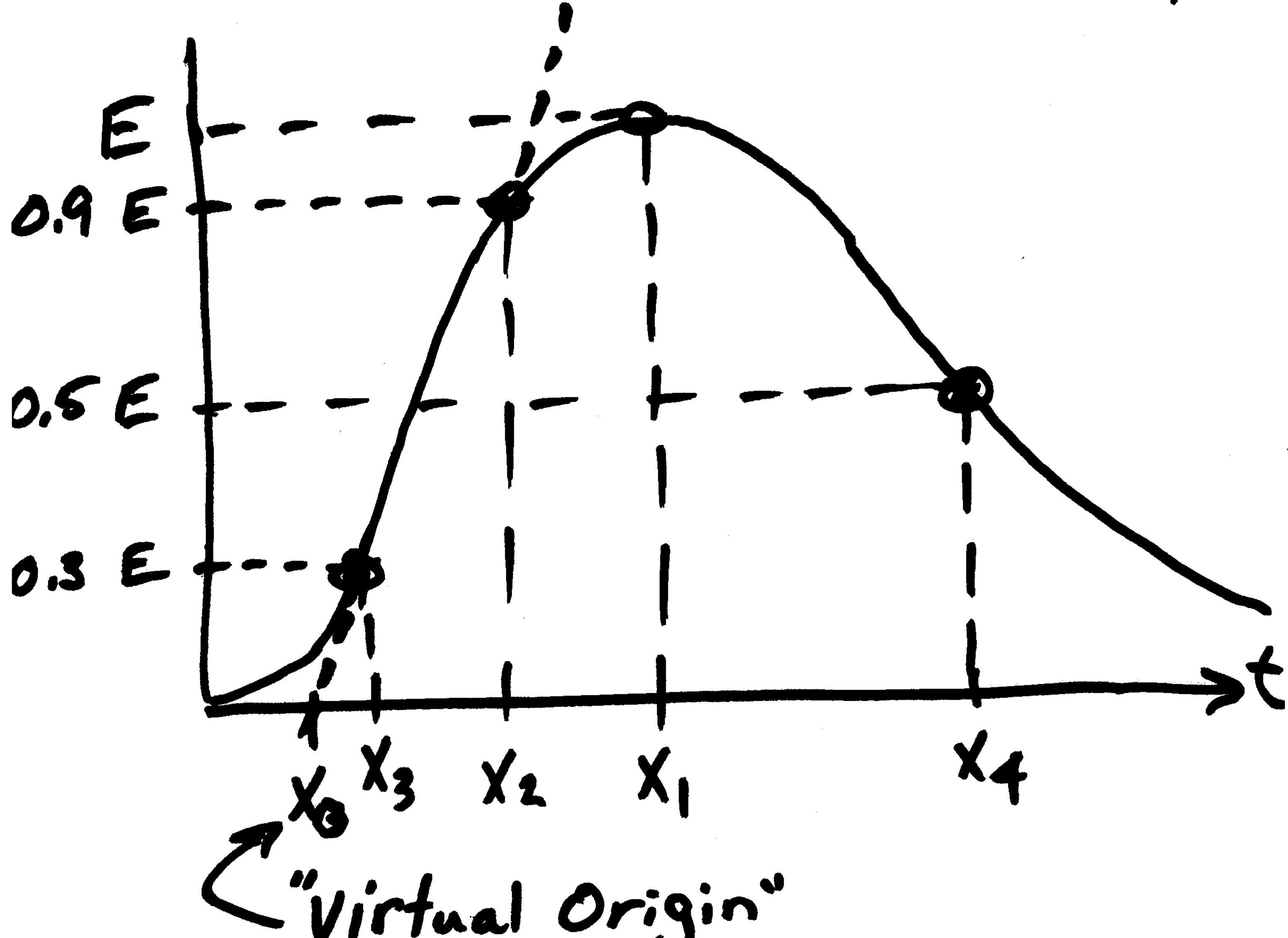


Difference: $v(t) = V_{MAX}(e^{-\alpha t} - e^{-\beta t})$

CRUDE APPROX:



Actual Lightning or Switching Surges:



Standard Reference:

$t_f \times t_t$

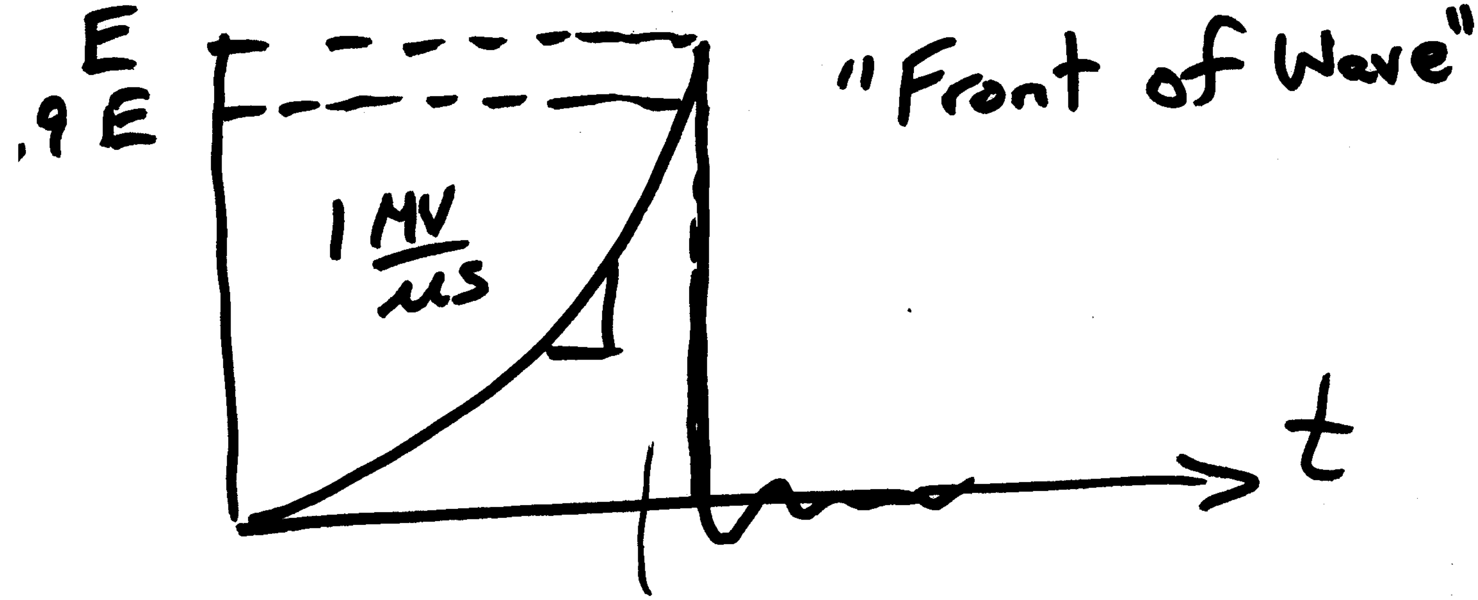
$t_f = 1.6(X_2 - X_3)$

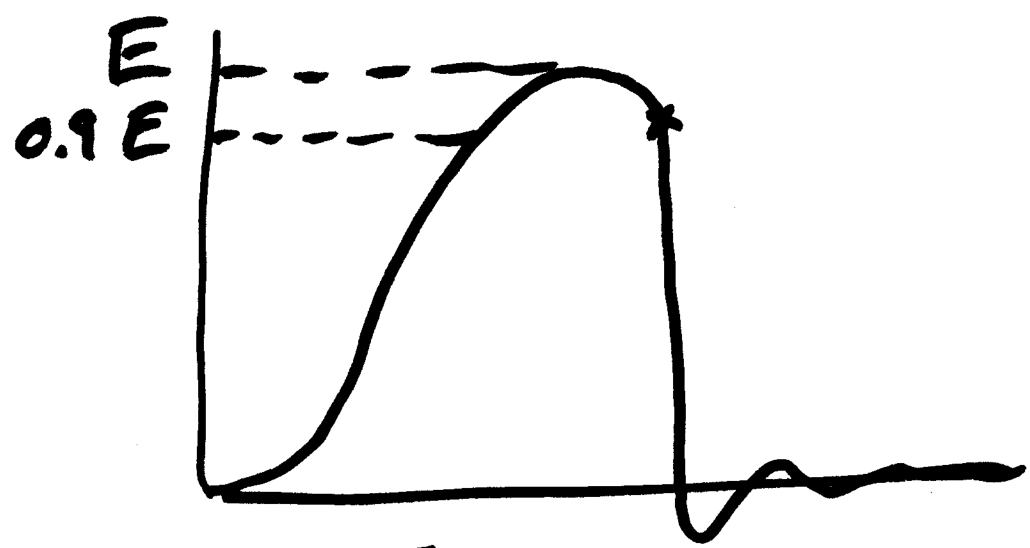
$t_t = (X_4 - X_0)$

C57.12.90

Stds: 1.2×50 μs (Lightning Surges)
5×200 μs (impulse)

~~Switching~~ Surges (Impulse) 13





Switching Surges: IEC Stds:

250 × 2500 μs

BIL = Basic Insulation Level (impulse & light)

BSL = (Switching)

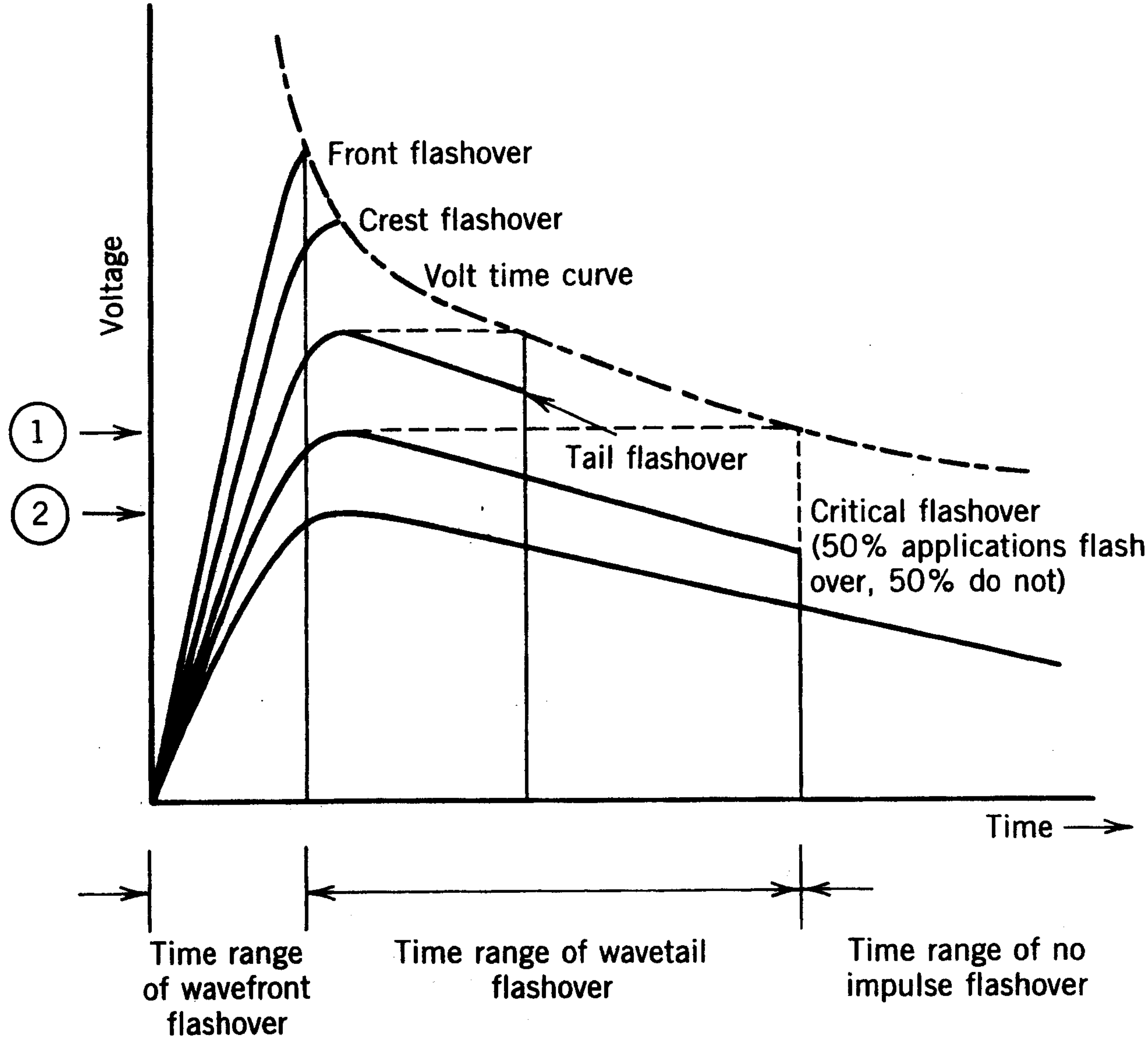
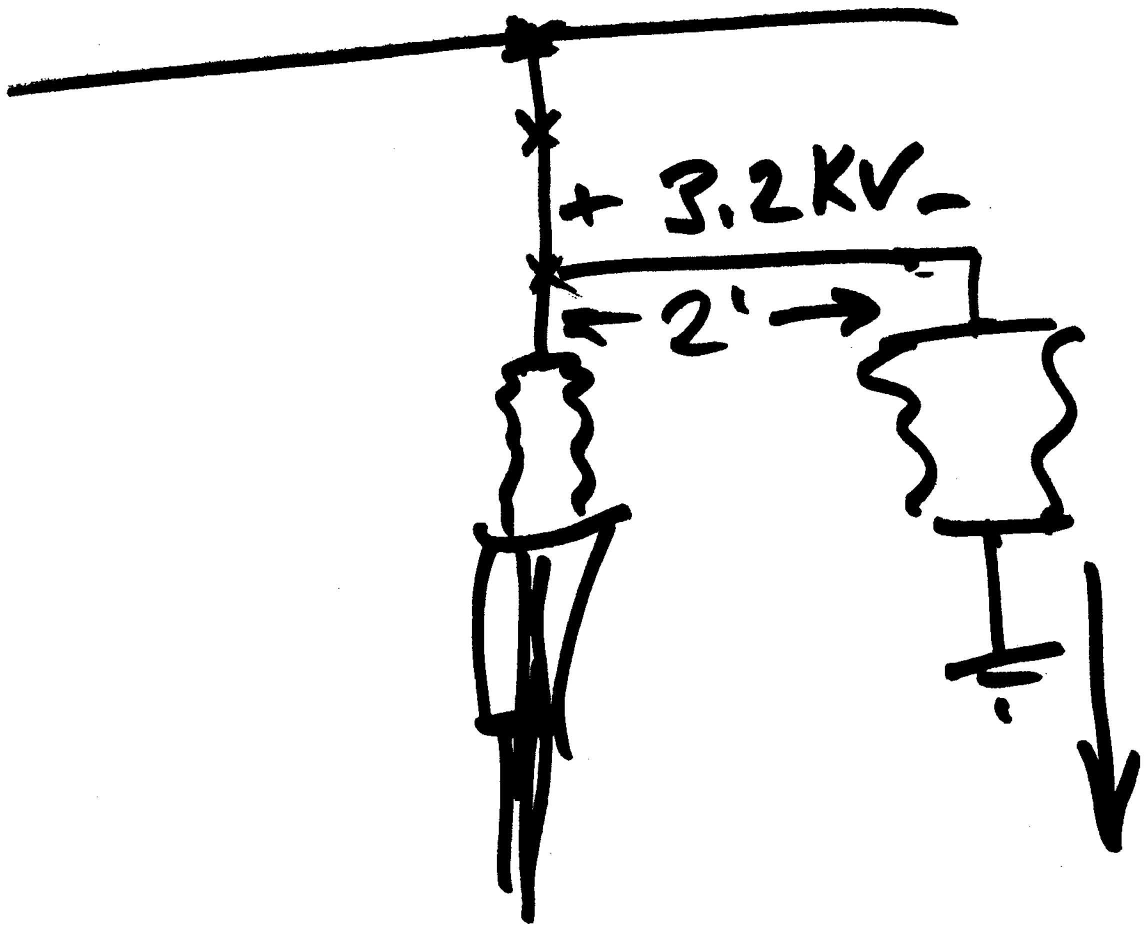
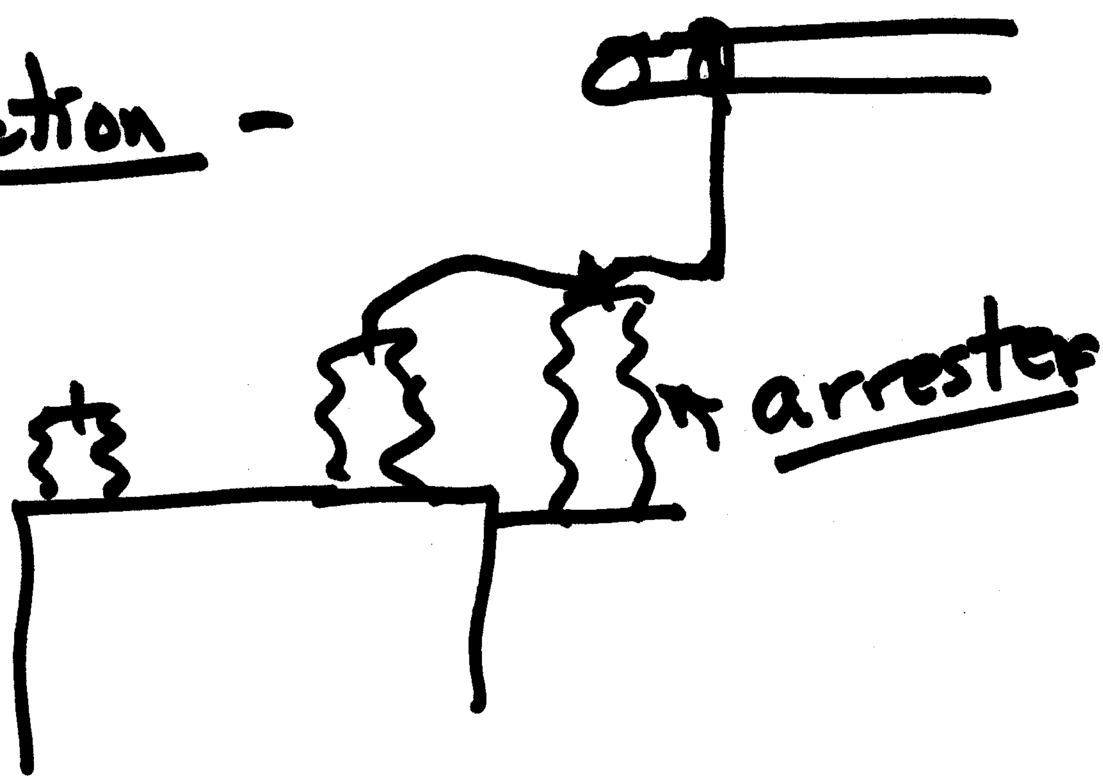


Fig. 15.2. Development of a volt/time curve. (1) Critical flashover voltage. (2) Withstand voltage.

At first there are no flashovers; the voltage is simply not high enough. Breakdowns begin to occur as the voltage is increased. On each occasion the

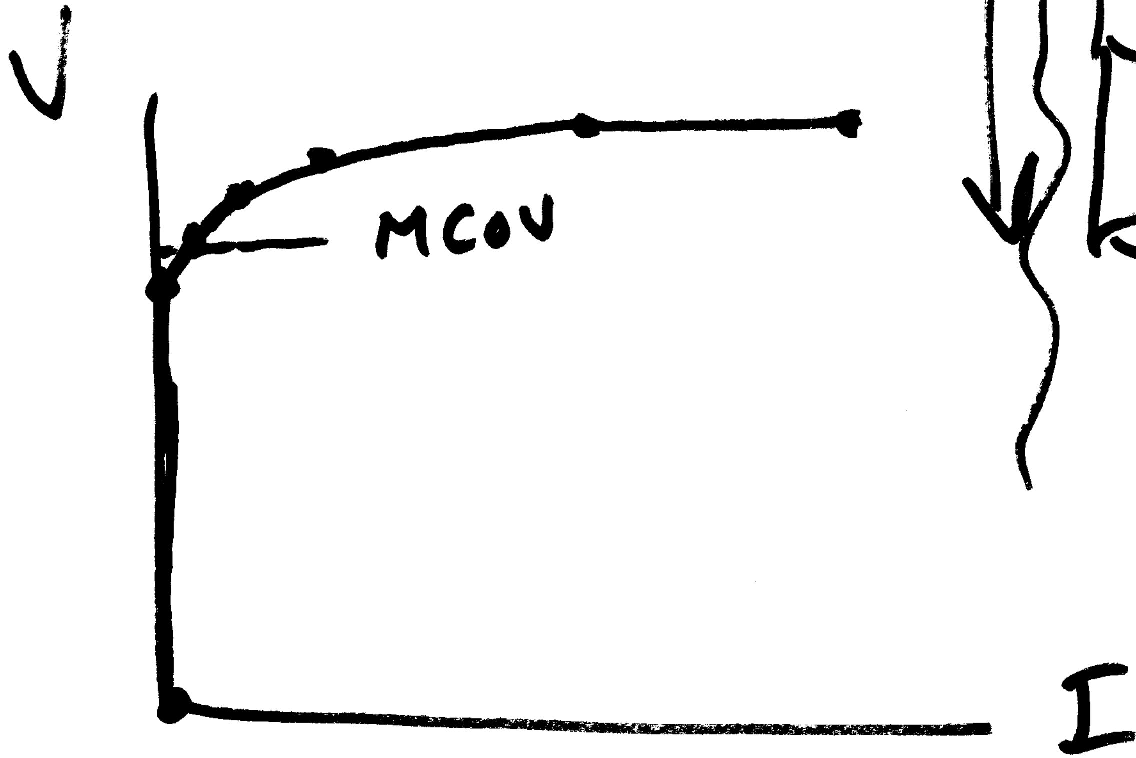


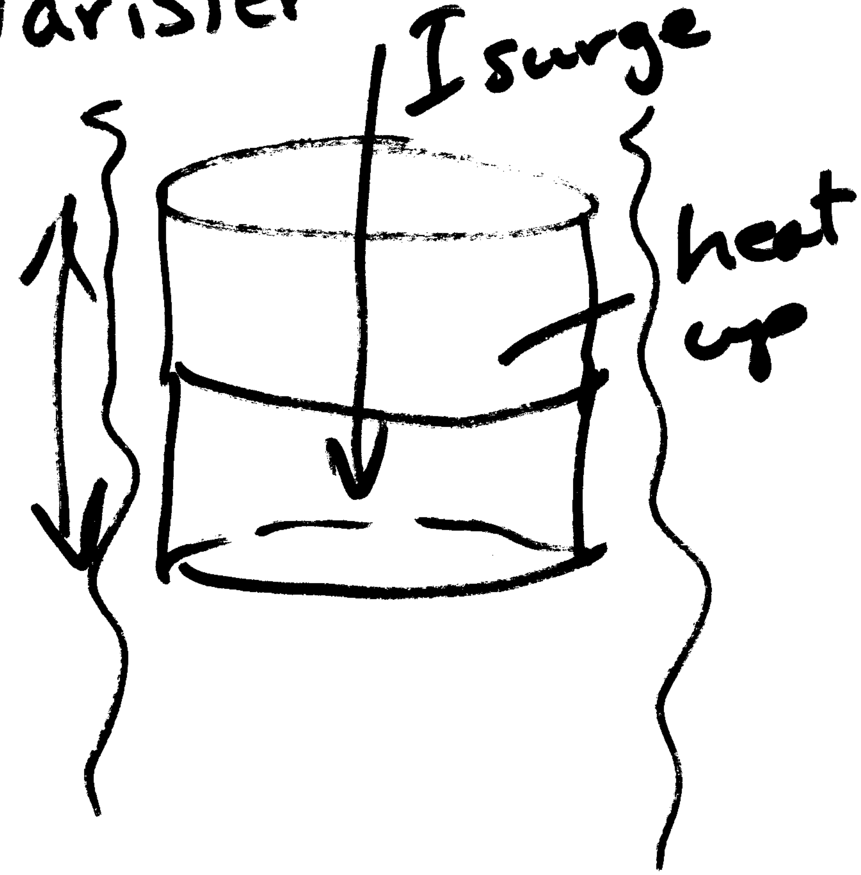
Substation -

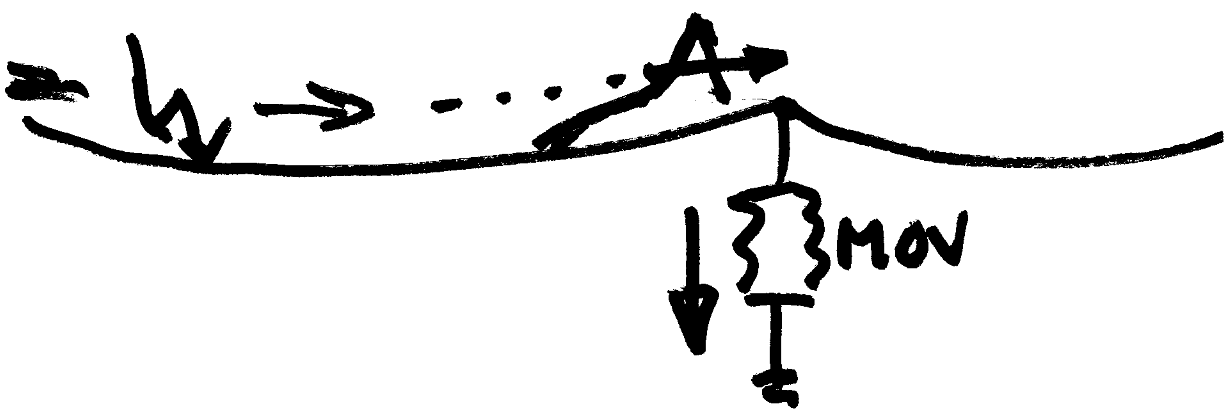


MOV - Metal Oxide Varister

ZnO

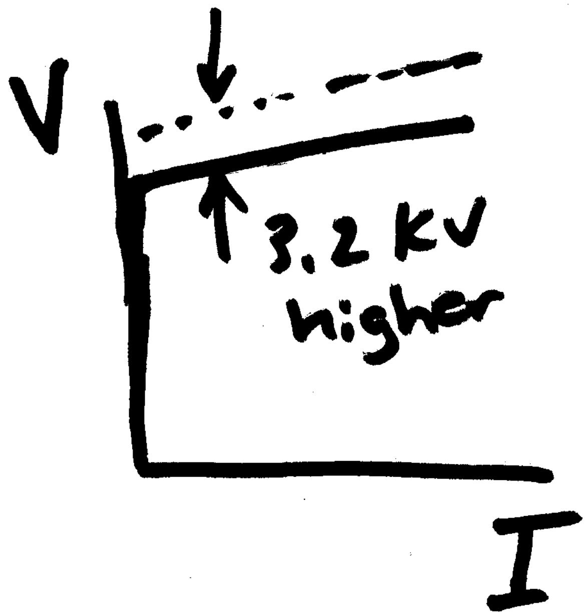


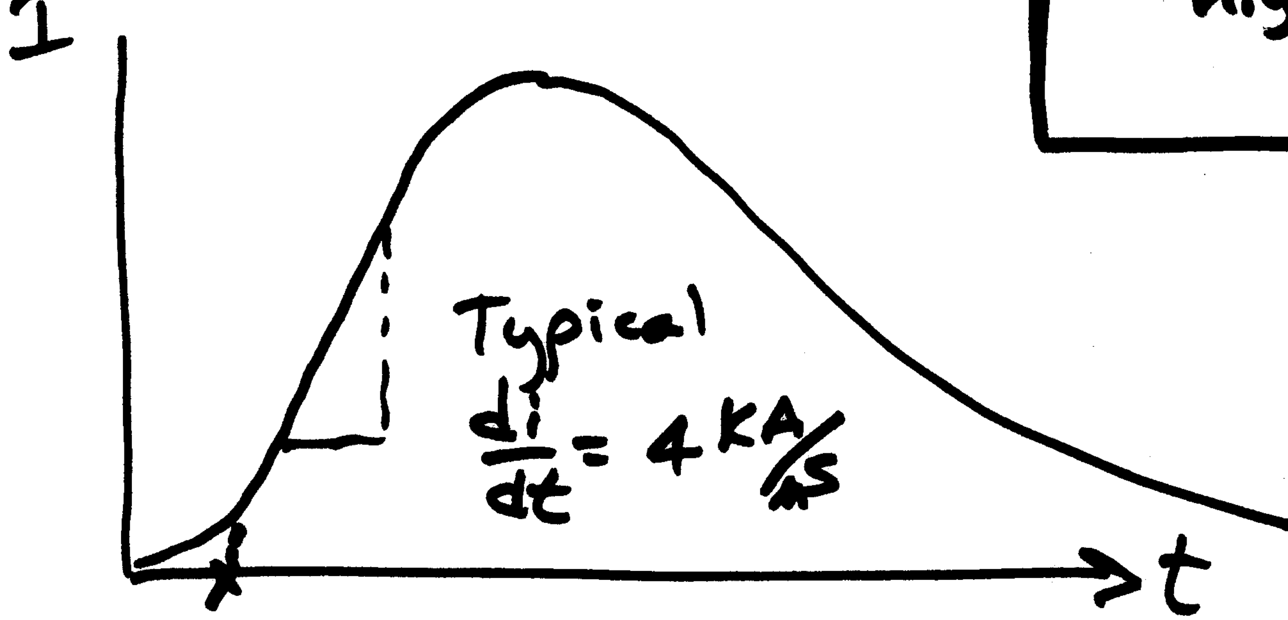




Arrester Leads:

$L = 0.4\ \mu H/ft$





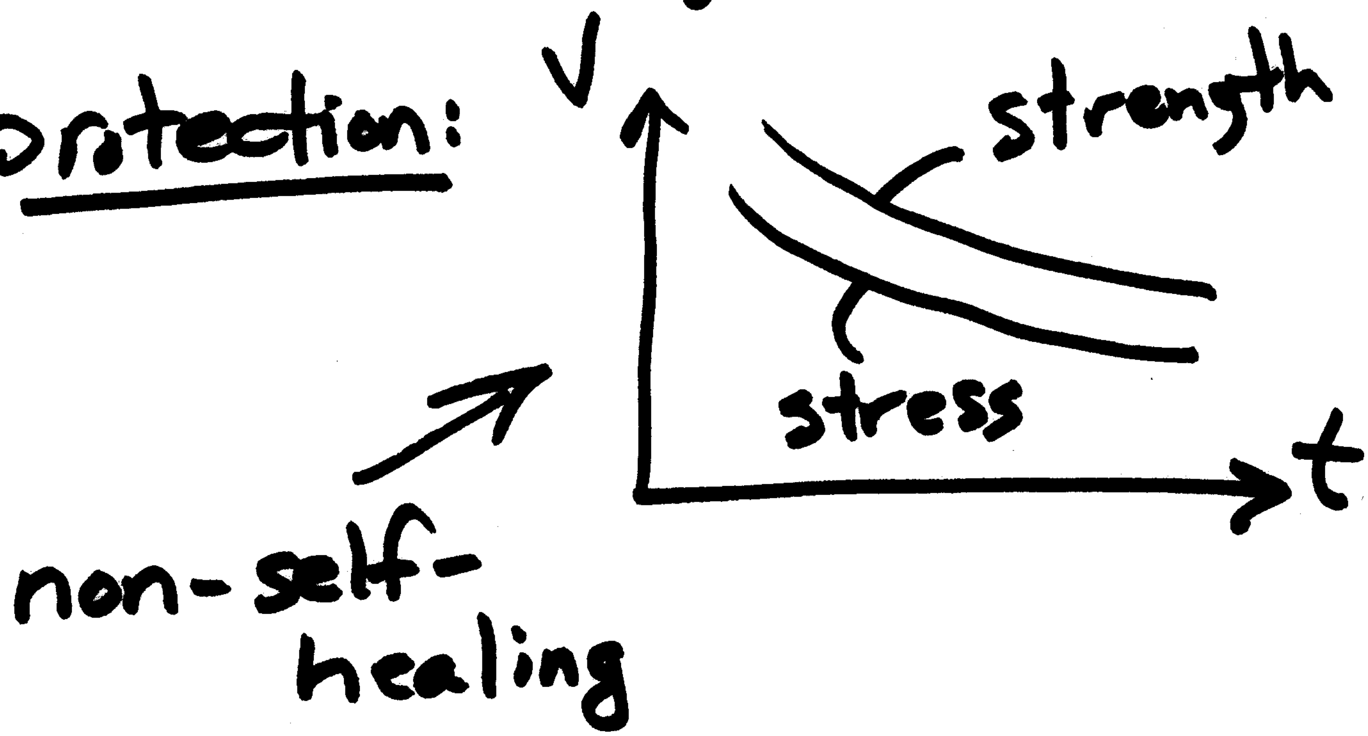
An extra 2 feet of lead length:

$$2 \times 4 \frac{KA}{\mu s} \times \frac{0.4\ \mu H}{ft} = \underline{\underline{3.2\ KV}}$$

<u>Stress</u> - mag of surge
→ Equip.

<u>strength</u> - withstand capability of equip.

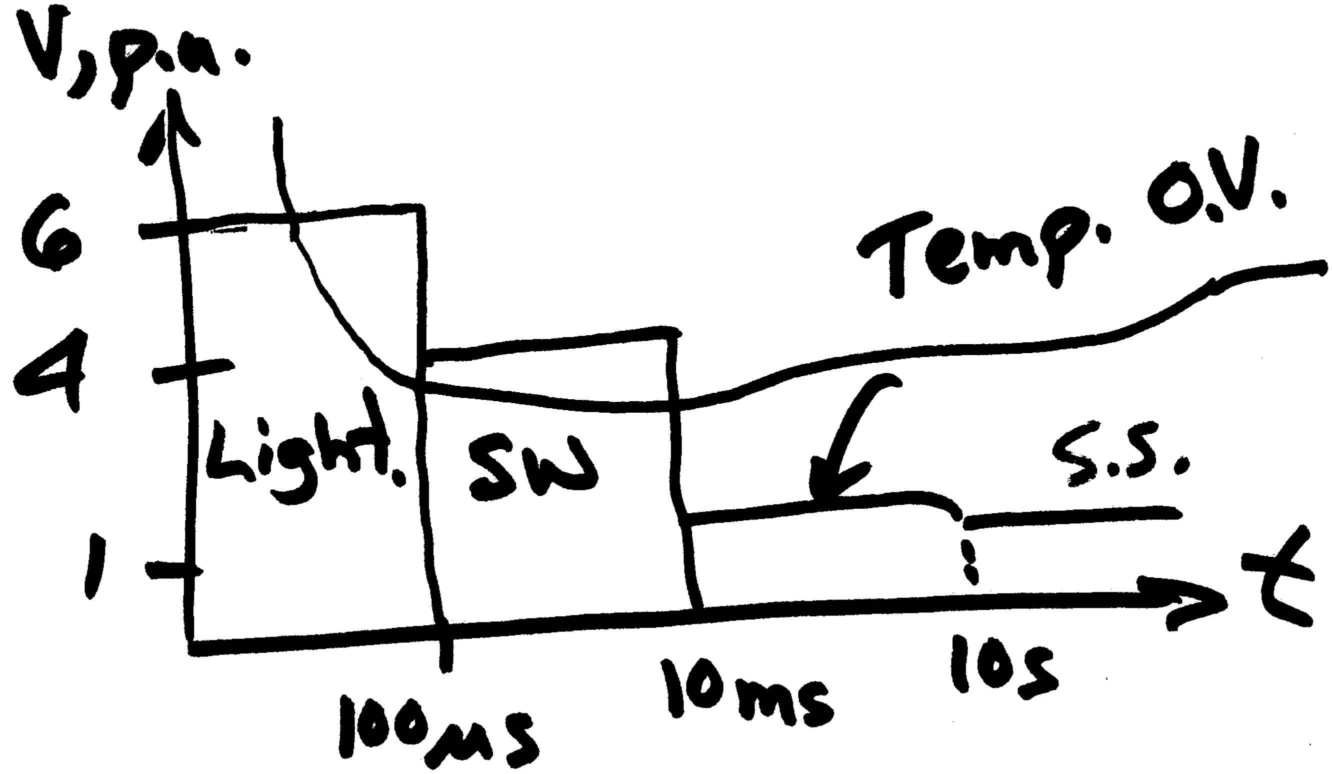
<u>protection:</u>



<u>Variables for strength:</u>

- Mag. of stress
- Rate of rise
- Duration

Withstand Capabilities



BIL vs Nominal V:
(Margin ↓ as V_{NOM} ↑.)

Table 2 Standard Values of BIL and BSL per ANSI C92, IEEE 1313.1

30	300	825	1925
45	350	900	2050
60	400	975	2175
75	450	1050	2300
95	500	1175	2425
110	550	1300	2550
125	600	1425	2675
150	650	1550	2800
200	700	1675	2925
250	750	1800	3050

Source: Ref. 7.

Table 3 Standard Values of BIL and BSL per IEC 71.1

20	325	1300	2550
40	450	1425	2700
60	550	1550	2900
75	650	1675	
95	750	1800	
125	850	1950	
145	950	2100	
170	1050	2250	
250	1175	2400	

Source: Ref. 5.

Table 4 Transformer and Bushings BILs and BSLs

System nominal/ max system voltage, kV	Transformers BIL, kV	Transformers BSL, kV	Transformer bushings BIL, kV	Transformer bushings BSL, kV
1.2/-	30, 45		45	
2.5/-	45, 60		60	
5.0/-	60, 75		75	
8.7/-	75, 95		95	
15.0/-	95, 110		110	
25.0/-	150		150	
34.5/-	200		200	
46/48.3	200, 250		250	
69/72.5	250, 350		350	
115/121	350	280	450	
	*450	375	50	
	550	460		
138/145	450	375	450	
	*550	460	550	
	650	540	650	
161/169	550	460	550	
	*650	540	650	
	750	620	750	
230/242	650	540	650	
	*750	620	750	
	825	685	825	
	900	745	900, 1050	
345/362	900	745	900	700
	*1050	870	1050	825
	1175	975	1175, 1300	825
500/550	1300	1080	1300	1050
	*1425	1180	1425	1110
	1550	1290	1550	1175
	1675	1390	1675	1175
765/800	1800	1500	1800	1360
	1925	1600	1925	—
	2050	1700	2050	—

* Commonly used.
Source: Ref. 7, 8.

Table 5 Insulation Levels for Outdoor Substations and Equipment

	NEMA Std, 6, outdoor substations		Circuit breakers		Disconnect switches	
Rated max voltage, kV	BIL, kV	10s power frequency voltage, kV	BIL, kV	BSL, kV	BIL, kV	BSL, kV estimate
8.25	95	30	95		95	
15.5	110	45	110		110	
25.8	150	60	150		125	
					150	
38.0	200	80	200		150	
					200	
48.3	250	100	250		250	
72.5	350	145	350		350	
121	550	230	550		550	
145	650	275	650		650	
169	750	315	750		750	
242	900	385	900		900	
	1050	455			1050	
362	1050	455	1300	825	1050	820
	1300	525		900	1300	960
550	1550	620	1800	1175	1550	1090
	1800	710		1300	1800	1210
800	2050	830	2050	1425	2050	1320
				1500		

Source: Ref. 5, 9.

Table 6 BILs/BSLs of Gas Insulated Stations

Max system voltage, kV		IEC [10]		ANSI [11]	
IEC	ANSI	BIL, kV	BSL, kV	BIL, kV	BSL, kV
72.5	72.5	325	—	300, 350	—
100		450	—		
123	121	550	—	450, 550	—
145	145	650	—	550, 650	—
170	169	750	—	650, 750	—
245	242	950	—	750, 900	—, 720
300		1050	850		
362	362	1175	950	900, 1050	720, 825
420		1300	1050		
525	550	1425	1175	1300, 1550	1050, 1175
765	800	1800	31425	1800	1425

Table 7 BILs of Cables (No BSLs provided), AEIC C54-79

Rated voltage, kV	BIL, kV
115, 120, & 130	550
138	650
161	750
230	1050
345	1300
500	1800

Source: Ref. 12.

Table 8 IEC 71.1: BILs are Tied to Max. System Voltages for Max. System Voltage from 1 to 245 kV

Max system voltage, kV	BILs, kV	Max system voltage, kV	BILs, kV
3.6	20 or 40	52	250
7.2	40 or 60	72.5	325
12	60, 75 or 95	123	450 or 550
17.7	75 or 95	145	450, 550, or 650
24	95, 125 or 145	170	550, 650, or 750
36	145 or 170	245	650, 750, 850, 950, or 1050

Source: Ref. 3.

Table 9 IEC BIL/BSLs, from IEC Publication 71.1

Max. system voltage, kV	Phase–ground BSL, BSL_g, kV	Ratio BSL_p/BSL_g	BIL, kV
300	750	1.50	850 or 950
	850	1.50	950 or 1050
362	850	1.50	950 or 1050
	950	1.50	1050 or 1175
420	850	1.60	1050 or 1175
	950	1.50	1175 or 1300
	1050	1.50	1300 or 1425
550	950	1.70	1175 or 1300
	1050	1.60	1300 or 1425
	1175	1.50	1425 or 1550
800	1300	1.70	1675 or 1800
	1425	1.70	1800 or 1950
	1550	1.60	1950 or 2100

Source: Ref. 3.

Onwards are pages from standards assembled together for circuit breakers, transformers and bushings.

5.5 Voltage ratings and taps

5.5.1 General

Standard nominal system voltages and maximum system voltages are included in ANSI C84.1 and listed in Table 4.

Table 4—Relationship of nominal system voltage to maximum system voltage and basic lightning impulse insulation level (BIL) for systems 765 kV and below

Application	Nominal system voltage, rms (kV)	Maximum system voltage, rms (from ANSI C84.1) (kV)	Basic lightning impulse insulation levels (BIL) in common use (kV crest)			
Distribution	**1.2**	—	30	—	—	—
	2.5	—	45	—	—	—
	5.0	—	60	—	—	—
	8.7	—	75	—	—	—
	15.0	—	95	—	—	—
	25.0	—	150	125	—	—
	34.5	—	200	150	**125**	—
	46.0	**48.3**	250	**200**	—	—
	69.0	**72.5**	350	**250**	—	—
Power	**1.2**	—	45	30	—	—
	2.5	—	60	45	—	—
	5.0	—	75	60	—	—
	8.7	—	95	75	—	—
	15.0	—	110	95	—	—
	25.0	—	150	—	—	—
	34.5	—	200	—	—	—
	46.0	**48.3**	250	**200**	—	—
	69.0	**72.5**	350	**250**	—	—
	115.0	**121.0**	**550**	450	**350**	—
	138.0	**145.0**	**650**	550	**450**	—
	161.0	**169.0**	**750**	650	**550**	—
	230.0	**242.0**	**900**	**825**	750	**650**
	345.0	**362.0**	**1175**	**1050**	**900**	—
	500.0	**550.0**	**1675**	**1550**	**1425**	**1300**
	765.0	**800.0**	**2050**	**1925**	—	—

Table 16 —Preferred dielectric withstand ratings for circuit breakers applied in gas-insulated substations [a]

Line No.	Rated maximum voltage U_r kV, rms	Rating table No.	Dielectric withstand test voltages			
			Power frequency 1 min dry kV, rms	Impulse test (2)	Switching impulse (2)	
				Full wave withstand (6) kV, peak	Withstand voltage terminal to ground with circuit breaker closed kV, peak	Withstand voltage terminal to terminal on one phase with circuit breaker open kV, peak
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
1	15	1	36	95	(3)	(3)
2	15	1	50	110	(3)	(3)
3	38	1, 5	60	150	(3)	(3)
4	38	1, 5	80	200	(3)	(3)
5	72.5	1, 5	140	300	(3)	(3)
6	72.5	1, 5	160	350	(3)	(3)
7	123	9	215	450	(3)	(3)
8	123	9	260	550	(3)	(3)
9	145	9	260	550	(3)	(3)
10	145	9	310	650	(3)	(3)
11	170	9	310	650	(3)	(3)
12	170	9	365	750	(3)	(3)
13	245	9	365	750	(3)	(3)
14	245	9	425	900	(3)	(3)
15	245	9	460	1050	(3)	(3)
16	362	9	425	900	720	800
17	362	9	500	1050	825	900
18	362	9	555	1300	825	900
19	550	9	615	1300	1050	1180
20	550	9	740	1550	1175	1300
21	550	9	860	1800	1175	1300
22	800	9	860	1800	1425	1550
23	800	9	960	2050	1425	1550

[a] Numbers in parenthesis refer to the items in 8.1.

Annex A

(informative)

Electrical insulation characteristics

Table A.1 includes the electrical insulation characteristics for ratings that were a part of IEEE Std C57.19.01-1991, but which were not included in Table 1 of this standard. This information is provided for replacement purposes only.

Table A.1—Electrical insulation characteristics for outdoor apparatus bushings (nominal system voltage 15–800 kV) (for replacement purposes only)

Basic lightning impulse insulation level (BIL)	System voltage	Rated maximum line-to-ground voltage	Creepage distance minimum		Withstand tests					
					60 Hz		Lightning impulse			Wet switching impulse
					1 min dry rms	10 s wet rms	Full wave	Chopped wave crest minimum time to flashover		
								2 µs withstand	3 µs withstand	
(kV)	(kV)	(kV)	(mm)[a]	(in)	(kV)	(kV)	(kV)	(kV)	(kV)	(kV)
Col. 1	Col. 2	Col. 3	Col. 4		Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10
110	15	10	280	11	50	45	110	142	126	—
150	25	16	430	17	60	50	150	194	175	—
250	46	29	890	35	105	95	250	322	290	—
450	92TR[b]	73	1 680	66	185	155	450	—	520	—
550	115	88	2 010	79	260	230	550	710	632	—
650	138	102	2 340	92	310	275	650	838	750	—
750	161	102	2 900	114	365	315	750	968	865	—
750	161TR[b]	146	3 560	140	365	315	750	—	865	—
900	196	146	3 560	140	425	350	900	1 160	1 040	—
900	362	220	5 590	220	395	—	900	—	1 035	700
1 050	362	220	5 590	220	460	—	1 050	—	1 210	825
1 300	550	318	8 080	318	575	—	1 300	—	1 500	1 050
1 425	550	318	8 080	318	630	—	1 425	—	1 640	1 110
1 550	550	318	8 080	318	690	—	1 550	—	1 780	1 175
1 800	800	485	12 320	485	800	—	1 800	—	2 070	1 360

NOTES

1—Dry negative switching impulse withstand voltage of the bushing must be at least equal to the dry switching impulse withstand voltage for the corresponding BIL specified in IEEE Std C57.12.00-1993.

2—The above ratings are not a part of the main standard and are included in this annex for replacement purposes only.

[a]Primary units for dimensions are in millimeters.
[b]For reduced BIL transformers only.

8

References

[1]. "IEEE Standard for Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers," *IEEE Std C57.12.00-2006 (Revision of IEEE Std C57.12.00-1999)* , vol., no., pp.c1-57, Feb. 28 2007.

[2]. "IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis - Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V," *IEEE Std C37.06-2009* , vol., no., pp.1-46, Nov. 6 2009

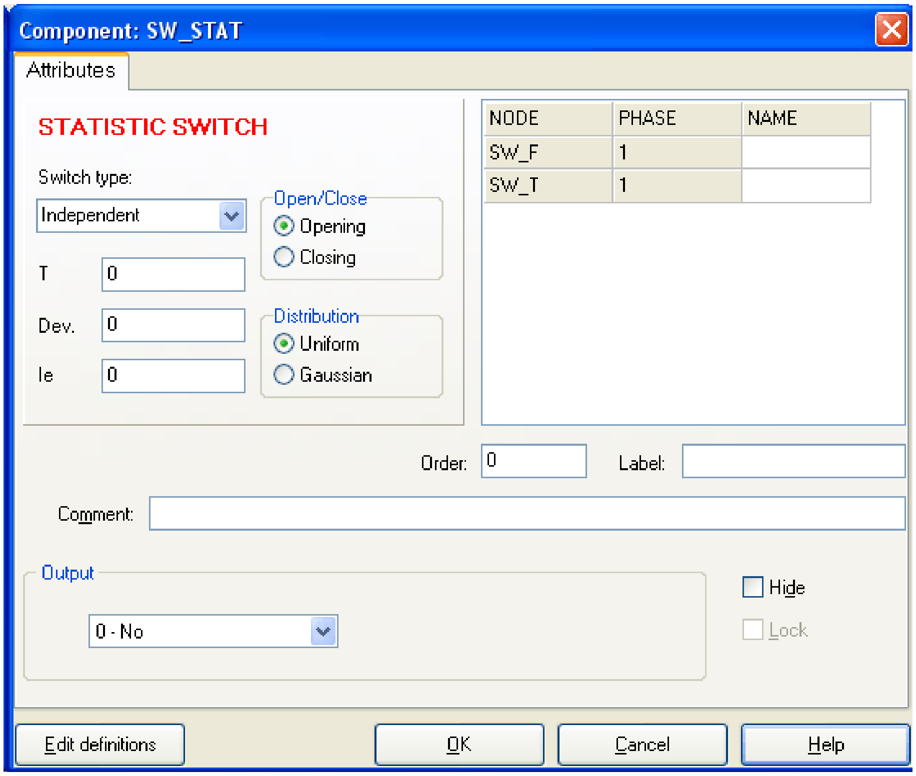
[3]. "IEEE Standard General Requirements and Test Procedure for Power Apparatus Bushings," *IEEE Std C57.19.00-2004 (Revision of IEEE Std C57.19.00-1991)* , vol., no., pp.0_1-17, 2005

[4]. "IEEE Standard Performance Characteristics and Dimensions for Outdoor Apparatus Bushings," *IEEE Std C57.19.01-2000* , vol., no., pp.1-, 2000

[5]. "Insulation Coordination for Power Systems" ,Andrew R. Hileman, *Monroeville, Pennsylvania, USA*

References from Hilemans book :-

1. ANSI C92.1–1982, "Insulation Coordination," under revision.
2. IEEE 1313.1, "IEEE Standard for Insulation Coordination, Principles and Rules," 1996.
3. IEC Publication 71.1, "Insulation Coordination Part I, Definitions, Principles and Rules." 1993-12.
4. IEC Publication 60, "High-Voltage Test Techniques" and IEEE 4–1978, "IEEE Standard Techniques for High-Voltage Testing."
5. ANSI/IEEE C37.04–1979, "IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Basis."
6. IEC Publication 71.2, "Insulation Coordination Part II, Application Guide, 1996-12.
7. ANSI/IEEE C57.12.00–1987, "IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers."
8. IEEE C37.12.14, "Trial Use Standard for Dielectric Test Requirements for Power Transformer for Operation at System Voltages from 115 kV through 230 kV."
9. ANSI/IEEE C37.32–1972, "Schedules of Preferred Ratings, Manufacturing Specifications, and Application Guide for Air Switches, Bus Supports, and Switch Accessories."
10. IEC Publication 517, "Gas Insulated Stations."
11. ANSI/IEEE C37.122–1983, "IEEE Standard for Gas-Insulated Stations."
12. AEIC C54-79, "Cables."
13. C. Menemenlis, G. Carrara, and P. J. Lambeth, "Application of Insulators to Withstand Switching Surges I: Switching Impulse Insulation Strength,"' IEEE Trans. on Power Delivery, Jan. 1989, pp. 545–60.
14. A. R. Hileman, "Weather and Its Effect on Air Insulation Specifications," *IEEE Trans. on PA&S*, Oct. 1984, pp. 3104–3116.
15. IEEE C62.11, "IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits."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Attributes
STATISTIC SWITCH
Switch type:
Independent
Open/Close
Opening
Closing
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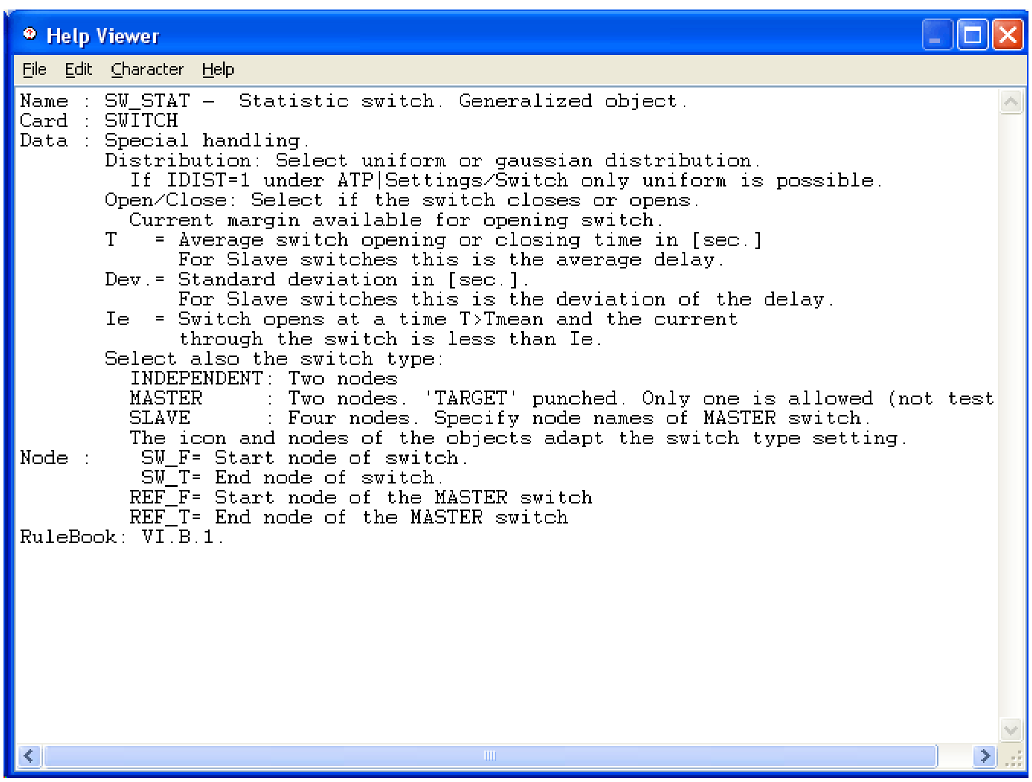
Dev. 0
Ie 0
Distribution
Uniform
Gaussian
NODE PHASE NAME
SW_F 1
SW_T 1
Order: 0
Label:
Comment:
Output
0 - No
Hide
Lock
Edit definitions
OK
Cancel
Help


Help Viewer
File Edit Character Help
Name : SW_STAT – Statistic switch. Generalized object.
Card : SWITCH
Data : Special handling.
Distribution: Select uniform or gaussian distribution.
If IDIST=1 under ATP|Settings/Switch only uniform is possible.
Open/Close: Select if the switch closes or opens.
Current margin available for opening switch.
T = Average switch opening or closing time in [sec.]
For Slave switches this is the average delay.
Dev.= Standard deviation in [sec.].
For Slave switches this is the deviation of the delay.
Ie = Switch opens at a time T>Tmean and the current
through the switch is less than Ie.
Select also the switch type:
INDEPENDENT: Two nodes
MASTER : Two nodes. 'TARGET' punched. Only one is allowed (not test
SLAVE : Four nodes. Specify node names of MASTER switch.
The icon and nodes of the objects adapt the switch type setting.
Node : SW_F= Start node of switch.
SW_T= End node of switch.
REF_F= Start node of the MASTER switch
REF_T= End node of the MASTER switch
RuleBook: VI.B.1.

1) ---

Statistical distribution of peak voltage at node "MIDA ". The base voltage for per unit printout is V-base = 3.43000000E+05

Interval number	voltage in per unit	voltage in physical units	Frequency (density)	Cumulative frequency	Per cent .GE. current value
25	1.2500000	4.28750000E+05	0	0	100.000000
26	1.3000000	4.45900000E+05	18	18	82.000000
27	1.3500000	4.63050000E+05	5	23	77.000000
28	1.4000000	4.80200000E+05	2	25	75.000000
29	1.4500000	4.97350000E+05	2	27	73.000000
30	1.5000000	5.14500000E+05	2	29	71.000000
31	1.5500000	5.31650000E+05	5	34	66.000000
32	1.6000000	5.48800000E+05	3	37	63.000000
33	1.6500000	5.65950000E+05	8	45	55.000000
34	1.7000000	5.83100000E+05	4	49	51.000000
35	1.7500000	6.00250000E+05	3	52	48.000000
36	1.8000000	6.17400000E+05	5	57	43.000000
37	1.8500000	6.34550000E+05	8	65	35.000000
38	1.9000000	6.51700000E+05	1	66	34.000000
39	1.9500000	6.68850000E+05	2	68	32.000000
40	2.0000000	6.86000000E+05	4	72	28.000000
41	2.0500000	7.03150000E+05	2	74	26.000000
42	2.1000000	7.20300000E+05	2	76	24.000000
43	2.1500000	7.37450000E+05	2	78	22.000000
44	2.2000000	7.54600000E+05	7	85	15.000000
45	2.2500000	7.71750000E+05	14	99	1.000000
46	2.3000000	7.88900000E+05	0	99	1.000000
47	2.3500000	8.06050000E+05	1	100	.000000

Summary of preceding table follows:	Grouped data	Ungrouped data
Mean =	1.73600000E+00	1.73890232E+00
Variance =	1.19271717E-01	1.14805855E-01
Standard deviation =	3.45357376E-01	3.38830127E-01