Insulation Coordination

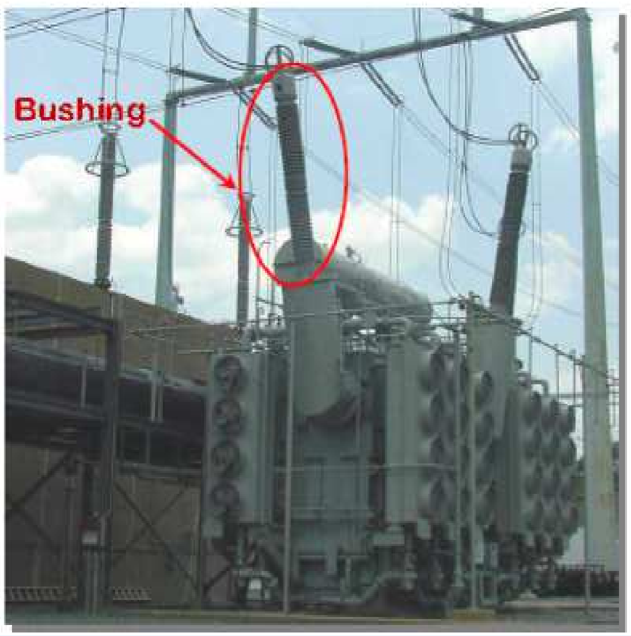
Note Title 12/6/2014

Examples of Electrical Insulation - Transformer

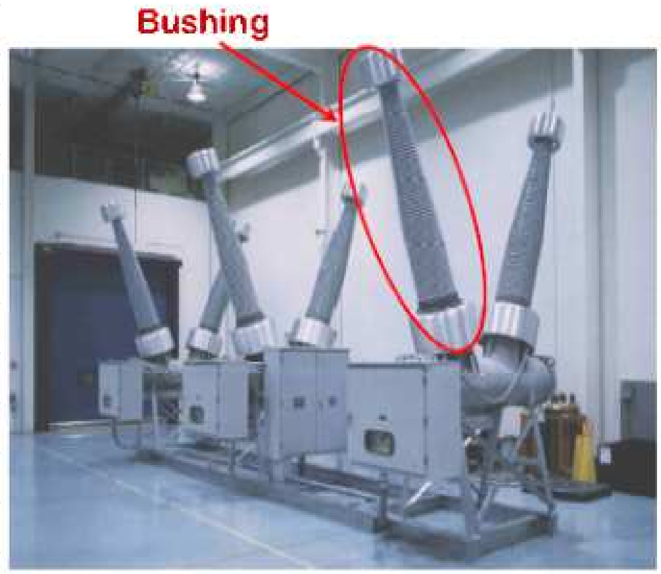
Examples of Electrical Insulation Gas-Filled Transformer

Examples of Electrical Insulation - Cable

Examples of Electrical Insulation - Transformer



Examples of Electrical Insulation - Gas Circuit Breaker



Examples of Electrical Insulation - Air Insulated Substation (AIS)

Examples of Electrical Insulation - Transmission Lines

Types of Insulations:

- *Self-restoring insulation*. The electrical power systems which use air as an insulating medium for external insulation are called the self-restoring insulation systems. The breakdown in air is strongly dependent on gap configuration, shape, and polarity of the surge and the ambient conditions. In an outdoor environment, the effects of rain, fog, humidity, and pollution become important. For GIS systems, the effects of temperature, pressure, and internal irregularities play an important role. Failure of air insulation is self-healing, as removal of overvoltage will restore the insulation, though not in every case of overvoltage. It is therefore, acceptable to tolerate a small probability of insulation failure to minimize the cost. Probabilistic methods are, therefore, applied for this type of insulation. We can say that the methodology tends to optimize the cost versus failure rate, though it is not so easy to accomplish this objective due to incomplete data of the systems and extensive modeling that may be required.

- *Non-selfrestoring insulation*. An insulation failure can cause a permanent fault and damage. This is true of solid dielectric materials. The mechanical stresses also impact the insulation strength. Degradation of insulation tends to increase with time. Any flashover is undesirable and unacceptable. The insulation characteristics must be selected with zero percent chance of flashover with some margin of safety. Practically, the cost of equipment and voltage is an important factor. An 800-MVA transformer will receive a more thorough analysis compared to a 500-kVA distribution transformer in meeting these criteria.

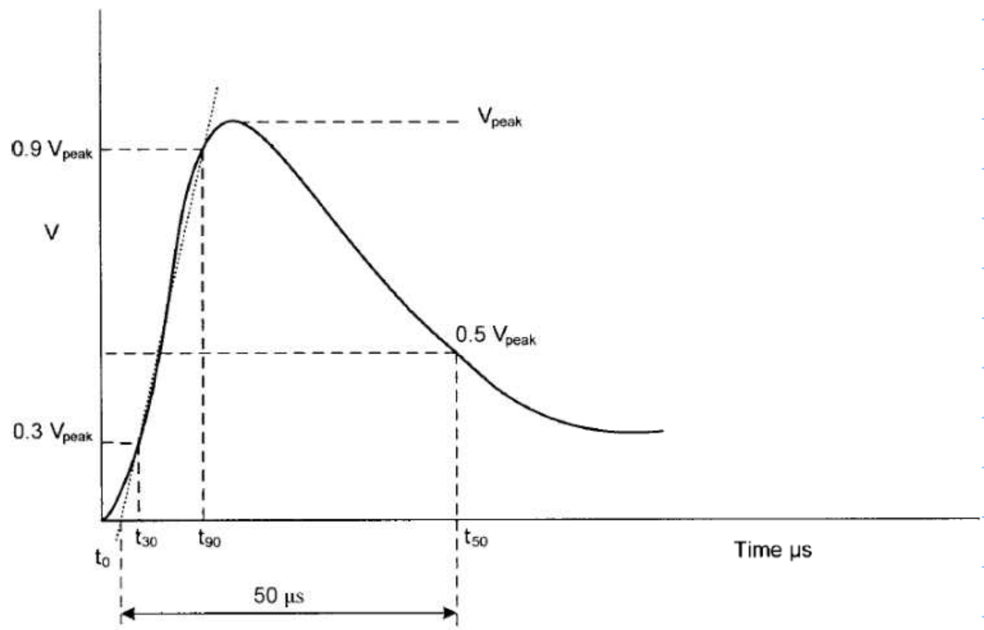
*BIL and BSL:

- [illegible] [116]: It is the electrical strength expressed in terms of the crest value of the standard lightning impulse, at standard dry atmospheric conditions. The BIL may be either statistical or conventional. The "statistical BIL" is the crest value of standard lightning impulse for which the insulation exhibits a 90% probability of withstand; that is, a 10% probability of failure. The "conventional BIL" is the crest value of a standard lightning impulse for which the insulation does not exhibit disruptive discharge when subjected to a specific number of applications of this impulse. The statistical BIL is applicable only to self-restoring insulations, whereas the conventional BIL is applicable to non-self-restoring insulations. In IEC Std 60071 [117], the BIL is defined in the same way but known as the lightning impulse withstand voltage.

- [illegible] [116]: It is the electrical strength expressed in terms of the crest value of a standard switching impulse, at standard wet atmospheric conditions. The BSL may be either statistical or conventional. As with the BIL, the statistical BSL is applicable only to self-restoring insulations, while the conventional BSL is applicable to non-self-restoring insulations. The statistical BSL is the crest value of a standard switching impulse for which the insulation exhibits a 90% probability of withstand, a 10% probability of failure. The conventional BSL is the crest value of a standard switching impulse for which the insulation does not exhibit disruptive discharge when subjected to a specific number of applications of this impulse. In IEC Std 60071 [117], the BSL is called the switching impulse withstand voltage and the definition is the same.

* Standerd Impulses:

- 1.2/50 μs Test wave:



- Tail-chopped Wave:

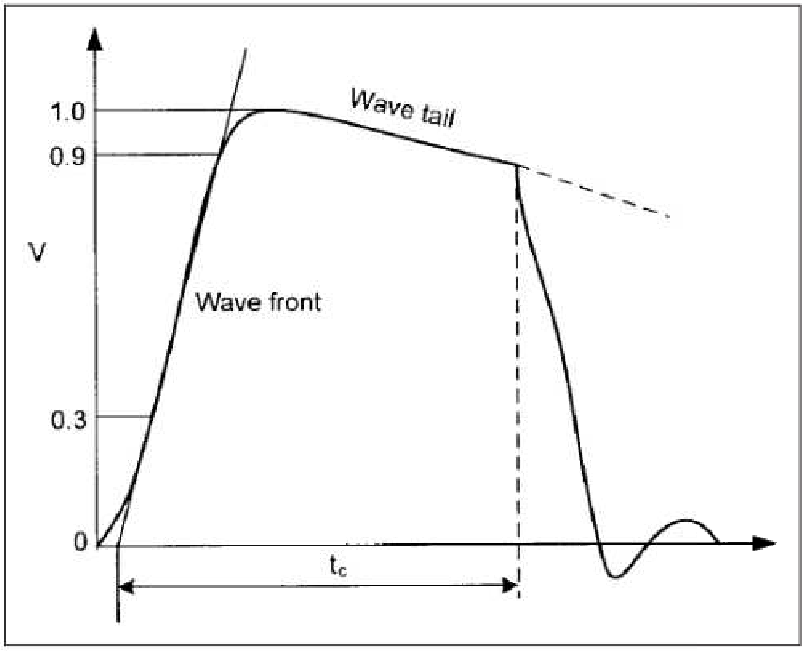


FIGURE 17-6 Tail-chopped 1.2/50-μs wave.

- Front-chopped Wave:

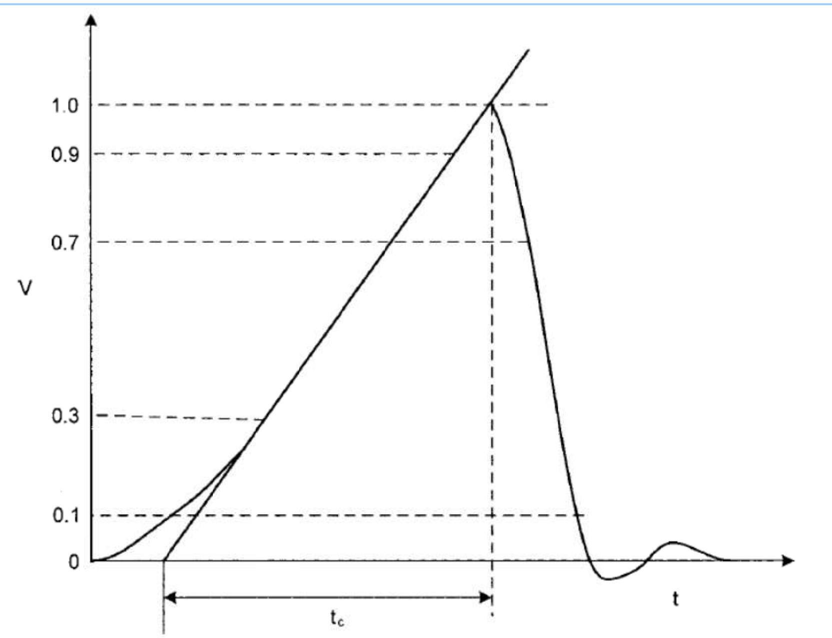


FIGURE 17-7 Front-chopped 1.2/50-μs wave.

- Standard Switching Impulse:

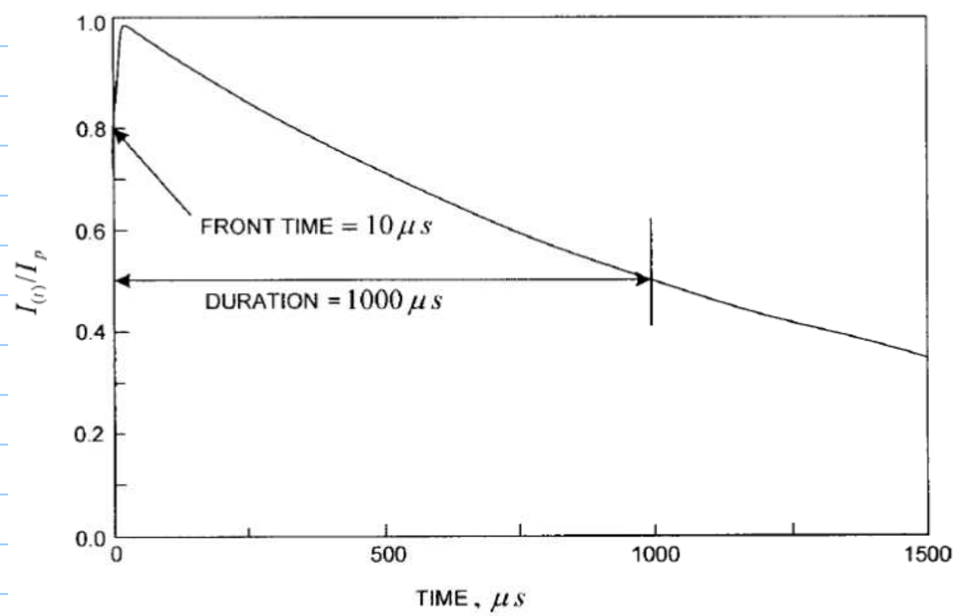


FIGURE 19-11 Waveform of 10/1000-μs current surge. *Source: ANSI/IEEE Standard C62.41.*[6]

* Conventional Withstand Strenght Test:

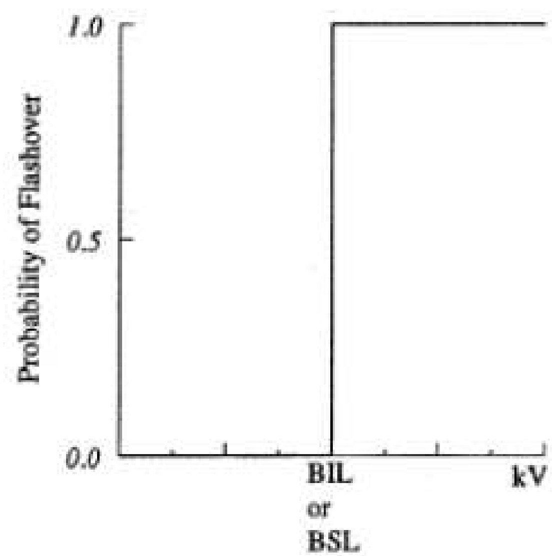


Figure 4 Insulation strength characteristic for non-self-restoring insulation.

* Statistical Withstand Strenght Test:

$$\text{BIL or BSL} = \text{CFO}\left(1 - 1.28\frac{\sigma}{\text{CFO}}\right)$$

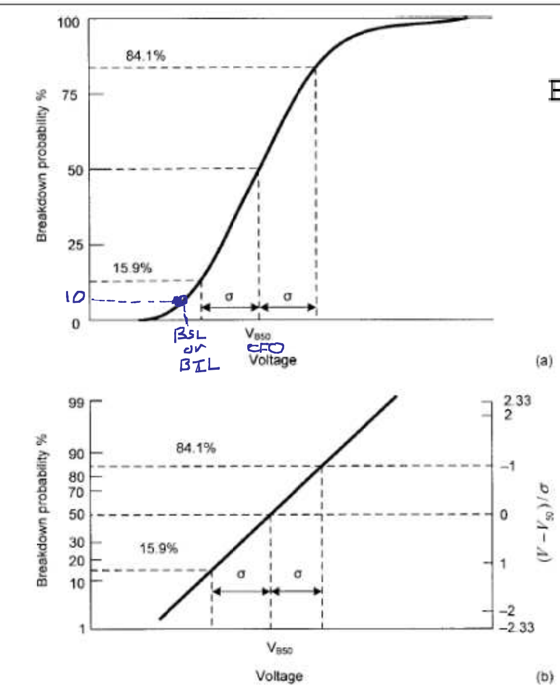
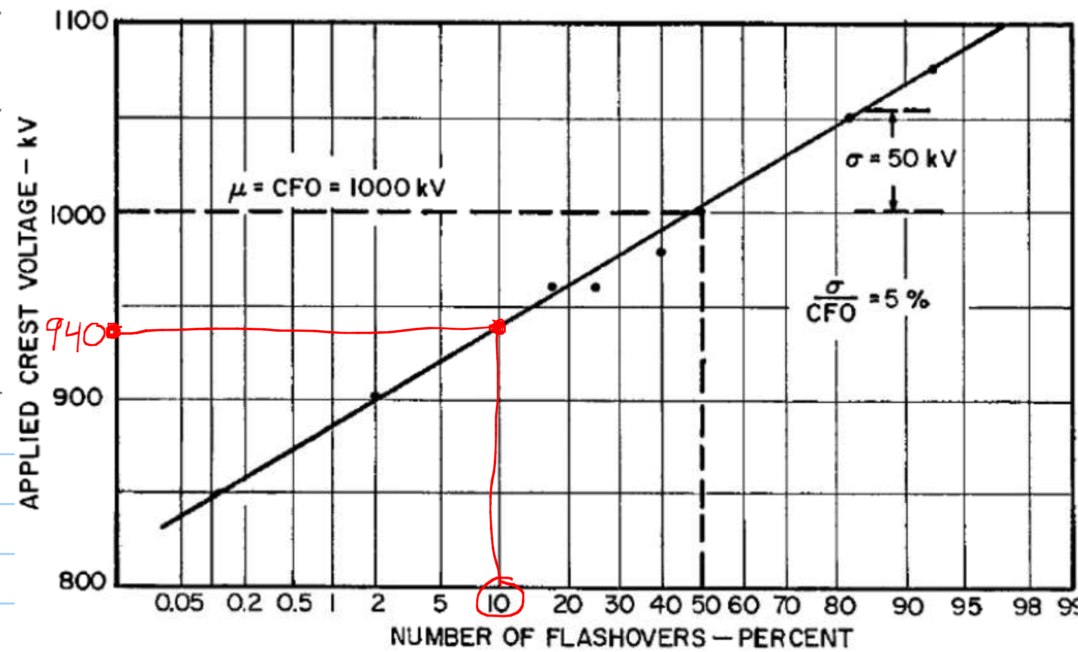


FIGURE 17-11 (*a*) Breakdown probability of external insulation, linear scale Gaussian distribution (*b*) Breakdown probability of external insulation, Gaussian scale, σ, standard deviation.

Example:

Applied crest voltage, kV	No. of "shots"	No. of flashovers	Percent of flashovers
900	100	2	2
1000	40	20	50
1050	40	33	82.5
1075	100	93	93
960	40	7	17.5
980	40	16	40
960	40	10	25



* Generation of time-volts Curve:

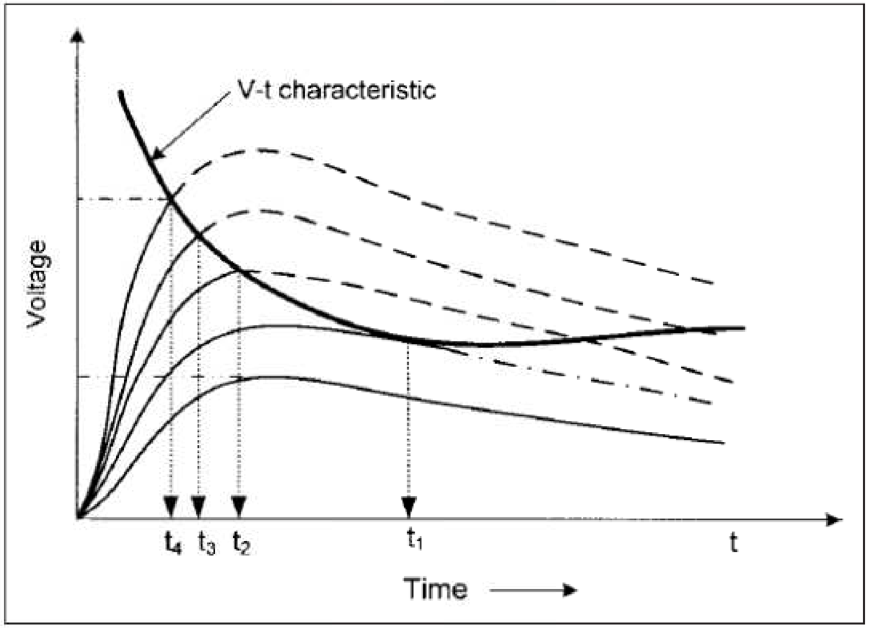


FIGURE 17-8 Construction of volt-time breakdown characteristics.

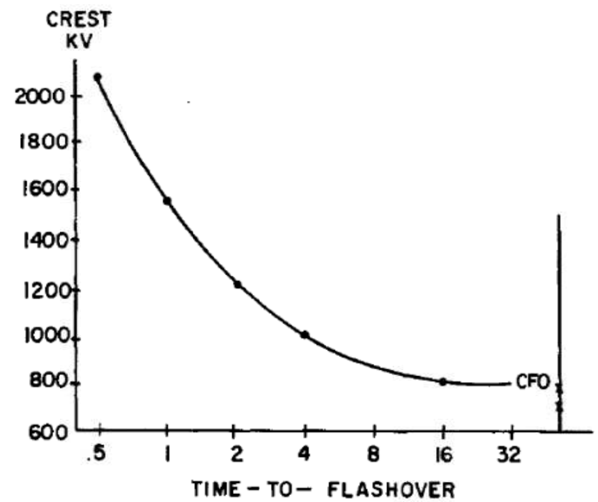


Figure 9 A sample time-lag curve.

Crest Voltage kV	Time to Flashover µs
700	no flashover
780	no flashover
800	16
1000	4
1200	2
1550	1
2050	0.5

*Standard Insulation Ratings:

TABLE 7-1 Dielectric Insulation Levels for Class II Transformers

Nominal System Voltage (kV) 1	BIL (kV Crest) 2	Chopped-Wave Level (kV Crest) 3	Switching-Impulse Level (kV Crest) 4	Induced Voltage Test (Phase-to-Ground): 1-hr Level (kV rms) 5	Induced Voltage Test (Phase-to-Ground): Enhancement Level (kV rms) 6	Applied Voltage Test Level (kV rms) 7
15 and below	110	120				34
25	150	165				50
34.5	200	220				70
46	250	275				95
69	250	275				95
	300	385				140
115	350	385	280	105	120	140
	450	495	375	105	120	185
	550	605	460	105	120	230
138	450	495	375	125	145	185
	550	605	460	125	145	230
	650	715	540	125	145	275
161	550	605	460	145	170	230
	650	715	540	145	170	275
	750	825	620	145	170	325
230	650	715	540	210	240	275
	750	825	620	210	240	325
	825	905	685	210	240	360
	900	990	745	210	240	395
345	900	990	745	315	360	395
	1050	1155	870	315	360	460
	1175	1290	975	315	360	520
500	1300	1430	1080	475	550	
	1425	1570	1180	475	550	
	1550	1705	1290	475	550	
	1675	1845	1390	475	550	
765	1800	1950	1500	690	800	
	1925	2120	1600	690	800	
	2050	2255	1700	690	800	

a. For chopped wave tests, the minimum time to flashover shall be 3.0 μs, except for 110-kV BIL, in which case, the minimum time to flashover shall be 2.0 μs.
b. Although Col. 4 establishes phase-to-ground switching impulse levels, it is not always possible to test these levels on low-voltage windings.
c. Columns 5 and 6 provide phase-to-ground test levels, which would normally be applicable to wye windings. When the test voltage is to be measured phase to phase, as is normally the case with delta windings, then the levels in Col. 5 are multiplied by 1.732 to obtain the required phase-to-phase induced voltage test level.
d. The applied voltage test is not applicable to wye-windings terminals, unless they have been specified to be suitable for ungrounded systems.
e. The BIL levels in bold are commonly used.
Source: ANSI/IEEE Standard.[5]

TABLE 17-6 Standard Withstand Voltages for Class I[8]

Highest Voltage for Equipment V_m (Phase-to-Phase) (kV, rms)	Low-Frequency, Short-Duration Withstand (Phase-to-Ground) (kV, rms)	Lightning Impulse Withstand Voltage (kV) Crest
15	34	95
		110
26.2	40	125
	50	150
36.2	50	150
	70	200
48.3	95	120
72.5	95	250
	140	350
121	140	350
	185	450
	230	550
145	185	450
	230	550
	275	650
169	230	550
	275	650
	325	750
242	275	650
	325	750
	360	825
	395	900
	480	975
		1050

TABLE 17-7 Standard Withstand Voltages for Class II[8]

Highest Voltage for Equipment V_m (Phase-to-Phase) (kV, rms)	BIL (Phase-to-Ground) (kV, Peak)	BSL (Phase-to-Ground) (kV Peak)
362	900	650
	975	750
	1050	825
	1175	900
	1300	975
		1050
420	1050	850
	1175	950
	1300	1050
	1425	
550	1300	1175
	1425	1300
	1550	1425
	1675	1550
	1800	
800	1800	1300
	1925	1425
	2050	1550
		1675
		1800

TABLE 17-8 Voltage Ratings for Gas-Insulated Substations[9]

System Voltage	Type Test Voltages		
Rated Maximum Voltage (Phase-to-Phase) (kV, rms)	Rated BIL (kV) Crest	Low-Frequency (Phase-to-Ground) Withstand (kV, rms)	Switching Surge Withstand (kV), Crest
72.5	350	160	
121	550	215	
145	650	310	
169	750	365	
242	900	425	
362	1050	500	825
550	1550	740	1175
800	2100	960	1550

Note: Disconnect switch open-gap withstand shall be 10 percent higher than the substation type test values.

TABLE 17-9 IEC BIL and BSL[7]

Maximum System Voltage (kV)	Phase-to-Ground BSL_g (kV, Peak)	Ratio BSL_p/BSL_g	BIL (kV, Peak)*
300	750	1.5	850, 950
	850	1.5	950, 1050
362	850	1.5	950, 1050
	950	1.5	1050, 1175
420	850	1.6	1050, 1175
	950	1.5	1175, 1300
	1050	1.5	1300, 1425
550	950	1.70	1175, 1300
	1050	1.60	1300, 1425
	1175	1.50	1425, 1550
800	1300	1.70	1675, 1800
	1425	1.70	1800, 1950
	1550	1.60	1950, 2100

*For each of the two BILs in this column.

TABLE 17-10 Factors for Estimating Withstand Voltages of Mineral Oil–Immersed Equipment[11]

Impulse Duration	BIL Multiplier	Equipment Type
Front of wave (0.5 µs)	1.30–1.50	Transformers and reactors
Chopped wave (2 µs)	1.29	Breakers 15.5 kV and above
Chopped wave (3 µs)	1.10–1.15	Transformers and reactors
Chopped wave (3 µs)	1.15	Breakers 15.5 kV and above
Full wave (1.2/50 µs)	1.00	Transformer and reactor windings
Switching surge, 250/2500 wave	0.83	Transformer and reactor windings
Switching surge, 250/2500 wave	0.63–0.69	Bushings
Switching surge, 250/2500 wave	0.63–0.69	Breakers 362–800 kV*

*Includes air blast and SF6 breakers.

*Non-Standard Atmospheric Conditions:

All insulation specification of strength are based on the following atmospheric conditions:

- Ambient temperature
  - 20° C
- Air pressure
  - 101.3 kPa or 760 mm Hg
- Absolute humidity
  - 11 grams of water per m³ of air
- For wet tests
  - 1 to 1.5 mm of water/minute

$$V_A = \delta^m H_c^w V_S \tag{5}$$

where δ is the relative air density, H_c is the humidity correction factor, and m and w are constants dependent on the factor G_0 which is defined as

$$G_0 = \frac{CFO_S}{500S} \tag{6}$$

where S is the strike distance or clearance in meters and CFO_S is the CFO under standard conditions.

By definition, Eq. 5 could also be written in terms of the CFO or BIL or BSL. That is,

$$CFO_A = \delta^m H_c^w CFO_S$$
$$BIL_A = \delta^m H_c^w BIL_S \tag{7}$$
$$BSL_A = \delta^m H_c^w BSL_S$$

The humidity correction factor, per Fig. 10, for impulses is given by the equation

$$H_c = 1 + 0.0096\left[\frac{H}{\delta} - 11\right] \tag{8}$$

$$H_c = 1 + 0.0096\left[\frac{H}{\delta} - 11\right] \quad (8)$$

where H is the absolute humidity in grams per m^3. For wet or simulated rain conditions, $H_c = 1.0$. The values of m and w may be obtained from Fig. 11 or from Table 10.

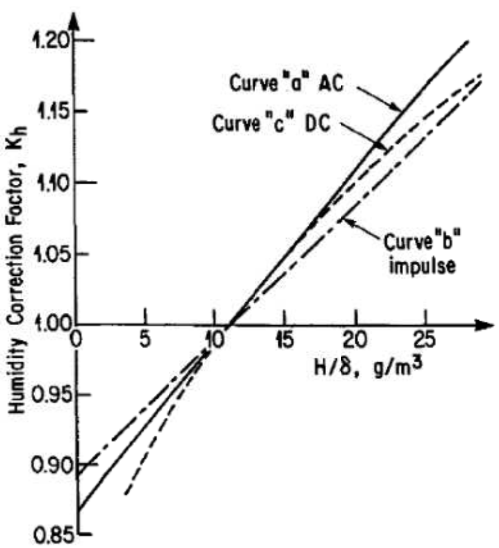


Figure 10 Humidity correction factors. (Copyright IEEE 1989 [13].

Table 10 Values of m and w

G_0	m	w
$G_0 < 0.2$	0	0
$0.2 < G_0 < 1.0$	$m = w = 1.25G_0(G_0 - 0.2)$	
$1.0 < G_0 < 1.2$	1	1
$1.2 < G_0 < 2.0$	1	$w = 1.25(2.2 - G_0)(2 - G_0)$
$G_0 > 2.0$	1	0

Lightning Impulse

For lightning impulses, G_0 is between 1.0 and 1.2. Therefore

$$\begin{aligned} V_A &= \delta H_c V_S \\ CFO_A &= \delta H_c CFO_S \\ BIL_A &= \delta H_c BIL_S \end{aligned} \tag{9}$$

In design or selection of the insulation level, wet or rain conditions are assumed, and therefore $H_c = 1.0$. So for design

$$\begin{aligned} V_A &= \delta V_S \\ CFO_A &= \delta (CFO_S) \\ BIL_A &= \delta (BIL_S) \end{aligned} \tag{10}$$

Switching Impulse

For switching impulses, G_0 is between 0.2 and 1, and therefore

$$m = w = 1.25 G_0 (G_0 - 0.2) \tag{11}$$

For dry conditions

$$V_A = (\delta H_c)^m V_S \tag{12}$$

However, in testing equipment, the BSL is always defined for wet or simulated rain conditions. Also in design for switching overvoltages, wet or rain conditions are assumed. Therefore, $H_c = 1$ and so

$$\begin{aligned} V_A &= \delta^m V_S \\ CFO_A &= \delta^m CFO_S \\ BSL_A &= \delta^m BSL_S \end{aligned} \tag{13}$$

The only remaining factor in the above correction equations is the relative air density. This is defined as

$$\delta = \frac{PT_0}{P_0 T} \tag{14}$$

where P_0 and T_0 are the standard pressure and temperature with the temperature in degrees Kelvin, i.e., degrees Celsius plus 273, and P and T are the ambient pressure and temperature. The absolute humidity is obtained from the readings of the wet and dry bulb temperature; see IEEE Standard 4.

Table 11 Regression Equations, A in km

Statistic	Linear equation for mean value	Exponential equation for mean value	Average standard deviation
Relative air density, δ			
Thunderstorms	$0.997–0.106A$	$1.000\,e^{-A/8.59}$	0.019
Nonthunderstorms	$1.025–0.090A$	$1.025\,e^{-A/9.82}$	0.028
Fair	$1.023–0.103A$	$1.030\,e^{-A/8.65}$	0.037
δH_c			
Thunderstorms	$1.035–0.147A$	$1.034\,e^{-A/6.32}$	0.025
Nonthunderstorms	$1.023–0.122A$	$1.017\,e^{-A/8.00}$	0.031
Fair	$1.025–0.132A$	$1.013\,e^{-A/7.06}$	0.034

Either form of the equation of Table 11 can be used, although the linear form should be restricted to altitudes less than about 2 km. The exponential form is more satisfactory, since it appears to be a superior model.

Example 1. A disconnecting switch is to be tested for its BIL of 1300 kV and its BSL of 1050 kV. In the laboratory, the relative air density is 0.90 and the absolute humidity is 14 g/m^3. Thus the humidity correction factor is 1.0437. As per standards, the test for the BIL is for dry conditions and the test for the BSL is for wet conditions. The σ_f/CFO is 0.07. The test voltages applied for the BIL is

$$\mathrm{BIL_A} = (\delta H_c)\mathrm{BIL_S} = 1221\,\mathrm{kV} \tag{19}$$

Thus to test for a BIL of 1300 kV, the crest of the impulse should be 1221 kV. For testing the BSL, let the strike distance, S, equal 3.5 m. Then

$$\mathrm{BSL_A} = \delta^m \mathrm{BSL_S}$$

$$\mathrm{CFO_s} = \frac{\mathrm{BSL_s}}{1\text{-}1.28\,\sigma_f / \mathrm{CFO_s}} = 1153\,\mathrm{kV}$$

$$G_0 = \frac{\mathrm{CFO_S}}{500S} = 0.6591 \tag{20}$$

$$m = 1.25G_0(G_0 - 0.2) = 0.3782$$

$$\mathrm{BSL_A} = 0.90^{0.3782}(1050) = 1009\,\mathrm{kV}$$

Thus to test for a BSL of 1050 kV, the crest of the impulse should be 1009 kV.

Example 2. The positive polarity switching impulse CFO at standard conditions is 1400 kV for a strike distance of 4.0 meters. Determine the CFO at an altitude of 2000 meters where $\delta = 0.7925$. Assume wet conditions, i.e., $H_c = 1$.

$$G_0 = \frac{1400}{4.0(500)} = 0.700$$

$$m = 1.25G_0(G_0 - 0.2) = 0.4375 \tag{21}$$

$$\mathrm{CFO_A} = (1400)0.7925^{0.4375} = 1265$$

Example 3. Let the CFO for lightning impulse, positive polarity at standard atmospheric conditions, be equal 2240 kV for a strike distance of 4 meters. Assume wet conditions, i.e., $H_c = 1$. For a relative air density of 0.7925, the CFO is

$$\mathrm{CFO_A} = 0.7925(2240) = 1775\,\mathrm{kV} \tag{22}$$