Reliability of HVDC Cables:
the role played by the enlargement law

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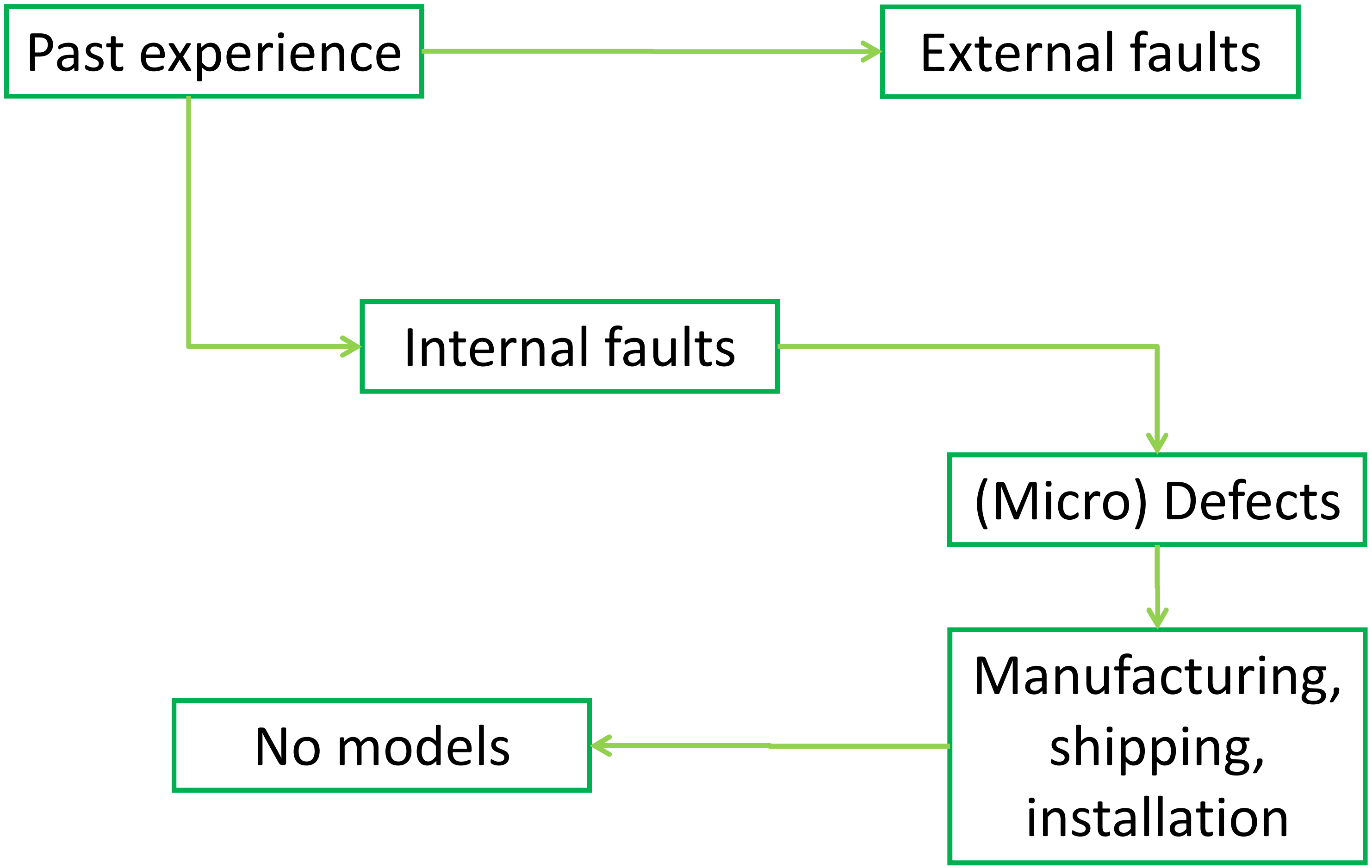
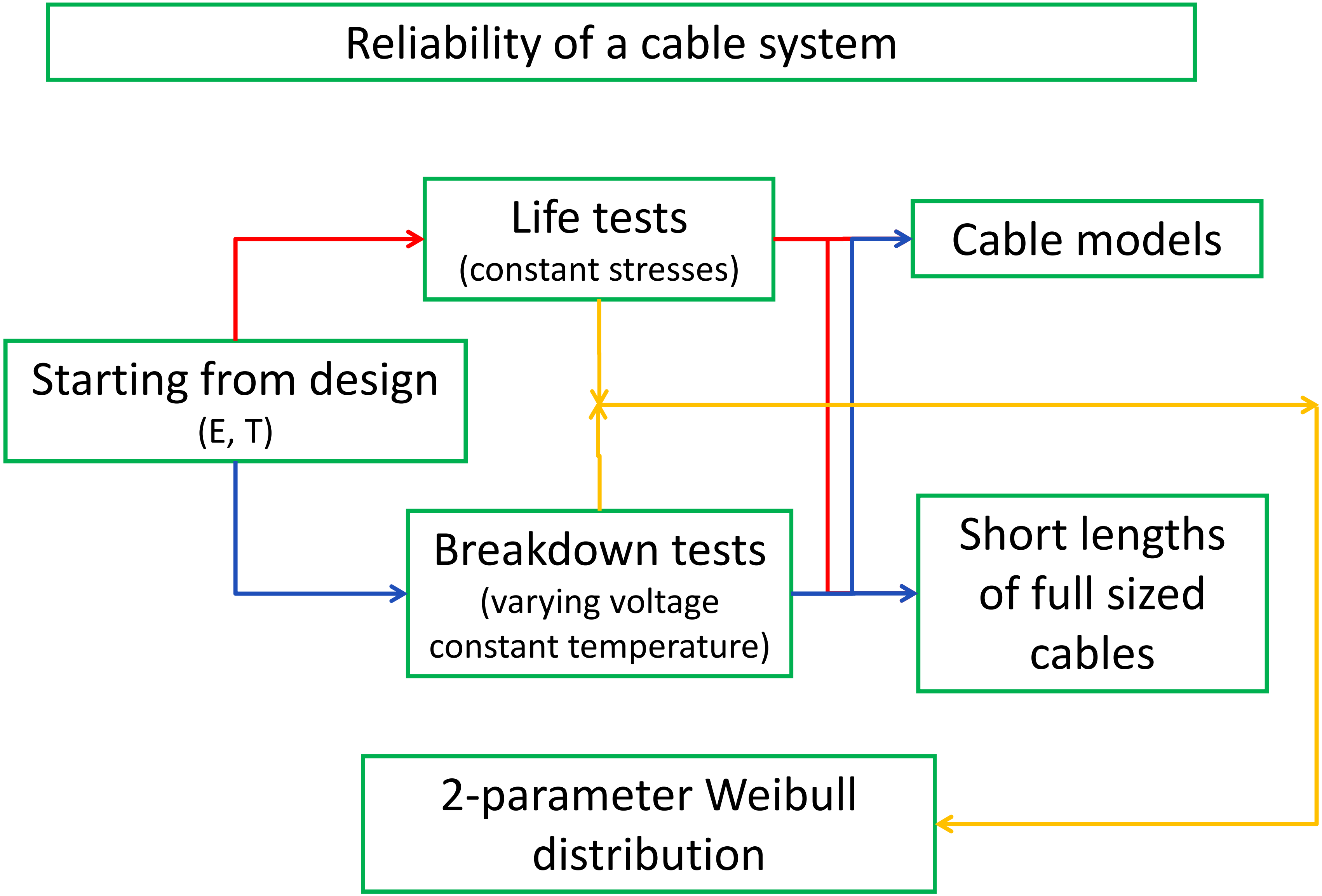
ITALY

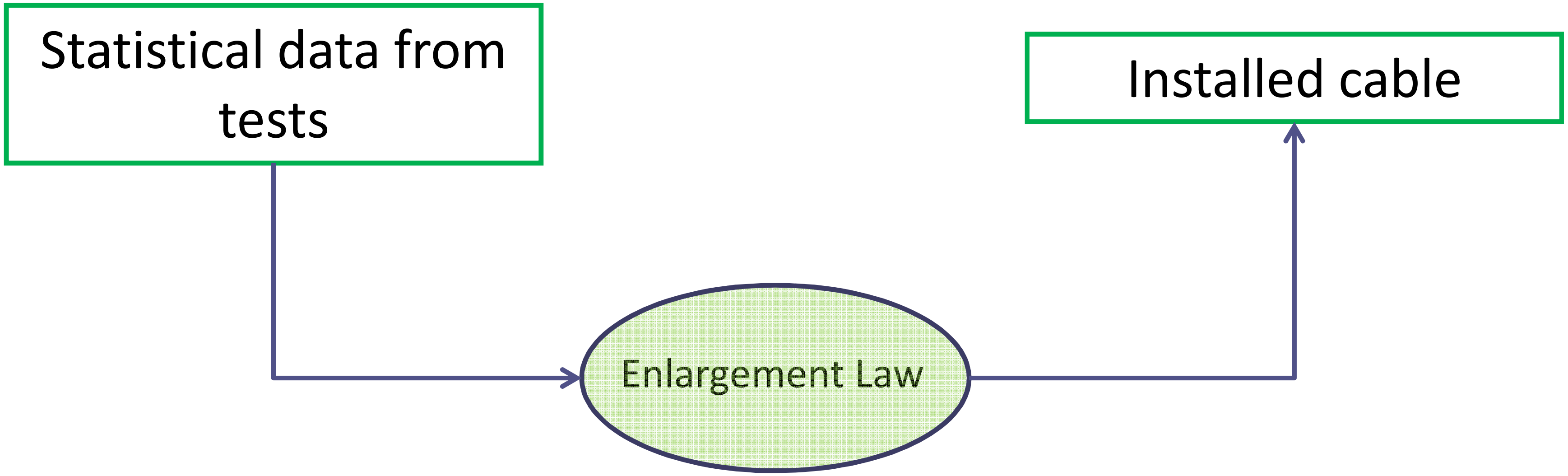
Reliability of a cable system




Reliability of a cable system
Life tests
(constant stresses)
Cable models
Starting from design
(E, T)
Breakdown tests
(varying voltage
constant temperature)
Short lengths
of full sized
cables
2-parameter Weibull
distribution

Reliability of a cable system

How can reliability be inferred for a cable line starting from tests on cable models?



Life tests

Considering life tests performed on cable samples:

- well-fit 2-parameter Weibull distribution

- estimation of scale and shape parameters

$$P = 1 - \exp\left\{ -\left(\frac{t}{\alpha_t} \right)^{\beta_t} \right\}$$

α_t: scale parameter (63.2 percentile)

β_t: shape parameter

Close and Return

Life model

For polymeric cables a life model that combine both thermal and electrical stress is the following:

$$\alpha_t(E,T) = \alpha_{ot}\left(\frac{E}{E_o}\right)^{-(n_o - b_L cT)} \exp(-B_L cT)$$

$$\alpha_{ot} = \alpha_t(E_o, T_o)$$

$$cT = \frac{1}{T_o} - \frac{1}{T}$$

$$B_L = \frac{\Delta W}{k_B}$$

E_o: Electric field with negligible E ageing
T_o: Reference Temperature
n_o: Voltage Endurance Coefficient (VEC) at T_o
b_L: Synergism between E and T
ΔW: Activation energy of the main thermal degradation reaction
k_B: Bolzman constant (1.38×10^{-23} J/K)

Life tests performed on cable samples made of a number of specimen each:

- Sample 1 → E,T → α_t β_t
- Sample 2 → E_o ,T_o → α_{ot} β_{ot}

$$P = 1 - \exp\left\{ -\left(\frac{t_P}{\alpha_t(E,T)} \right)^{\beta_t} \right\}$$

$$P_o = 1 - \exp\left\{ -\left(\frac{t_{oP}}{\alpha_{ot}(E_o,T_o)} \right)^{\beta_{ot}} \right\}$$

$$\alpha_t(E,T) = \frac{t_P}{\left[-\ln(1-P) \right]^{\frac{1}{\beta_t}}}$$

$$\alpha_{ot}(E_o,T_o) = \frac{t_{oP}}{\left[-\ln(1-P_o) \right]^{\frac{1}{\beta_{ot}}}}$$

$$\alpha_t(E,T)=\frac{t_P}{\left[-\ln(1-P)\right]^{\frac{1}{\beta_t}}}$$

$$\alpha_{ot}(E,T)=\frac{t_{oP}}{\left[-\ln(1-P_o)\right]^{\frac{1}{\beta_{ot}}}}$$

$$\alpha_t(E,T)=\alpha_{ot}\left(\frac{E}{E_o}\right)^{-(n_o-b_L cT)}\exp\left(-B_L cT\right)$$

$$t_P(E,T)=t_{oP}(E_o,T_o)\frac{\left[-\ln(1-P)\right]^{\frac{1}{\beta_t}}}{\left[-\ln(1-P_o)\right]^{\frac{1}{\beta_{ot}}}}\left(\frac{E}{E_o}\right)^{-(n_o-b_L cT)}\exp\left(-B_L cT\right)$$

P: Probability of breakdown after a time $t_P(E,T)$

P_o: Probability of breakdown after a time $t_{oP}(E_o,T_o)$

$$t_P(E,T) = t_{oP}(E_o,T_o)\frac{\left[-\ln(1-P)\right]^{\frac{1}{\beta_t}}}{\left[-\ln(1-P_o)\right]^{\frac{1}{\beta_{ot}}}}\left(\frac{E}{E_o}\right)^{-(n_o - b_L cT)} \exp(-B_L cT)$$

When increasing cable lengths, the probability of breakdown increases if E is not lowered

This is taken into account by the statistical enlargement law, a practical application of the multiplication law for non-dependent probabilities in the framework of Weibull statistics for solid-extruded cable insulation:

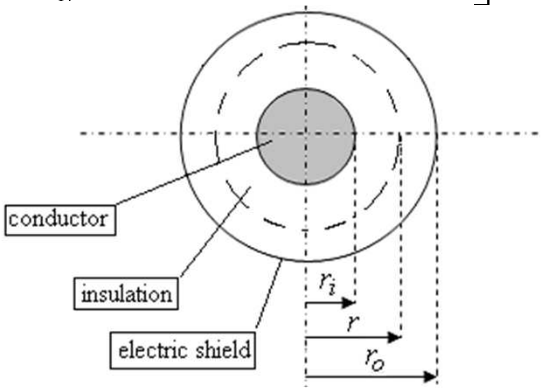
$$P_N = 1 - \exp\left[\frac{1}{V_1}\int_{V_N} \ln[1 - P_1(x,\alpha,\beta)]dv\right]$$

The enlargement law for AC cables

$$P_N = 1 - \exp\left[\frac{1}{V_1}\int_{V_N} \ln[1 - P_1(x, \alpha_E, \beta_E)]dv\right]$$

$$N = V_N / V_1$$

$$P_1 = 1 - \exp\left\{-\left(\frac{E}{\alpha_{\nu E}}\right)^{\beta_E}\right\}$$



$$E_{r,AC} = \frac{V_{AC}}{r \ln(r_o / r_i)}$$

$$E_{r,i} = \frac{V_{AC}}{r_i \ln(r_o / r_i)}$$

$$P_N = 1 - \exp\left\{\frac{1}{V_\nu}\int_{r_i}^{r_o} [-(E_{r,i}/\alpha_{\nu E})]^{\beta_E} 2\pi r l dr\right\}$$

$$\boxed{\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta_E}} \left(\frac{r_{i2}}{r_{i1}}\right)^{\frac{2}{\beta_E}} \mathrm{H}_{AC}(r_{i1}, r_{i2}, r_{o1}, r_{o2})}$$

....

Cable 1 (subscript 1)

Cable 2 (subscript 2)

$$\mathrm{H}_{AC}(r_{i1}, r_{i2}, r_{o1}, r_{o2}) = \left[\frac{\left(\frac{r_{o2}}{r_{i2}}\right)^{2-\beta_E} - 1}{\left(\frac{r_{o1}}{r_{i1}}\right)^{2-\beta_E} - 1}\right]^{\frac{1}{\beta_E}} \qquad \beta_E \neq 2$$

The enlargement law for DC cables

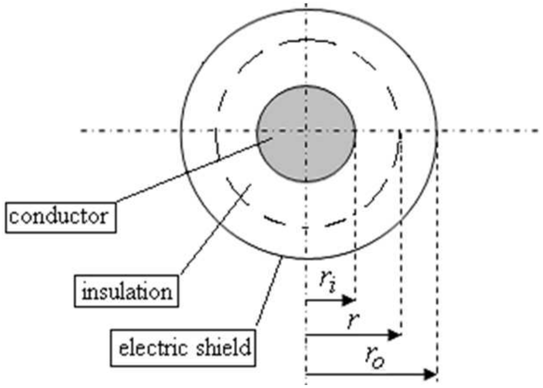
$$P_N = 1 - \exp\left[\frac{1}{V_1}\int_{V_N} \ln[1 - P_1(x, \alpha_E, \beta_E)]dv\right]$$

$$N = V_N / V_1$$

$$P_1 = 1 - \exp\left\{-\left(\frac{E}{\alpha_{vE}}\right)^{\beta_E}\right\}$$

$$E_{r,DC} = \frac{\delta V_{DC}\left(\frac{r}{r_o}\right)^{\delta-1}}{r_o\left[1-\left(\frac{r}{r_o}\right)^{\delta}\right]}$$

$$E_{r,i} = \frac{\delta V_{DC}\left(\frac{r_i}{r_o}\right)^{\delta-1}}{r_o\left[1-\left(\frac{r_i}{r_o}\right)^{\delta}\right]}$$



$$\delta = \frac{\dfrac{aW_C}{2\pi\lambda_{T,d}} + \dfrac{bV_{DC}}{(r_o - r_i)}}{\dfrac{bV_{DC}}{(r_o - r_i)} + 1}$$

$$E_{r,DC} = E_r = E_{r,i}\,\frac{r^{\delta-1}}{r_0^{\delta-1}}\frac{r_0^{\delta-1}}{r_i} = E_{r,i}\left(\frac{r_i}{r}\right)^{1-\delta}$$

$$P_N = 1 - \exp\left\{\frac{1}{V_v}\int_{r_i}^{r_o}[-(E_{r,i}/\alpha_{vE})]^{\beta_E}\,2\pi r l dr\right\}$$

The enlargement law for DC cables

$$P_N = 1 - \exp\left\{ -\frac{2\pi d}{V_\nu} \left(\frac{E_{r,i}}{\alpha_{\nu E}} \right)^{\beta_E} \int_{r_i}^{r_o} \left[\left(\frac{r_i}{r} \right)^{\eta} \right] r dr \right\}$$

$$\eta = (1-\delta)\beta_E$$

$$P_N = 1 - \exp\left\{ -\frac{2\pi d}{V_\nu} \left(\frac{E_{r,i}}{\alpha_{\nu E}} \right)^{\beta_E} r_i^{\eta} \int_{r_i}^{r_o} r^{1-\eta} dr \right\}$$

$$P_N = 1 - \exp\left\{ -\frac{2\pi d}{(2-\eta)V_\nu} \left(\frac{E_{r,i}}{\alpha_{\nu E}} \right)^{\beta_E} r_i^2 \left[\left(\frac{r_o}{r_i} \right)^{2-\eta} - 1 \right] \right\}$$

$$n(\eta) = \frac{2\pi d r_i^2}{(2-\eta)V_\nu} \left[\left(\frac{r_o}{r_i} \right)^{2-\eta} - 1 \right]$$

$$\boxed{P_N = 1 - \exp\left\{ -n \left(\frac{E_{r,i}}{\alpha_{\nu E}} \right)^{\beta_E} \right\} = 1 - \exp\left\{ -\left(\frac{E_{r,i}}{\alpha_{NE}} \right)^{\beta_E} \right\}}$$

$$\boxed{P_1 = 1 - \exp\left\{ -\left(\frac{E}{\alpha_{\nu E}} \right)^{\beta_E} \right\}}$$

The enlargement law for DC cables

$$\alpha_{NE} = \frac{\alpha_{\nu E}}{[n(\eta)]^{\frac{1}{\beta_E}}} \Leftrightarrow \alpha_{\nu E} = \alpha_{NE}\,[n(\eta)]^{\frac{1}{\beta_E}}$$

$$\alpha_{\nu E} = \alpha_1\,[n_1(\eta_1)]^{\frac{1}{\beta_E}} = \alpha_2\,[n_2(\eta_2)]^{\frac{1}{\beta_E}}$$

$$\boxed{\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta_E}} \left(\frac{r_{i2}}{r_{i1}}\right)^{\frac{2}{\beta_E}} \left[\frac{\left(\frac{r_{o2}}{r_{i2}}\right)^{2-\eta_2} - 1}{\left(\frac{r_{o1}}{r_{i1}}\right)^{2-\eta_1} - 1}\right]^{\frac{1}{\beta_E}}}$$

$\eta_1 > 2$ and $\eta_2 > 2$

or

$\eta_1 < 2$ and $\eta_2 < 2$

$$\mathrm{H}_{\mathrm{DC}}(r_{i1}, r_{i2}, r_{o1}, r_{o2}, V_{DC,1}, V_{DC,2}, W_{C1}, W_{C2}, \beta_E, a, b, \lambda_{Td}) = \left[\frac{\left(\frac{r_{o2}}{r_{i2}}\right)^{2-\eta_2} - 1}{\left(\frac{r_{o1}}{r_{i1}}\right)^{2-\eta_1} - 1}\right]^{\frac{1}{\beta_E}}$$

The enlargement law for DC cables

$$\frac{V_2}{V_1}=\frac{\alpha_2}{\alpha_1}\frac{k_1}{k_2}\frac{\delta_1}{\delta_2}=\frac{k_1}{k_2}\frac{\delta_1}{\delta_2}\left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta_E}}\left(\frac{r_{i2}}{r_{i1}}\right)^{\frac{2}{\beta_E}}\left[\frac{\left(\frac{r_{o2}}{r_{i2}}\right)^{2-\eta_2}-1}{\left(\frac{r_{o1}}{r_{i1}}\right)^{2-\eta_1}-1}\right]^{\frac{1}{\beta_E}}$$

$$\eta_j=(1-\delta_j)\beta_E$$

$$j=1,2$$

$$k_j=\frac{\left(\frac{r_{ij}}{r_{oj}}\right)^{\delta_j-1}}{r_{oj}\left[1-\left(\frac{r_{ij}}{r_{oj}}\right)^{\delta_j}\right]}$$

$$j=1,2$$

$$\delta_j=\frac{\frac{aW_{Cj}}{2\pi\lambda_{T,d}}+\frac{bV_{DCj}}{\left(r_{oj}-r_{ij}\right)}}{\frac{bV_{DCj}}{\left(r_{oj}-r_{ij}\right)}+1}$$

$$j=1,2$$

The enlargement law: AC vs.DC: concluding remarks

$$\boxed{\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta_E}} \left(\frac{r_{i2}}{r_{i1}}\right)^{\frac{2}{\beta_E}} \quad \mathrm{H}_{AC}}$$

$$\boxed{\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta_E}} \left(\frac{r_{i2}}{r_{i1}}\right)^{\frac{2}{\beta_E}} \quad H_{DC}}$$

$$\boxed{\mathrm{H}_{AC}(r_{i1}, r_{i2}, r_{o1}, r_{o2}, \beta_E) = \left[\frac{\left(\frac{r_{o2}}{r_{i2}}\right)^{2-\beta_E} - 1}{\left(\frac{r_{o1}}{r_{i1}}\right)^{2-\beta_E} - 1}\right]^{\frac{1}{\beta_E}}}$$

$$\boxed{\mathrm{H}_{DC}(r_{i1}, r_{i2}, r_{o1}, r_{o2}, V_{DC,1}, V_{DC,2}, W_{C1}, W_{C2}, \beta_E, a, b, \lambda_{Td}) = \left[\frac{\left(\frac{r_{o2}}{r_{i2}}\right)^{2-\eta_2} - 1}{\left(\frac{r_{o1}}{r_{i1}}\right)^{2-\eta_1} - 1}\right]^{\frac{1}{\beta_E}}}$$

If no radial enlargement exhist, i.e. only enlargement in length:

$$\boxed{\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta_E}}}$$

The enlargement law for DC cables

Cavo 1: 350 kV – 1000 mm^2 – E_m = 16 kV/mm
Cavo 2: 350 kV – 1000 mm^2 – E_m = 18 kV/mm

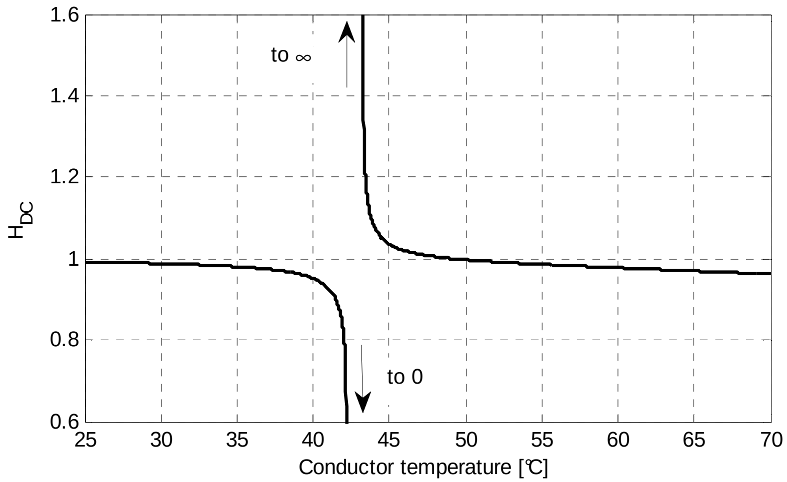
Application of brushing process and spline interpolant:

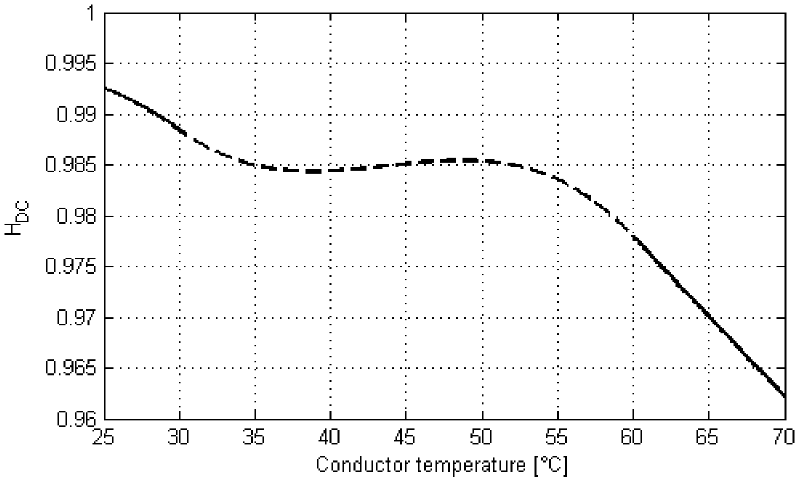
* 25 – 55 °C reduction of the max E in the insulation walls and increase of ΔE ($E_2 - E_1$)

The former give rise to a reduction of H_{DC} since for the enlargement process cable #1 shall have a lower dielectric strength, the latter gives rise to an increase of H_{DC} since a reduction of electric field on both cable gives a higher benefit to cable #2 that is the one more stressed. Such counterbalance effect can be an explanation of a quite constant behavior of the H_{DC} function in such temperature range.

* Above 55 °C increase of the max E in the insulation walls and ΔE ($E_2 - E_1$) becomes quite constant

the reduction of the H_{DC} function is mainly a consequence of the absolute electric field values increase in the insulation wall of both cables while the maximum electric field difference between the two cables is quite constant.





The enlargement law for DC cables

Cavo 1: 350 kV – 1000 mm^2 – E_m = 16 kV/mm
Cavo 2: 350 kV – 1000 mm^2 – E_m = 18 kV/mm

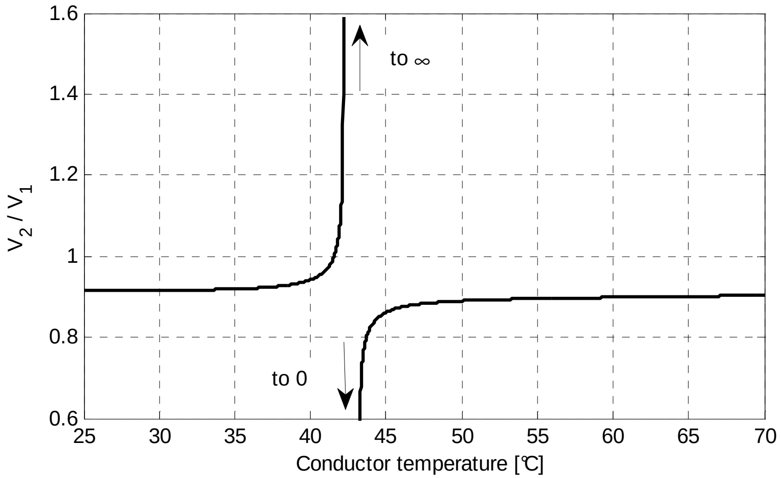
Application of brushing process and spline interpolant:

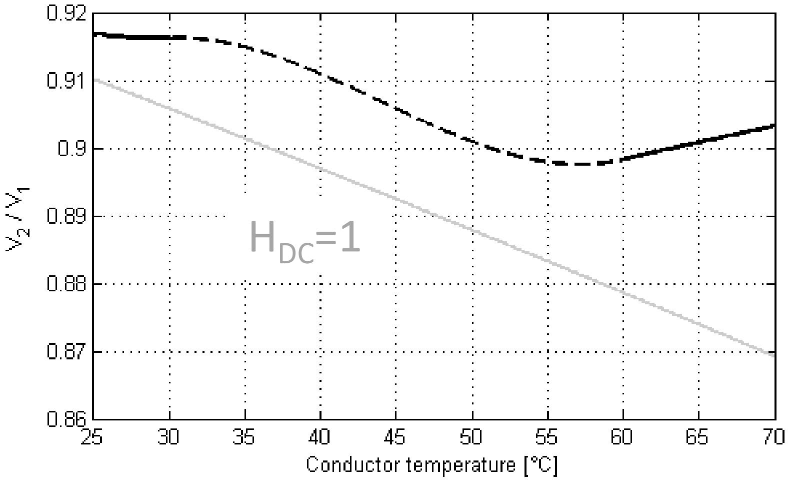
* 25 – 55 °C reduction of the max E in the insulation walls and increase of ΔE ($E_1 - E_2$)

cable #1 increases the breakdown voltage in respect of cable #4 since the absolute value of the maximum electric field on the insulation wall of both cables decreases with temperature. Cable #1 has lower value of maximum electric field than cable #2. The rate of decrease is lower for cable #1..

* Above 55 °C increase of the max E in the insulation walls and ΔE ($E_2 - E_1$) becomes quite constant

the maximum electric field in the insulation wall of both cables turns to increase but the increasing rate is quite the same for both cables and consequently the breakdown voltage of cable #1 reduces faster than that of cable #2 for the larger volume of cable #1.





The enlargement law for DC cables

❖ 2 extruded HVDC cables with same conductor (Cu) and insulation (XLPE), but different insulation thickness: cable 1 ≡ 12 mm (200 kV); cable 2 ≡ 20 mm (300 kV)

❖ From the 63.2% breakdown voltage of a length L_1=10 m of the 200 kV cable, V_1, evaluate the 63.2% breakdown voltage of the 300 kV cable, V_2, vs. cable length, L_2, for:

- two conductor temperatures, 25 °C (unloaded cable) and 70 °C;
- three values of shape parameter β, i.e. 5, 10, 15

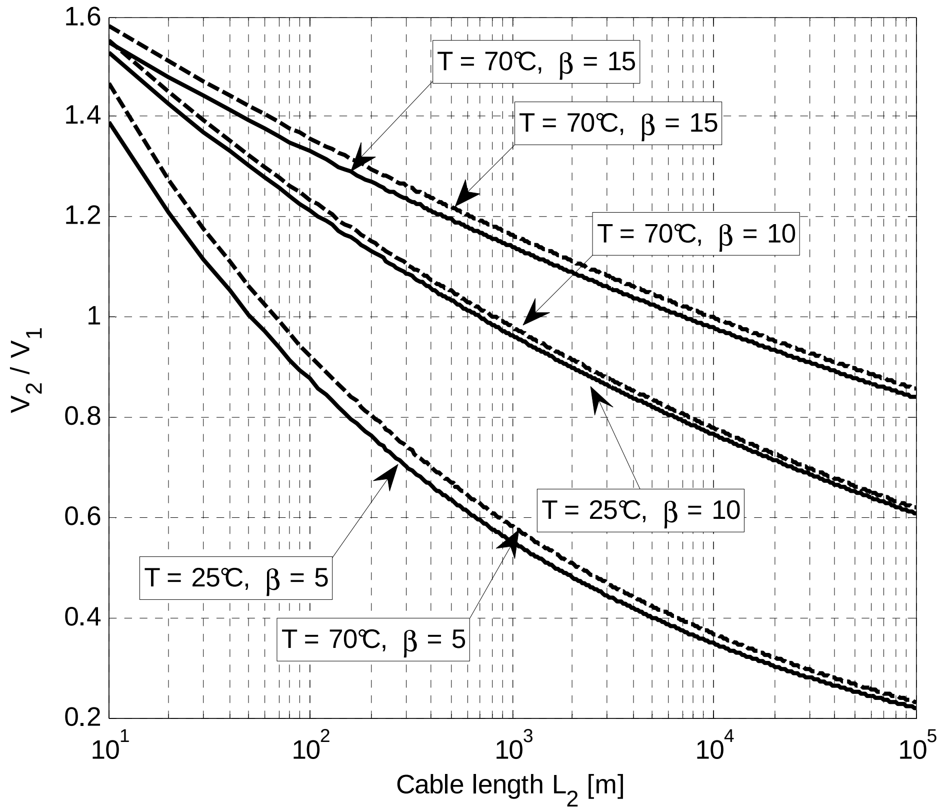
	dimensions	**200 kV cable**	**300 kV cable**
copper cond.x-section	mm^2	1400	1400
r_i	mm	22	22
r_o	mm	34	42
a (after [5])	$°C^{-1}$	0.084	0.084
b (after [5])	mm/kV	0.0645	0.0645
$\lambda_{T,d}$	W/(m K)	0.286	0.286

The enlargement law for DC cables

Application of the law for HVDC cables: real cable designs (1)

- **For long HVDC cable lines, strong decrease of breakdown voltage with respect to test length**

- **Fastest decrease for the lowest value of β (lower β ⇒ higher inhomogeneity of the compound ⇒ higher number of weak points over a given volume of insulation)**

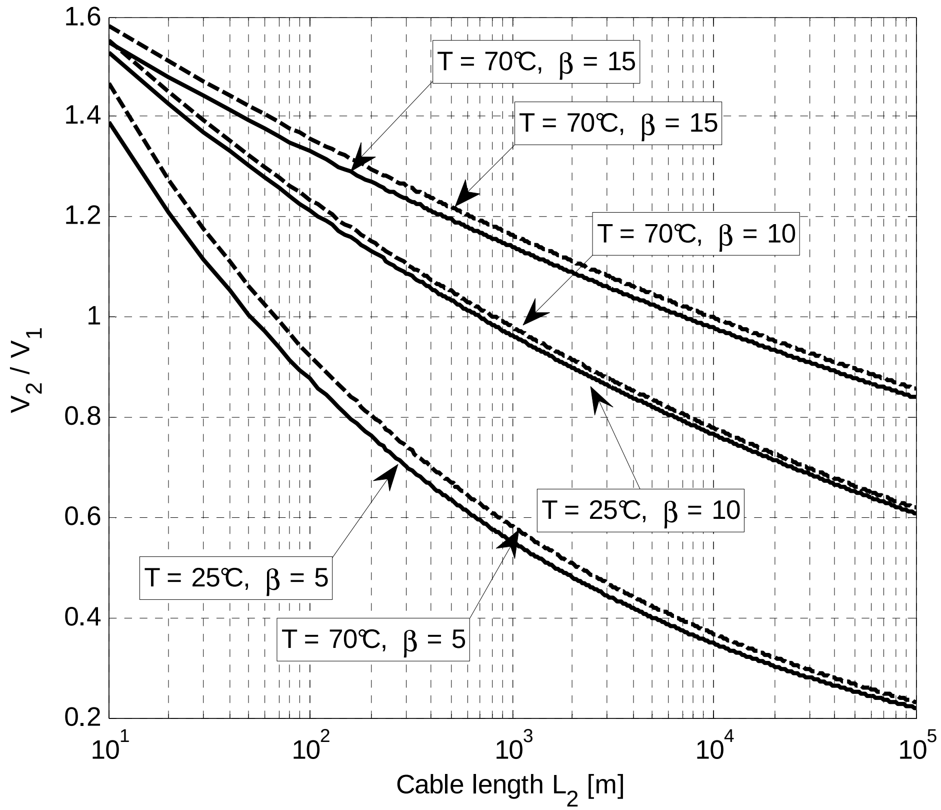


V_2/V_1 vs. L_2 for different β values at 25 °C and 70 °C.

The enlargement law for DC cables

Application of the law for HVDC cables: real cable designs (2)

- **A quicker decrease of breakdown voltage of the large cable with cable length is obtained for the loaded cable(70 ºC).**
- **Temperature does not seem to have a primary effect: ratio [V_2/V_1(70 ºC)]/[V_2/V_1(25 ºC)] ranges from 1.05 (β=5) to 1.02 (β=15) when $L_2=L_1=10$ m, and is the same when $L_2=100$ km**



V_2/V_1 vs. L_2 for different β values at 25 °C and 70 °C.

The enlargement law for DC cables

Conclusions (1)

➢ **The new enlargement law for HVDC cables accounts for some aspects peculiar of such cables:**

1) **the dependence of DC electric field not only on geometry (inner and outer radii of the insulation, as in the AC case), but also on the volume electrical resistivity of the insulation;**

2) **the dependence of electrical resistivity on electric field and temperature;**

3) **the role played by the heat dissipated through the cable layers;**

4) **the role played by insulation thermal resistivity.**

The enlargement law for DC cables

Conclusions (2)

- **The application shows a major role played by length and a minor role played by temperature on the strong reduction of breakdown voltage with cable length.**
- **The effect of space charges in this enlargement law is not considered.**
- **Joints are not taken into account.**

M. Marzinotto "Experimental Validation of the Volume Effect in the Statistical Enlargement Law for Cable Lines", proceedings of the Nordic Insulation Symposium NORDIS 07, Lyngby, Copenhagen, Denmark, June 11-13, 2007.

Life model considering the enlargement law

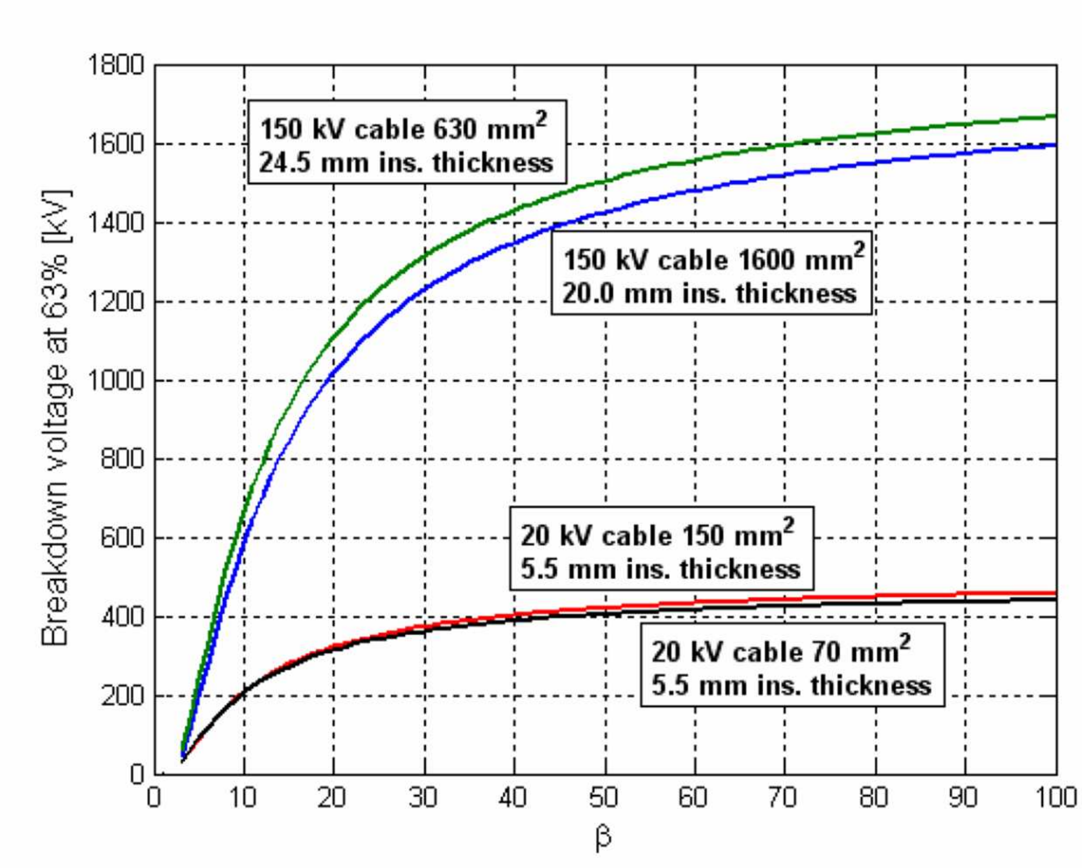
Radial and length enlargement

$$t_P(E_2,T)=t_{oP}(E_o,T_o)\frac{\left[-\ln(1-P_t)\right]^{\frac{1}{\beta_t}}}{\left[-\ln(1-P_{ot})\right]^{\frac{1}{\beta_{ot}}}}\left\{\frac{E_2}{E_o}\left[\frac{L_2}{L_1}\left(\frac{r_{i2}}{r_{i1}}\right)^2\frac{\left(\frac{r_{o2}}{r_{i2}}\right)^{2-\eta_2}-1}{\left(\frac{r_{o1}}{r_{i1}}\right)^{2-\eta_1}-1}\frac{\ln(1-P_{E1})}{\ln(1-P_{E2})}\right]^{\frac{1}{\beta_E}}\right\}^{-(n_o-b_L cT)}\exp(-B_L cT)$$

Length enlargement only

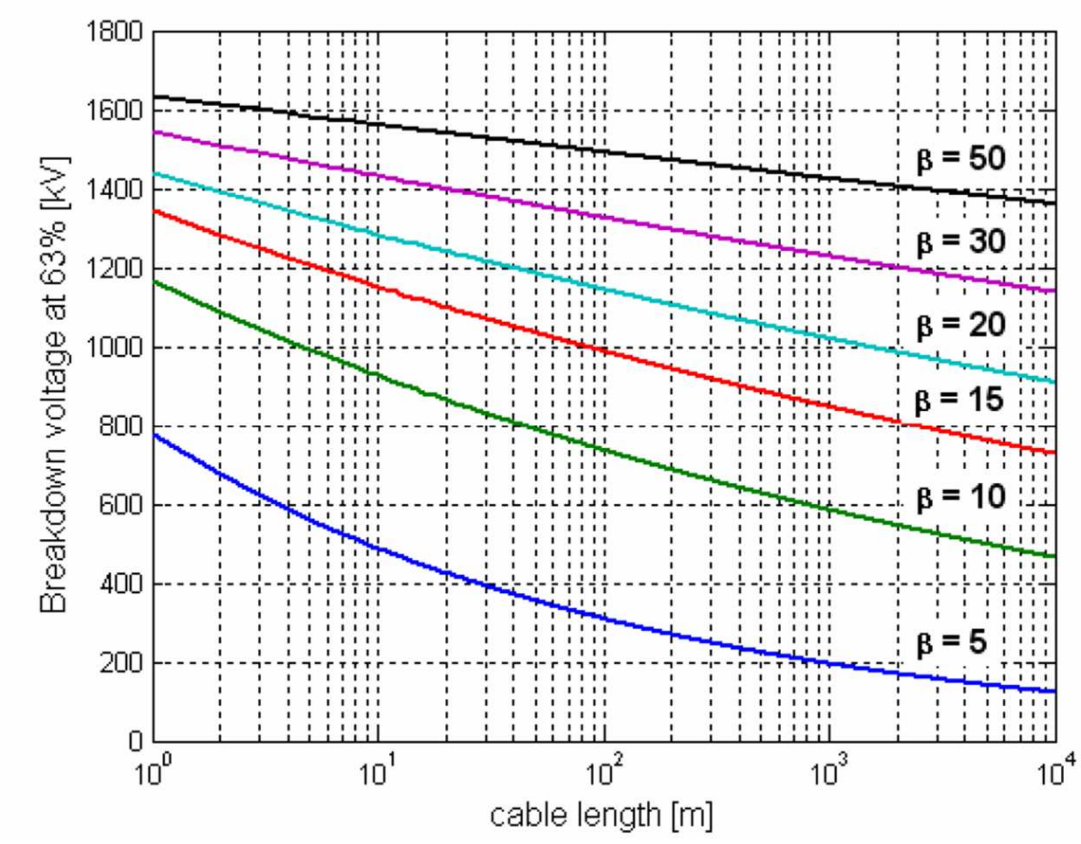
$$t_P(E_2,T)=t_{oP}(E_o,T_o)\frac{\left[-\ln(1-P_t)\right]^{\frac{1}{\beta_t}}}{\left[-\ln(1-P_{ot})\right]^{\frac{1}{\beta_{ot}}}}\left\{\frac{E_2}{E_o}\left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta_E}}\right\}^{-(n_o-b_L cT)}\exp(-B_L cT)$$

Effect of Weibull shape parameter on the enlargement law



M. Marzinotto, "On the application of the enlargement law to cable lines", proceedings of IEEE Power Tech 2005, St. Petersburg, Russia, June 27-30, 2005.

Effect of Weibull shape parameter on the enlargement law



M. Marzinotto, "On the application of the enlargement law to cable lines", proceedings of IEEE Power Tech 2005, St. Petersburg, Russia, June 27-30, 2005.

Weibull parameter estimation

Different methods of Weibull parameters estimation

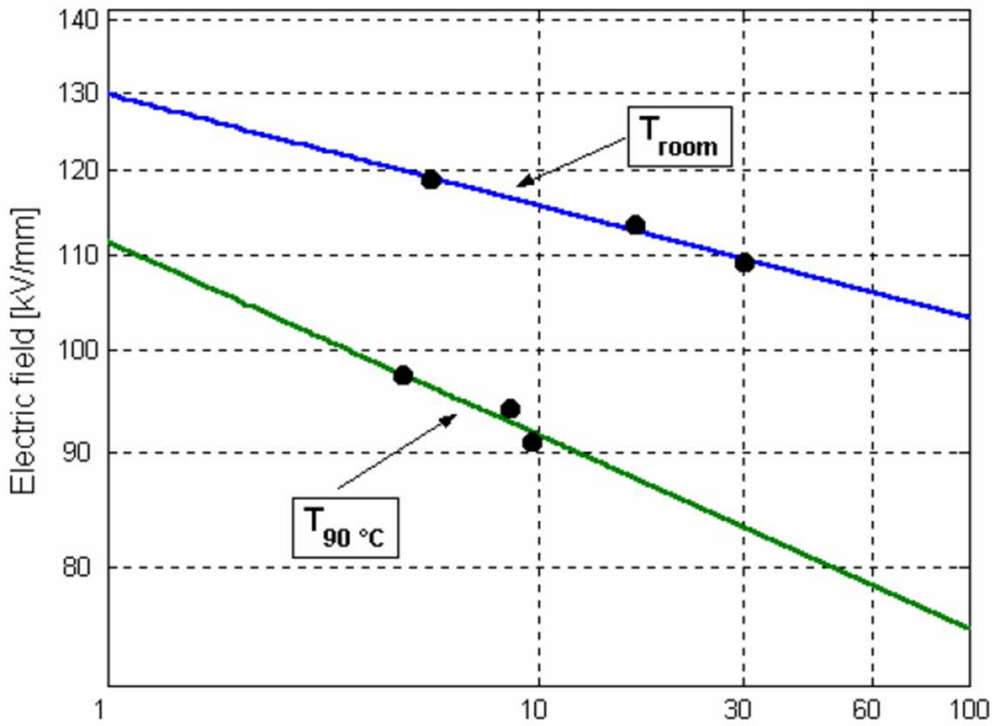
Method of estimation	Acronym	Reference
Thiel	Th	[10]
Modified Thiel	Tm	[10]
White	Wh	[6]
Bain-Engelhardt	BE	[7]
Mann	Mn	[8]
Johns-Lieberman	JL	[9]
Seki-Yokoyama	SY	[11]
Moments	Mt	[4]
Enel	En	[3]

Parametri campione 1												
n	5		6		7		8		9		10	
Stimatore	α [kV/mm]	β	α [kV/mm]	β	α [kV/mm]	β	α [kV/mm]	β	α [kV/mm]	β	α [kV/mm]	β
White	132,1	9,76	131,1	11,19	130,6	12,9	128,9	11,58	128,1	12,15	126,7	11,04
Bain-Engelhardt	134,2	8,67	133,6	9,24	131,2	13,49	129,6	11,92	129,1	12,1	127,7	10,94
Mann	133,2	10,92	132,2	11,79	131,6	12,85	129,9	11,62	129,1	11,92	127,6	10,91
Johns-Lieberman	130,4	11,58	130,1	12,19	130	13,01	128,3	11,71	127,8	11,89	126,3	10,86
Momenti	133,6	9,28	132,3	10,89	131,7	12,45	129,9	11,53	128,9	12,53	127,4	11,5
ENEL	132,8	8,19	131,9	9,48	131,5	10,56	129,7	9,97	128,8	10,82	127,3	10,3
Thiel	132,2	10,05	130,4	12,01	130,1	15,28	127,6	13,85	126	15,27	124,7	13,07
Thiel mod.	132,2	9,15	132,1	11,92	132,3	14,14	130,1	11,87	129,8	13,22	128,4	12,3

A. Galati, M. Marzinotto, C. Mazzetti, "Sensitivity of impulsive dielectric strength for the probabilistic coordination of cable lines insulation", proceedings of Nordic Insulation Symposium NORDIS 05, Trondheim, Norway, 13-15 June, 2005.

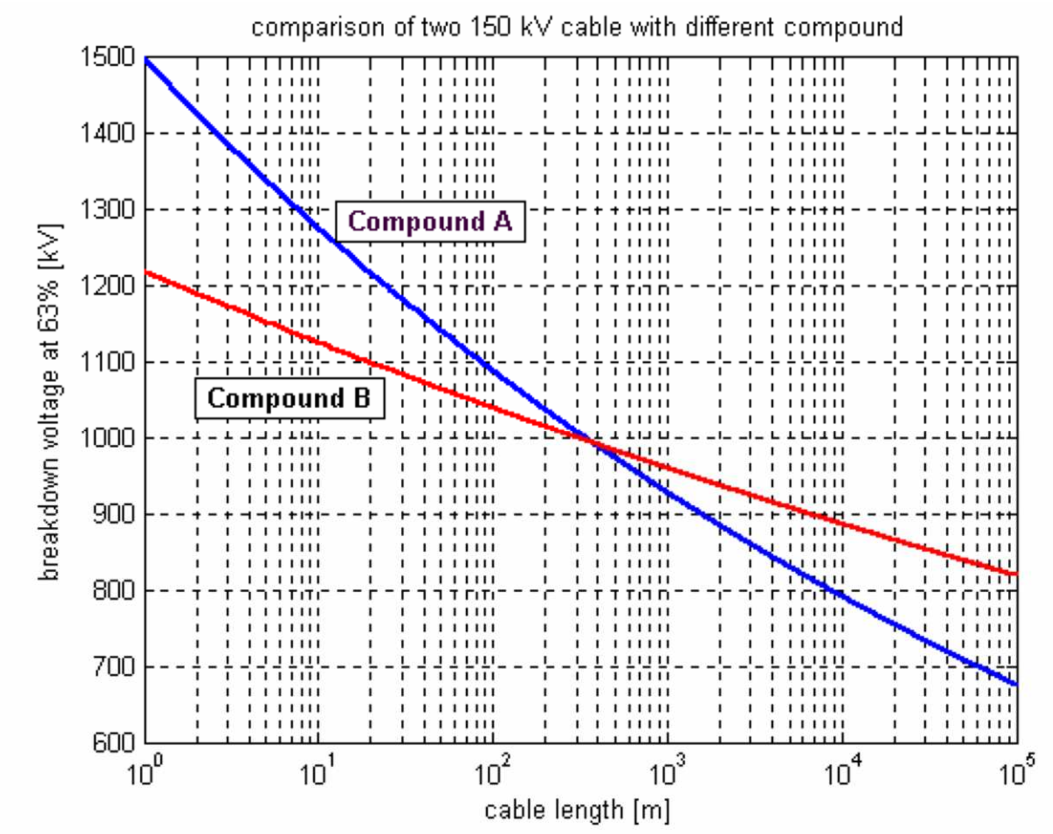
A. Galati, M. Marzinotto, C. Mazzetti, "Weibull parameters estimation from uncensored test data contaminated with outliers", proceedings of XIV International Symposium on High Voltage Engineering ISH 2005, Beijing, China, August 25–29, 2005.

IPM for impulsive stress



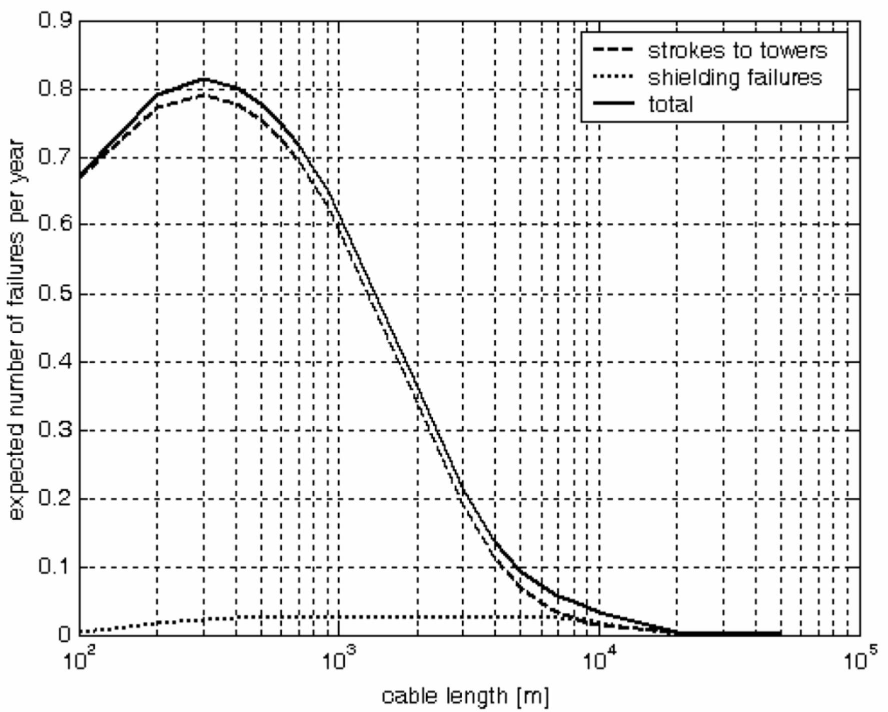
M. Marzinotto, C. Mazzetti, M. Pompili, P. Schiaffino, "EPR lifetime under impulsive voltage stress", *Conference on Electrical Insulation and Dielectric Phenomena CEIDP 2005*, Nashville, Tennessee, USA, October 16 – 19, 2005.

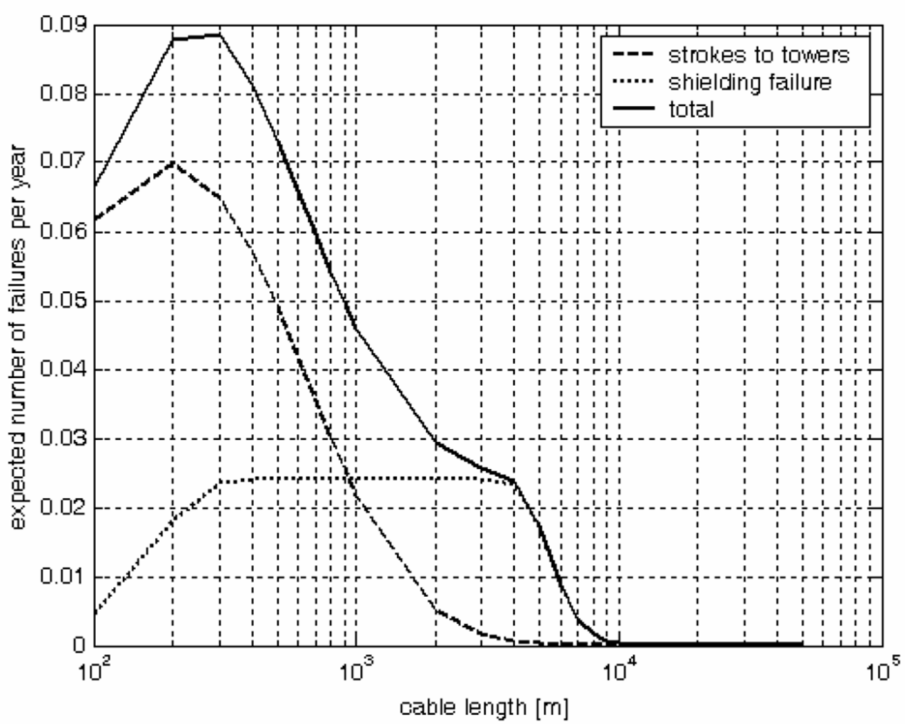
Enlargement law for comparisons



M. Marzinotto, "On the application of the enlargement law to cable lines", IEEE Power Tech 2005, St. Petersburg, Russia, June 27-30, 2005.

Enlargement law and insulation coordination





$$R = \int_{-\infty}^{+\infty} f_S(V) F_F(V)\, dV$$

M. Marzinotto, C. Mazzetti, P. Schiaffino, "Statistical approach to the insulation coordination of medium and high voltage cable lines", proceedings of IEEE Power Tech 2005, St. Petersburg, Russia, June 27-30, 2005.

M. Marzinotto, C. Mazzetti, "Propagation of transients in extruded MV and HV cables considering typical thickness and resistivity values of commercial semiconductive compounds", proceedings of the International Power System Transients Conference IPST 2007, Lyon, France, June 4-7, 2007.

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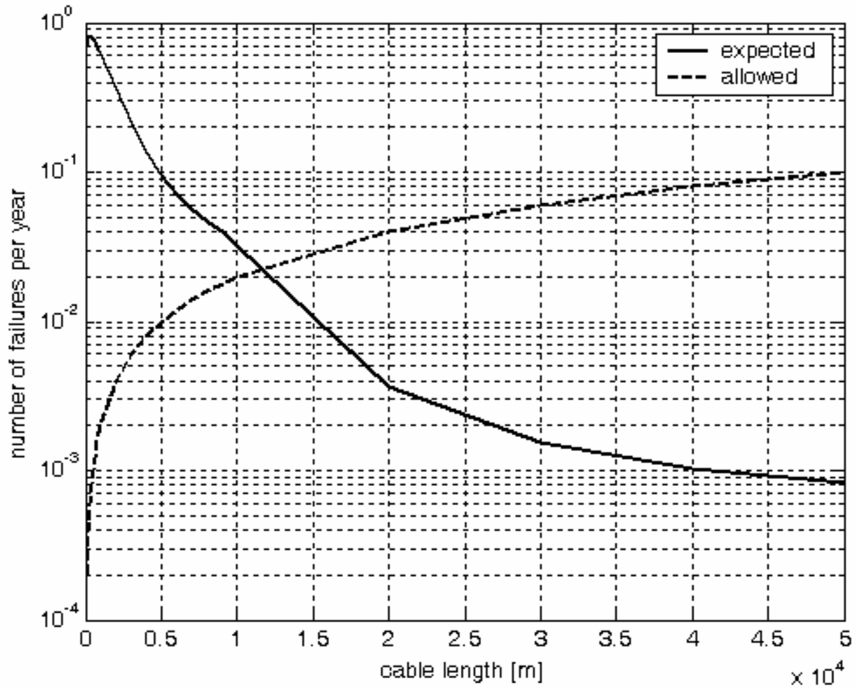
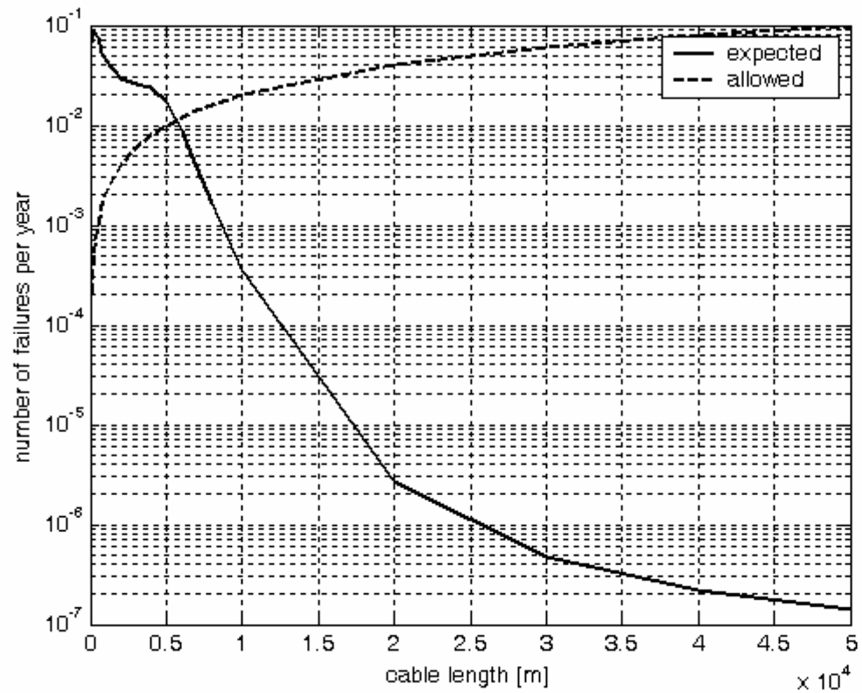
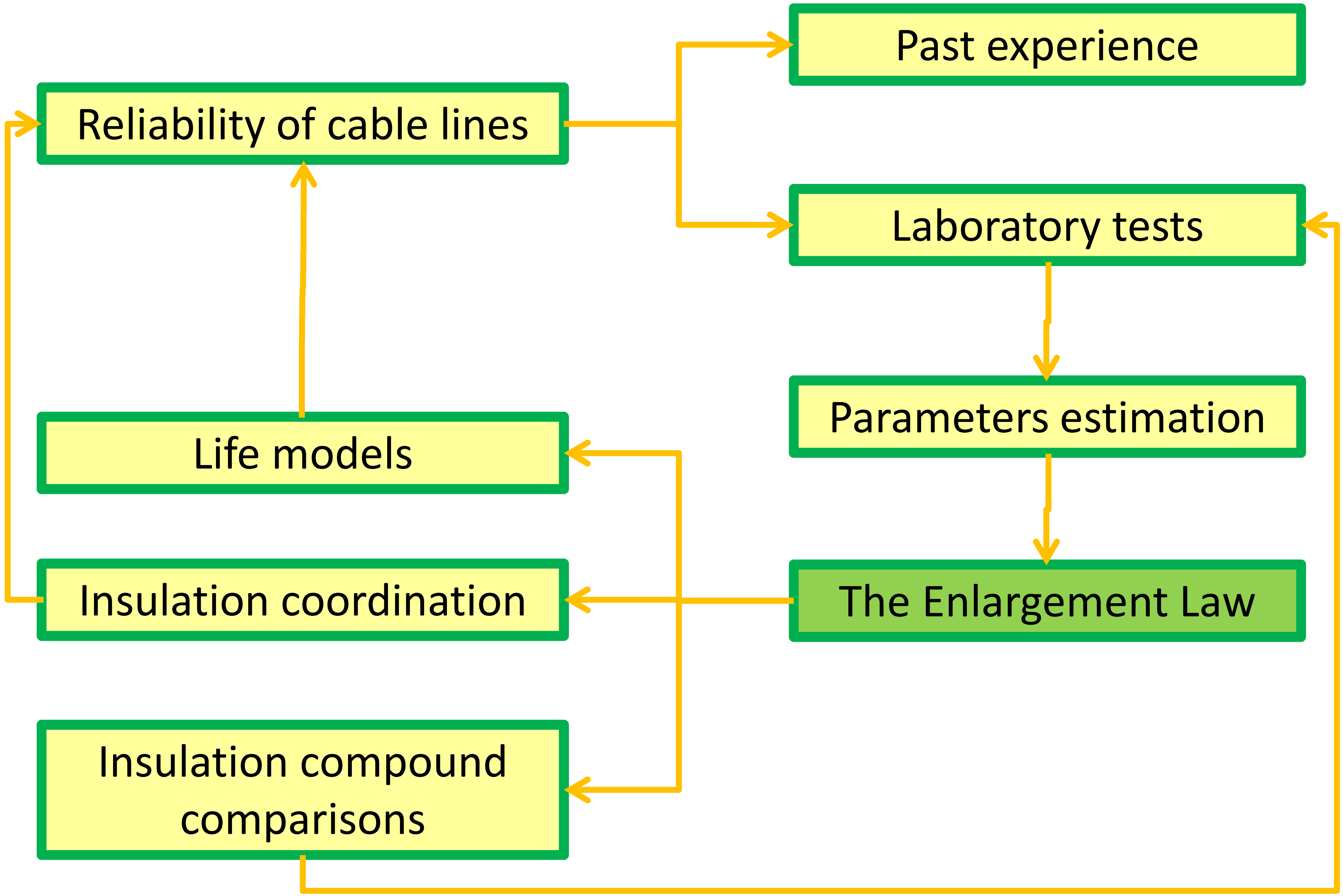




$$L_{IC} = \sum n \int_{-\infty}^{+\infty} f_S(V) F_F(V)\, dV$$

M. Marzinotto, "Relationship between Impinging and Stressing Overvoltages Statistical Distributions in Power Cable Lines", IEEE Power Tech 2007, Lausanne, Switzerland, July 1-5, 2007.

Close and Return



Thank you for your attention