CURRENT ISSUES ON LIGHTNING PROTECTION IN ELECTRIC POWER SYSTEMS, WITH PARTICULAR REFERENCE TO TRANSMISSION LINES

Presented at the University of Bologna

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Lightning and Power Lines

1) Lightning: Main cause of power line outages in T & D systems in the world. (In a global scale)

2) How lightning affects electric power systems:

MV lines ⇒ Direct hits
⇒ Close lightning

Remedial measures:

- Surge Arresters along the line,
- increase of Critical Flashover Voltage
- Use of overhead ground wire

HV, EHV, ~~UHV~~ ⇒ Direct strokes, (in high ρ areas)

Remedial measures

- Improved shielding angles
- Reduced Ground Footing Resistance
- Application of Surge Arresters

Introduction

- Discussion on most relevant topics in the area, addressing some of the on-going works in IEEE and CIGRE WG´s
- Modeling aspects
- Description of some experimental work
- Conclusions

Topics of Discussion

- Lightning parameters update
  - Positive and negative flashes
  - Peak-current as predictor of other parameters
  - Ground flash density
  - Multiple-stroke lightning and Surge Arresters for power line protection
- Influence of lightning on power lines
- Lightning protection trends

Table 1. Lightning current parameters for negative flashes, adapted from Berger et al (1975)

Parameters	Units	Sample size	Value exceeding in 50 % of the cases
Peak current (minimum 2 kA)			
First strokes	kA	101	30
Subsequent strokes		135	12
Charge (total charge)			
First strokes	C	93	5.2
Subsequent strokes		122	1.4
Complete flash		94	7.5
Impulse charge			
(exduding continuing current)	C		
First strokes		90	4.5
Subsequent strokes		117	0.95
Front duration (2 kA to peak)			
First strokes	μs	89	5.5
Subsequent strokes		118	1.1
Maximum di/dt			
First strokes	kA/μs	92	12
Subsequent strokes		122	40
Stroke duration			
(2 kA to half peak value on the tail)	μs		
First strokes		90	75
Subsequent strokes		115	32
Action integral ($\int i^2 dt$)	A^2s		
First strokes		91	$5.5x\ 10^4$
Subsequent strokes		88	$6.0x10^3$
Time interval between strokes	ms	133	33
Flash duration			
All flashes	ms	94	13
Excluding single-stroke flashes		39	180

Table 2. Lightning current parameters for positive flashes, adapted from Berger et al. (1975)

Parameters	Units	Sample Size	Value exceeding in 50 % of the cases
Peak current (minimum 2 kA)	kA	26	35
Charge (total charge)	C	26	80
Impulse charge (excluding continuing current)	C	25	16
Front duration (2 kA to peak)	μs	19	22
Maximum di/dt	kA/μs	21	2.4
Stroke duration (2 kA to half peak value on the tail)	μs	16	230
Action integral ($\int i^2 dt$)	A^2s	26	6.5×10^5
Flash duration	ms	24	85

On lightning parameters from direct measuments

- Guerrieri, S., Nucci, C. A., Rachidi, F., and Rubinstein, M., (1998), presented a comprehensive description of the effects of stucture reflections in direct measurements of lightning currents.
- This effect tends to produce a "contamination" of the waveform that affects:

  1. The lightning peak current value

  2. The radiated electric fields

  The above can have important implications on:

1. Peak current distributions derived from such studies, generally overestimating the mean values.
2. Peak current and rate of rise inferred from vertical electric fields radiated from distant lightning (should be addressed by Lightning Location System technologies)

On direct lightning:

- In spite of the described limitations, parameters of negative and positive lightning discharges, based on direct current measurements in Switzerland, are still considered as the most reliable data (except for the maximum rate of rise and perhaps front duration of current) in both lightning research and lightning protection studies.
- Roughly half of all cloud-to-ground discharges strike ground at more than one point with the spatial separation between the channel terminations being up to many kilometers.

On lightning parameters inferred from remote sensing of electric and magnetic fields

- Although the precise current waveshape is difficult to deduce from the electric or magnetic field waveform, the peak current can be estimated to within 20% from the measured broadband peak field using a simple Transmission Line Model (TLM).

  - Empirical studies by Willett et al. (1989) and Rakov et al. (1992) have demonstrated a strong linear relationship between peak electric field and peak current, suggesting that the one free parameter in the model – return stroke vertical velocity – is fairly constant.
- It is unknown if the same model parameters apply for very low and very high peak currents, for first strokes of negative flashes, or for positive flashes. Regarding negative first strokes, it is worth noting that median peak current estimates derived from magnetic-field-based measurements in the U.S. NLDN are 20-30% lower than those obtained by Berger and Garbagnati.

  -Similar differences were recently reported by Diendorfer et al. (1998b). These issues are areas of active research.

On lightning parameters inferred from remote sensing of electric and magnetic fields

- If the basic field measurement sensors have not been calibrated, which must be done on-site for electric field measurements, then there is no possibility for accurate estimates
- If the terrain and conductivity properties are not properly accounted for, then individual sensor measurements can produce errors in the average field strength estimate (Diendorfer et al., 1998a).
- Finally, networks of long baselines are more likely to miss lightning of small peak amplitudes. This results in a shift of the peak current distribution towards higher values.

These practical problems do not prevent an individual lightning detection network from providing useful relative peak current estimates for its own coverage area, but they can prevent inter-comparison of data obtained from different networks.

Lightning current as predictor of other lightning parameters

- Recent work (Dellera 97) illustrates the relationship between peak current and these lightning parameters, using data from the work reported in (Berger and Garbagnati,1984 and Anderson and and Ericksson, 1980).
- Dellera shows how to employ the correlation between peak current and other lightning parameters to obtain estimates of the total probability of a specific range of simultaneous values (e.g., $I>I_o$ and $Q>Q_o$), thereby refining the probability estimates for the conditions under which a lightning-related failure may occur.

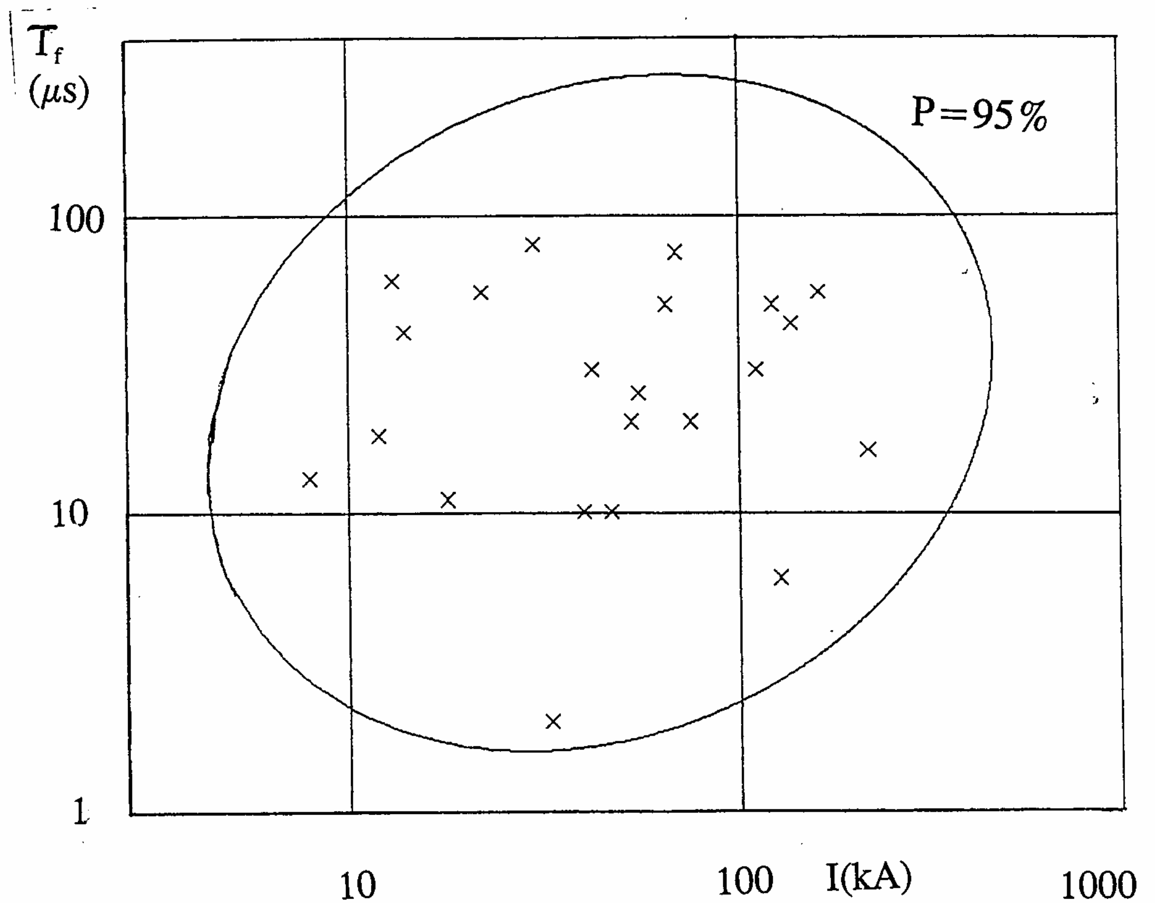


Fig. 4 Correlation between front duration T_f and peak value of the current I for positive polarity current with P=95% contour ellipse. Correlation coefficient r=0.18.
x recorded values

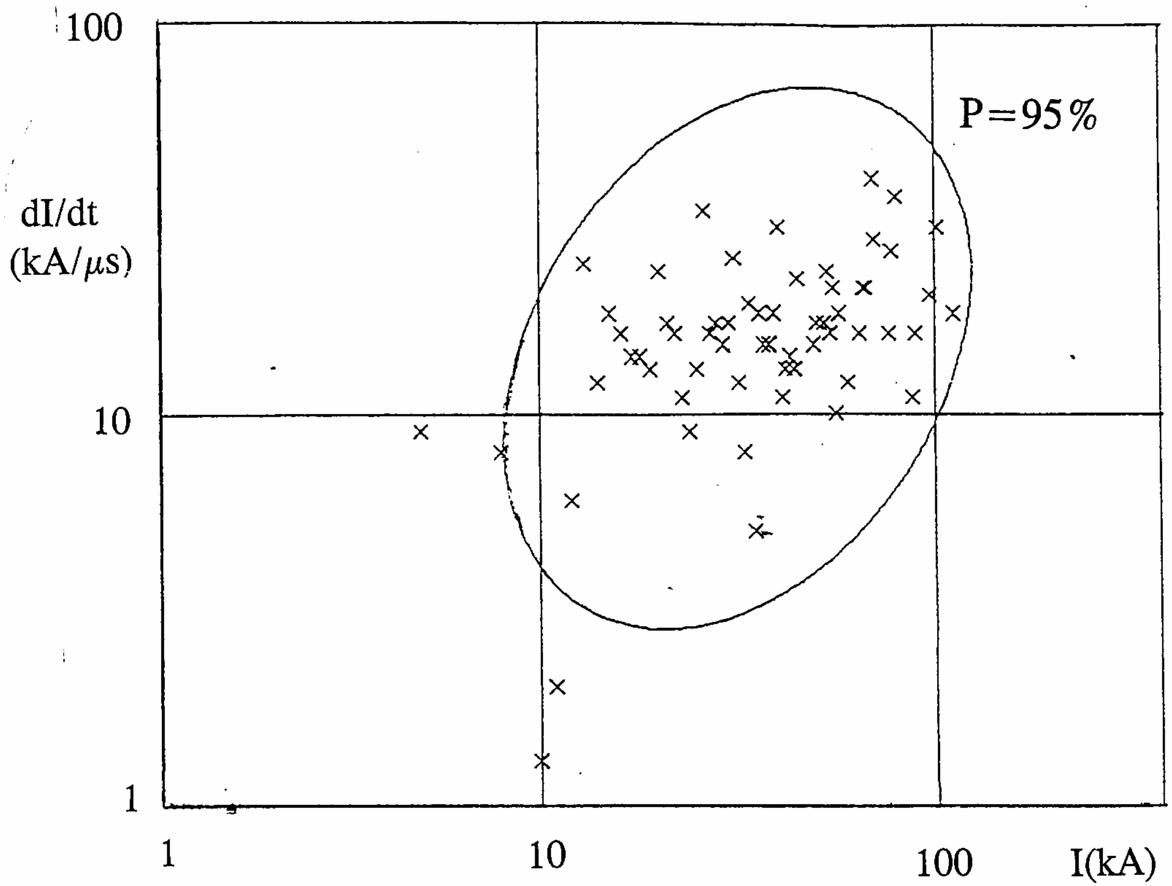


Fig. 5 Correlation between rate of rise dI/dt and peak value of the current I for the first impulses of negative polarity flashes with P=95% contour ellipse. Correlation coefficient r=0.32.

x Recorded values

Correlation between peak current and other lightning parameters, after (Dellera, 1997)

POSITIVE FLASHES

- Lightning Parameter — Correlation (corr. coeff) — Data Source
- Front Time (Tfront) — Low (0.18) — Berger
- peak rate-of-rise (dI/dt) — Moderate (0.55) — Berger
- Impulse Charge (Qimp) — High (0.77) — Berger
- Flash Charge (Qflash) — Moderate (0.59) — Berger
- Impulse Action Integral (Wimp) — -----
- Flash Action Integral (Wflash) — High (0.76) — Berger
- NEGATIVE FIRST STROKES
- Lightning Parameter — Correlation (corr. coeff) — Data Source
- Front Time (Tfront) — Low (---) — Weidman and Krider, 1984
- peak rate-of-rise (dI/dt) — Moderate/high (---) — Weidman and Krider, 1984
- Impulse Charge (Qimp) — High (0.75) Berger
- Flash Charge (Qflash) — Low (0.29) — Berger
- Impulse Action Integral (Wimp) — High (0.86) — Berger
- Flash Action Integral (Wflash) — ---
- (1) Inferred from electric field measurements propagated over salt water.
- NEGATIVE SUBSEQUENT STROKES
- Lightning Parameter — Correlation (corr. coeff) — Data Source
- Front Time (Tfront) — Low (0.13) Fisher, 1993
- peak rate-of-rise (dI/dt) — High (0.7-0.8) — Fisher, 1993; Leteinturier, 1991
- Impulse Charge (Qimp) — ----
- Impulse Action Integral (Wimp) — ----

(2) 30-90% slope, which corresponds to an "average" dI/dt (triggered lightning studies).

Probability of failure of a surge arrester

Stress in surge arresters is due to:

- Peak value of lightning current
- Charge in the flash

Failure probability determination:

$$P(I \leq Ic;Q\geq 2Qmax) = \int_{-\infty}^{Ie} \int_{2Qmax}^{\infty} p(\log I;\log Q)d(\log I)d(\log Q)$$

For example :

$P(I \leq 15\ kA;Q \geq 90As) = 15\%$

while taking only $P(Q \geq 90As) = 41\%$

Estimation of number of strikes to a transmission line:

- Average attractive radius on each side of a transmission line based jointly upon a simplified leader progression model and upon analysis of the observed incidence of lightning strikes to a number of practical transmission lines:

  $Ra = 14\ H_T^{0.6}$(meters), where H_T = average tower height in m.

- Expected average incidence of strikes to a line:

  NL=Ng(2 Ra + b)/10(strikes/100 km/year), where Ng = regional GFD and b = line width in m.

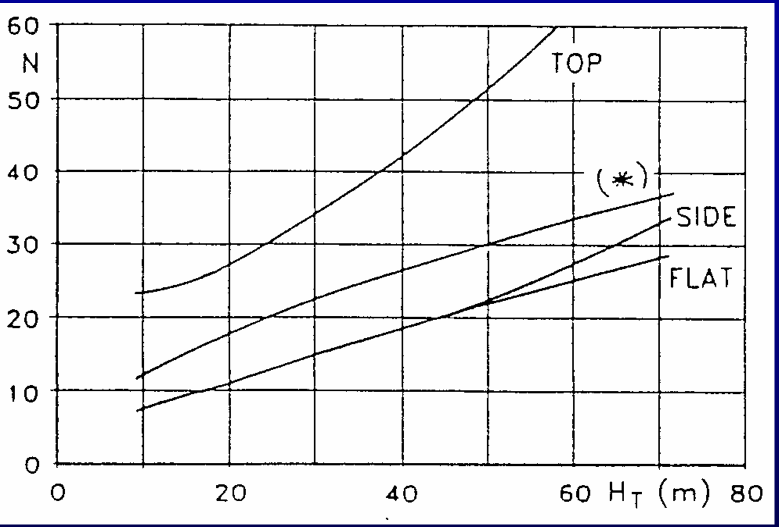
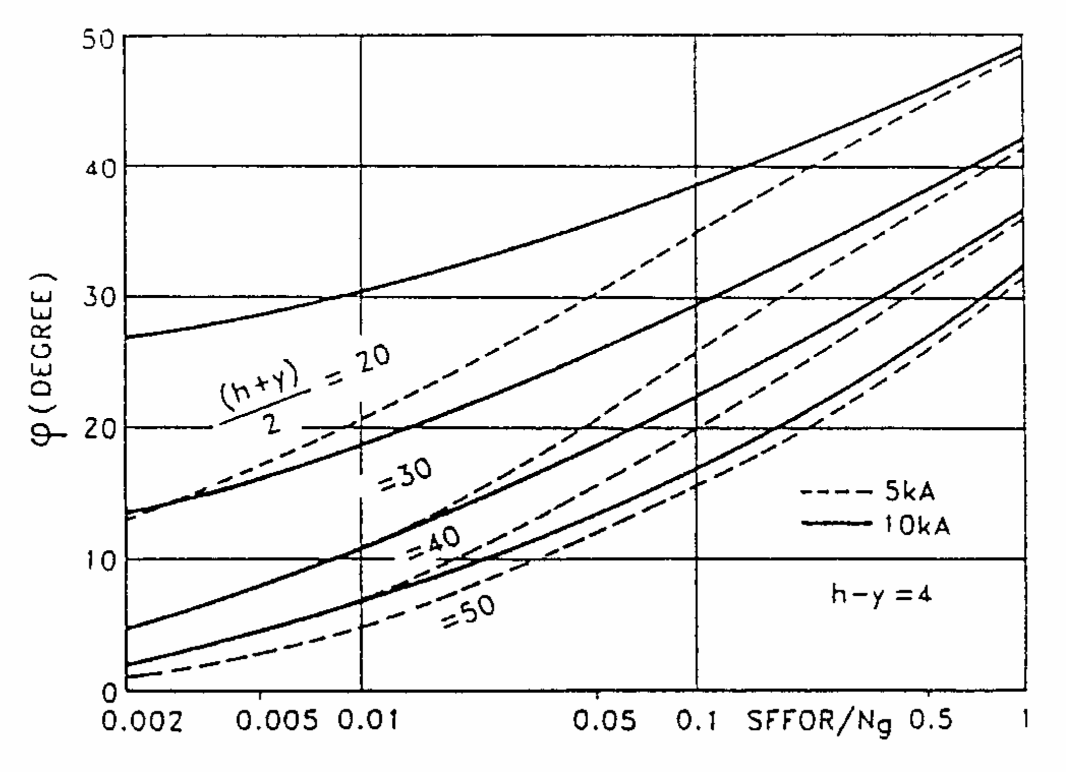


Fig 1.
Number of flashes to a line (per 100km/year) versus tower height for Ng = 1 - based upon leader propagation model(FLAT;SIDE;TOP) (*) Eriksson equation

Modeling aspects for lightning performance calculations in Transmission Lines

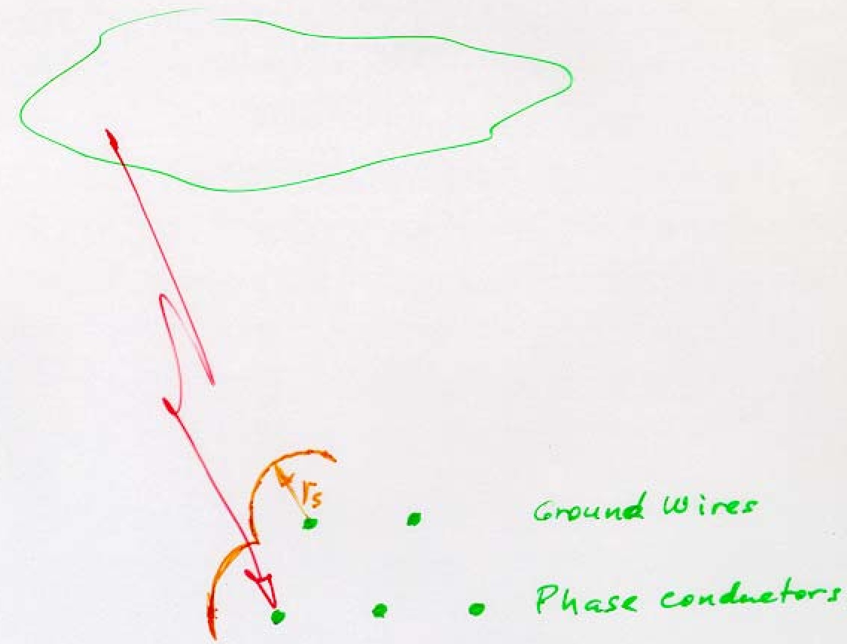
- a) Shielding failure estimates



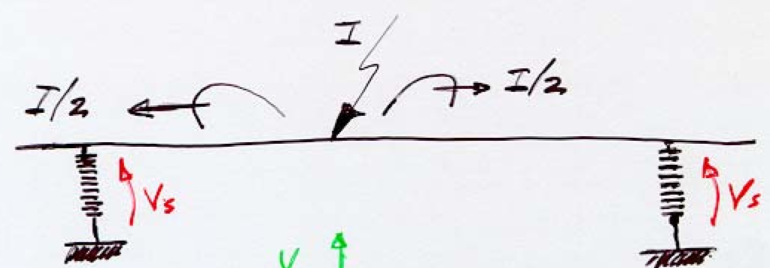
Example:

Let us take a design value of SFFOR= 0.05 per 100 km per year in an area with GFD=5, that produces a SFFOR/Ng = 0.01. For an avg. shield /phase conductor height of 30 m and a critical current of 5 kA, a shielding angle of 11 degrees is obtained. For same conditions but for GFD = 1, or a SFFOR/Ng = 0.05, a shielding angle of 21 degrees results. Alternatively, if SFFOR=1.0, for GFD =1, a shielding angle over 40 degrees may be adequate.

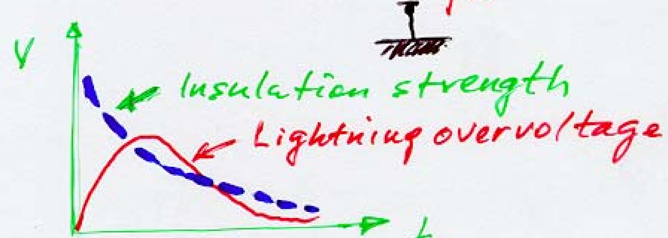
SHIELDING FAILURE:



Failure of the shielding wires to intercept the lightning strike

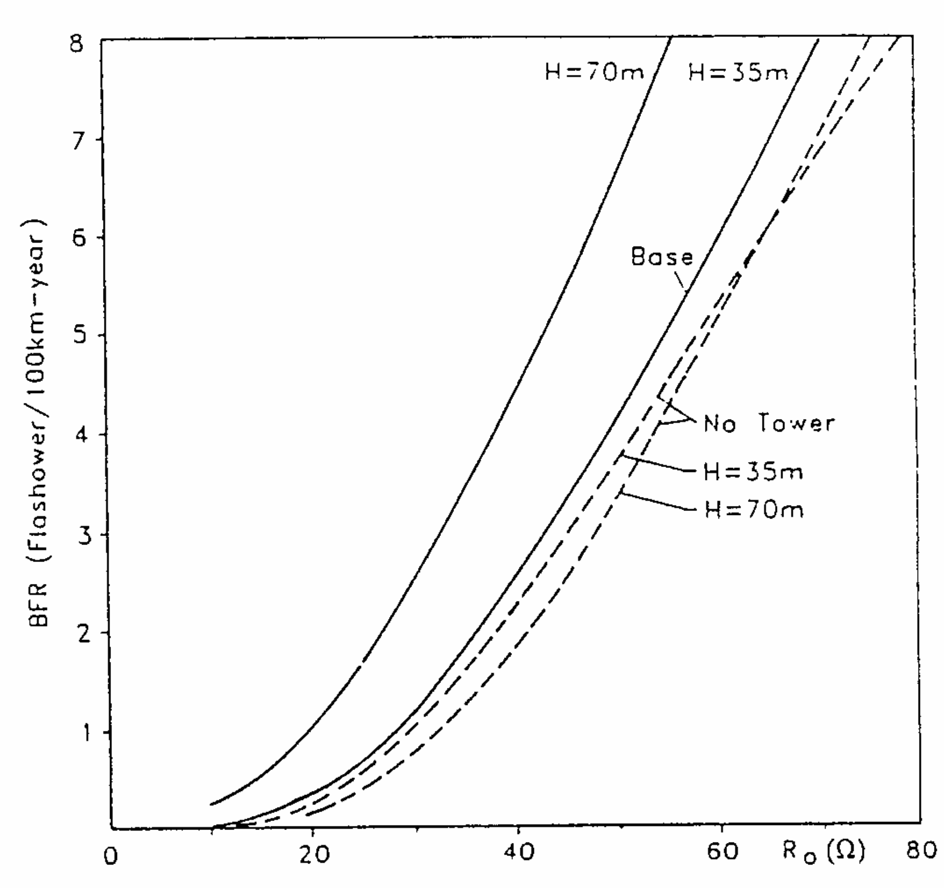


INSULATION BREAKDOWN:
IF $Z_c(I/2) > CFO$



Modeling aspects for lightning performance calculations in Transmission Lines

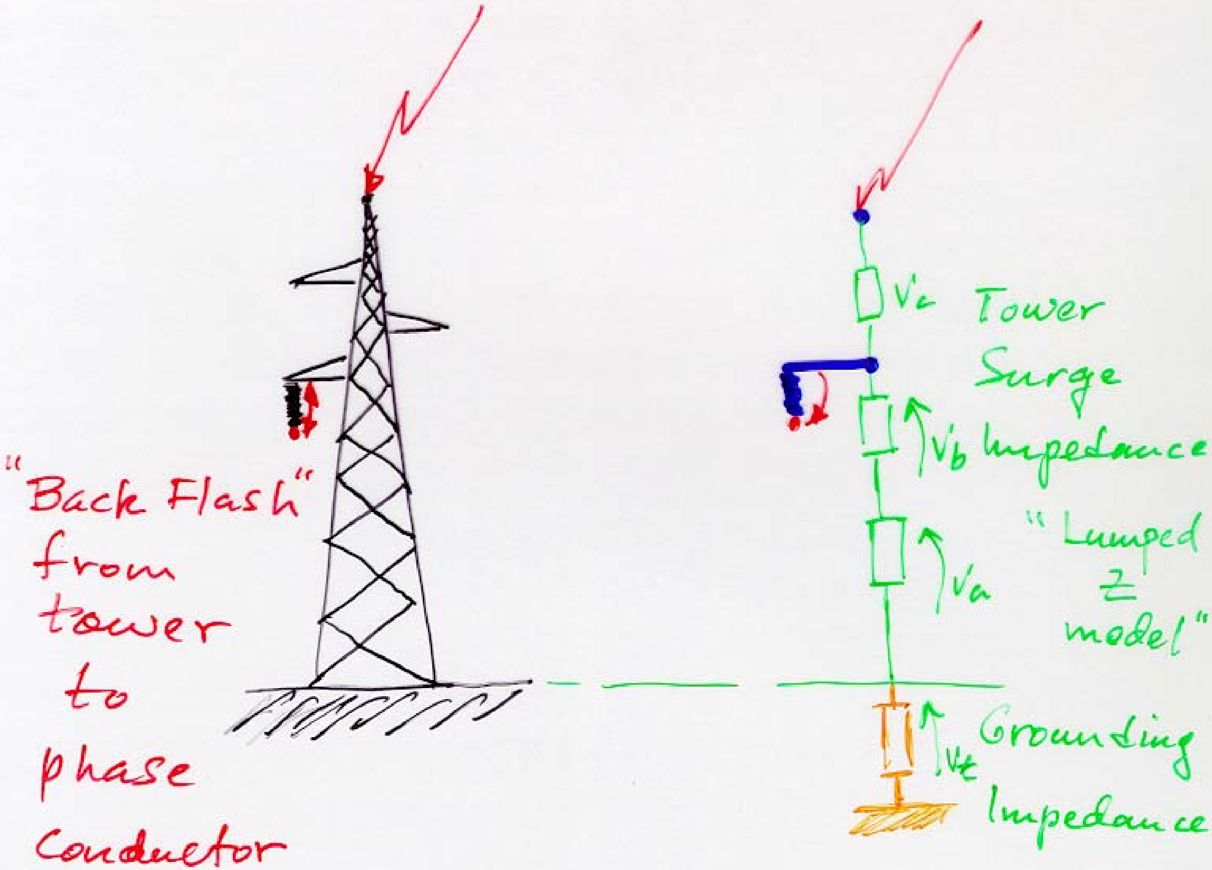
b1) Back flashover estimates



Effect of tower height. 230 kV double-circuit line.

ρ/Ro=20, 300 m span, U_{50}= 1400 kV. Ng = 4.

Backflashover:



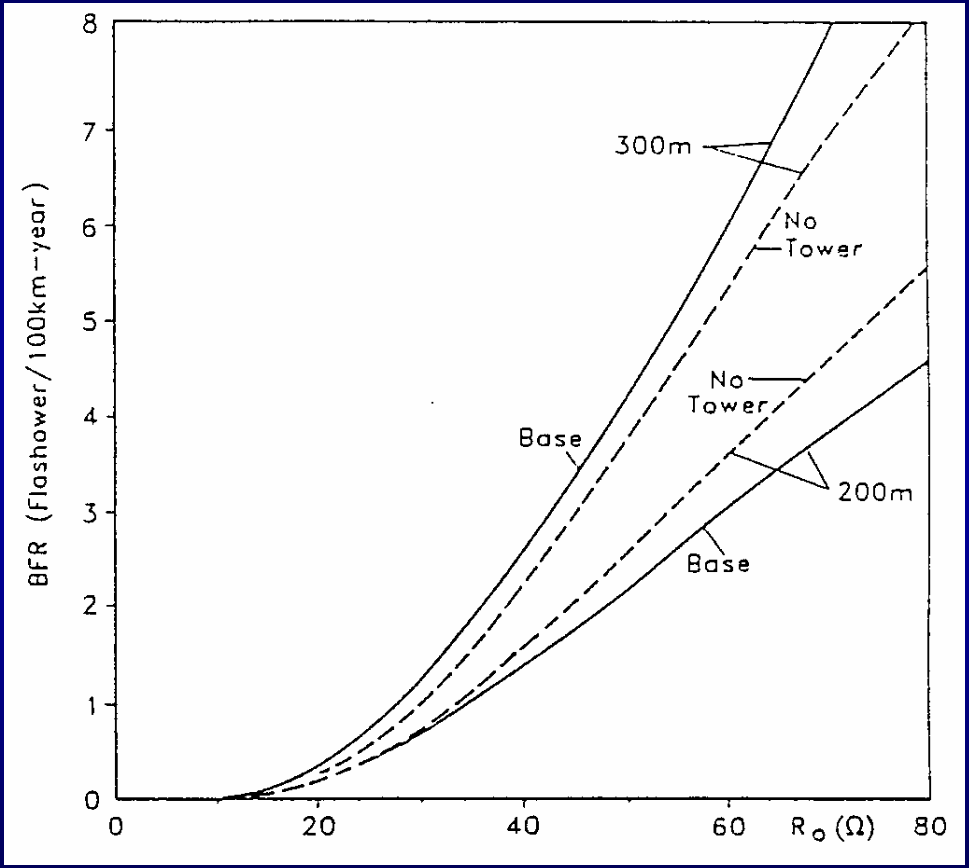
Breakdown criterion:

This phenomenon will take place if:

$(V_t + V_a + V_b) >$ CFO of line insulation

Modeling aspects for lightning performance calculations in Transmission Lines

b2) Back flashover estimates



Effect of span length. 230 kV double-circuit line.

$\rho/Ro = 20$; $U_{50} = 1400$ kV; Ng = 4.

STUDY OF LIGHTNING PERFORMANCE OF TRANSMISSION LINES IN MEXICO

Presented at University of Bologna

Sept. 6, 1999

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STUDY OF LIGHTNING PERFORMANCE OF TRANSMISSION LINES IN MEXICO

- 1) Lightning is the main cause of failures in the transmission system (115, 230 and 400 kV lines)
- 2) Aim of the study: To determine the reliability of different types of transmission towers presently used in standard line construction

Comisión Federal de Electricidad 400 kV system

ANEXO I.A "Red de 400 kV del Sistema Eléctrico Nacional"

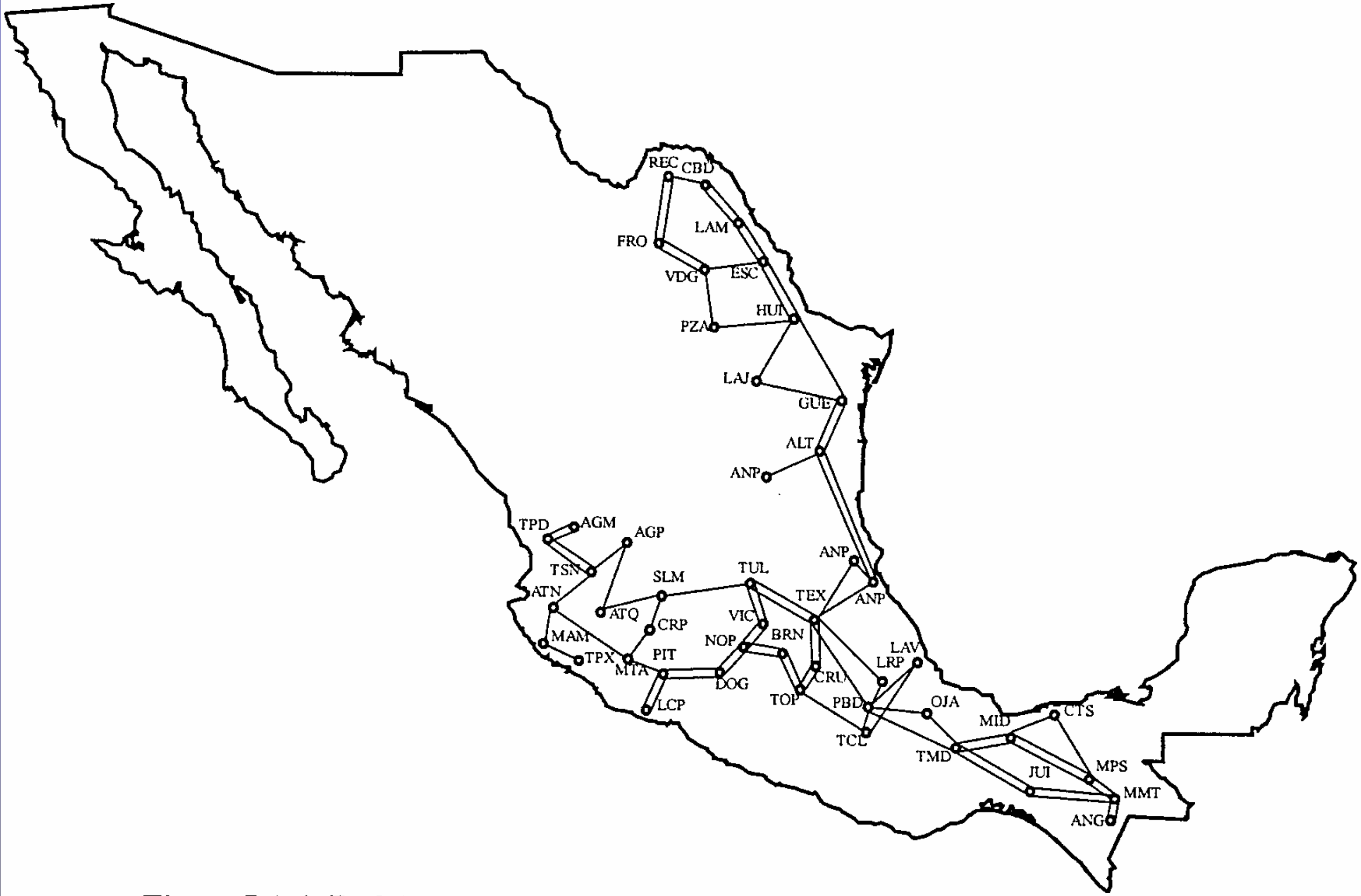


Figura I.A.1. Red de 400 kV del Sistema Eléctrico Nacional. Adaptada de [4].

Average GFD map of Mexico (1983-1993)

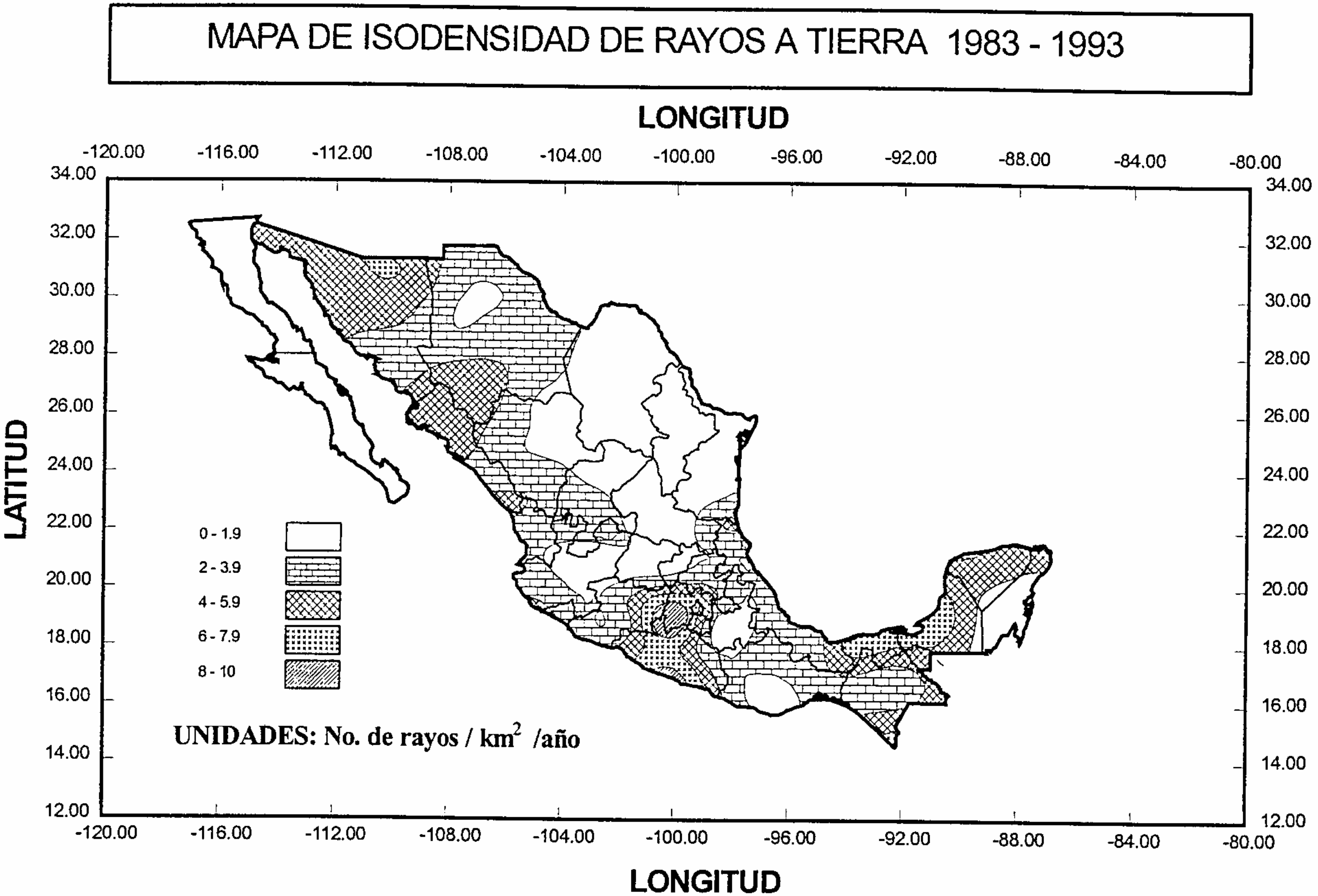


Figura III.A.1. Densidad de rayos a tierra de la República Mexicana. Adaptada de [6].

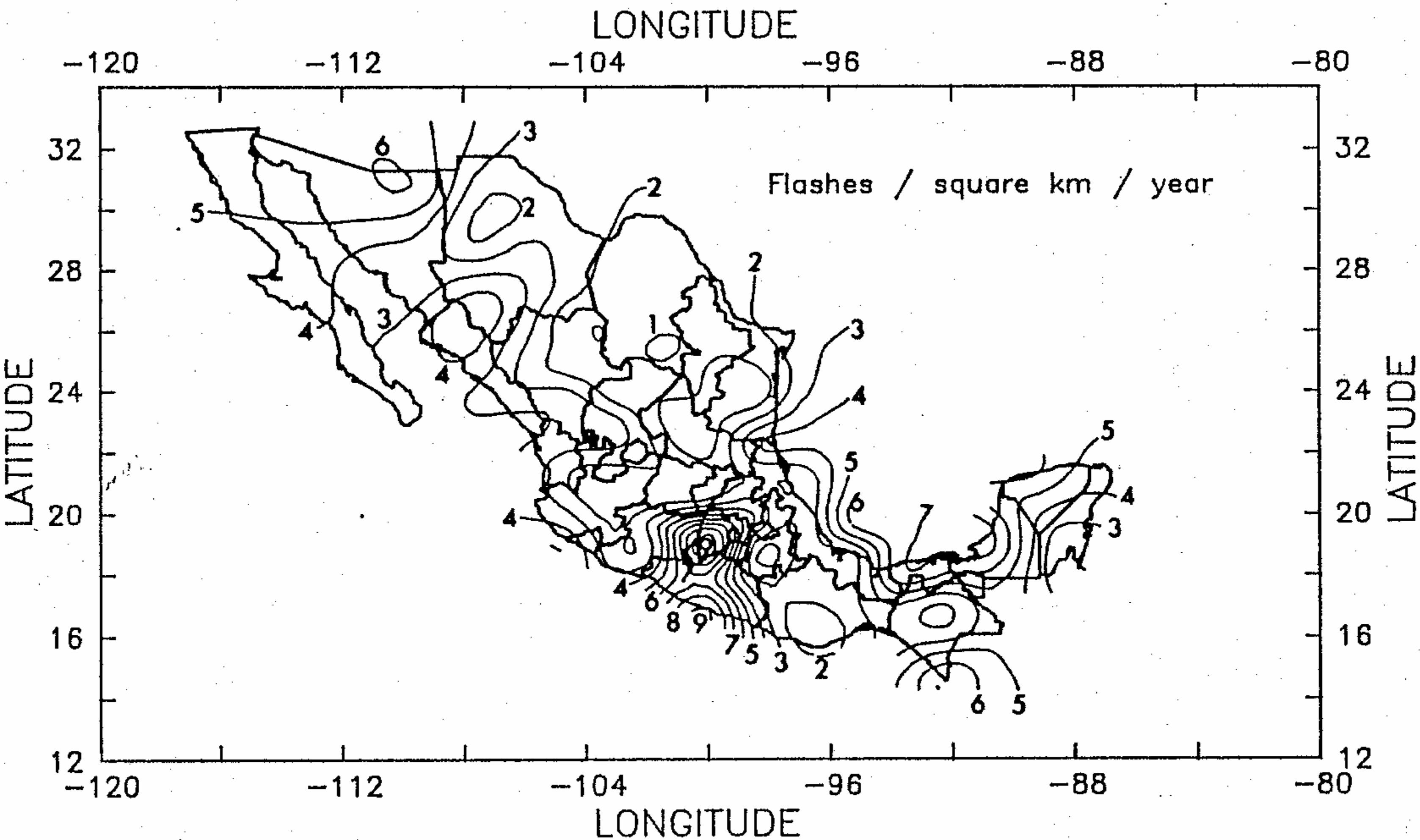


Figure 1 GFD map for the period 1983-1993

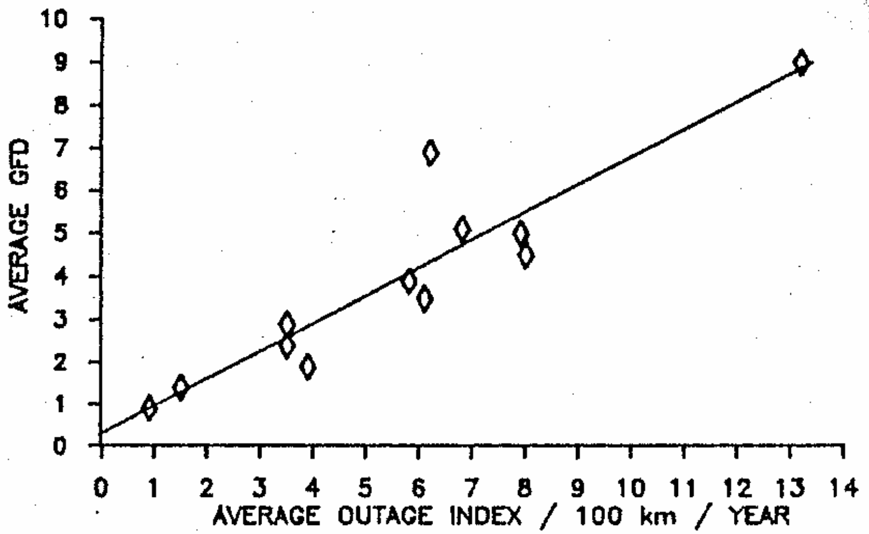


Figure 2 Correlation between average GFD and average outage index for 115 kV lines

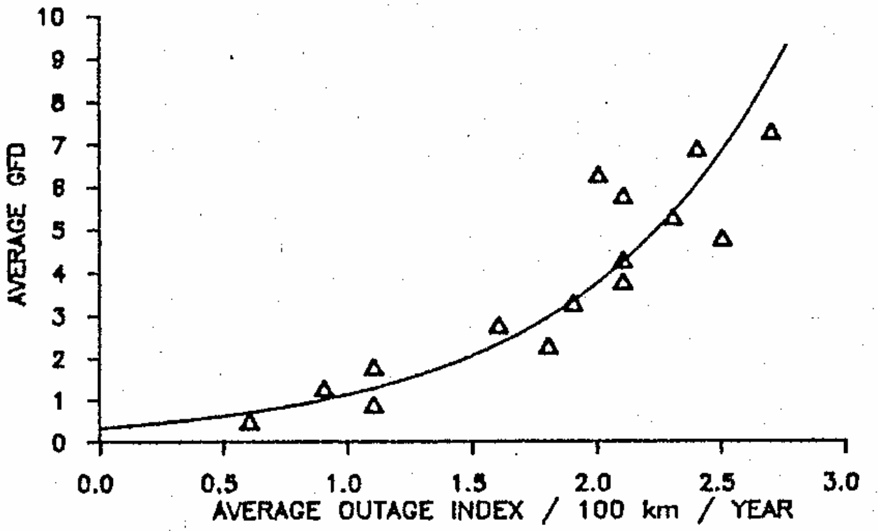


Figure 3 Correlation between average GFD and average outage index for 230 kV lines

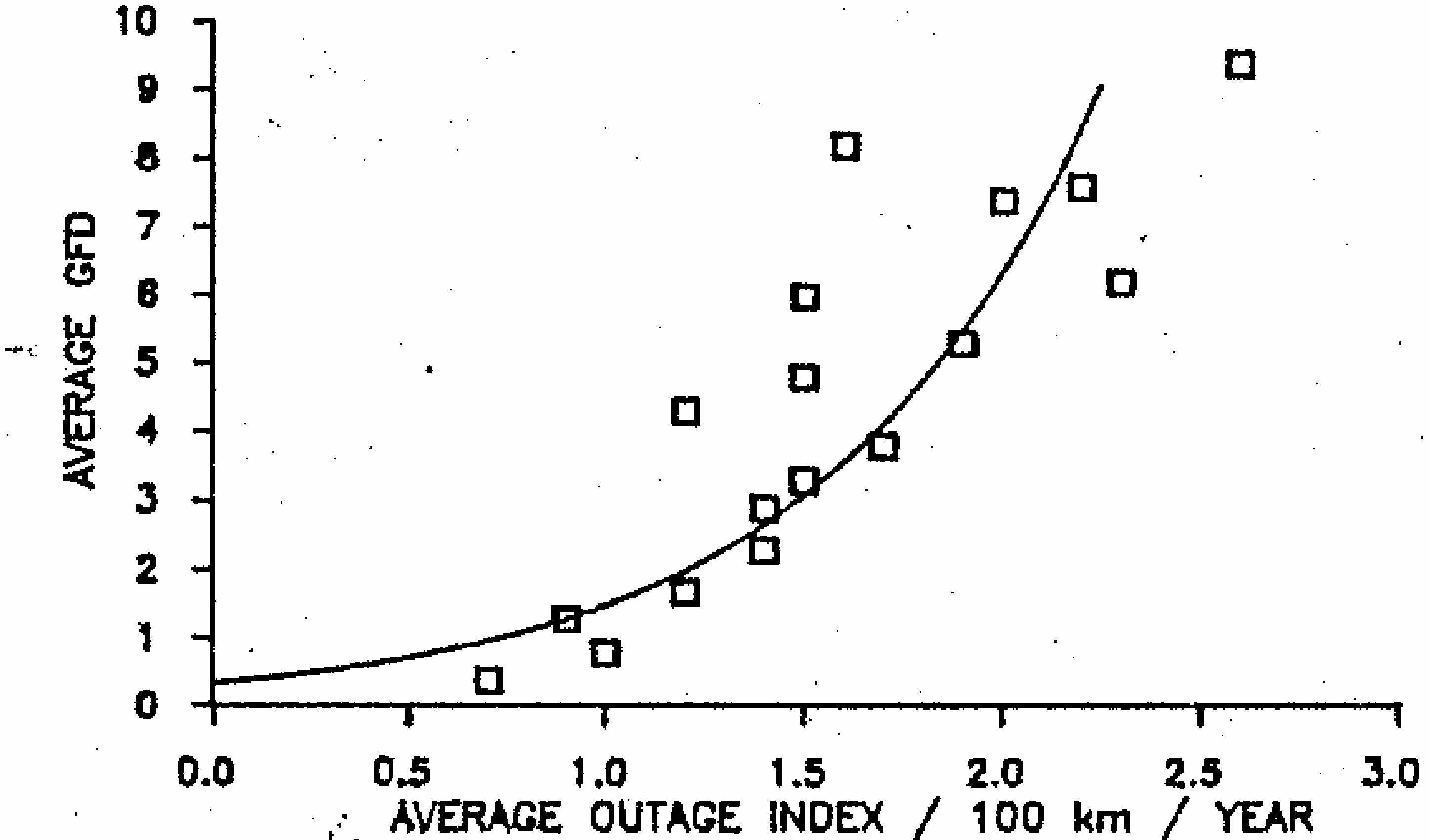


Figure 4 Correlation between average GFD and average outage index for 400 kV lines

AM

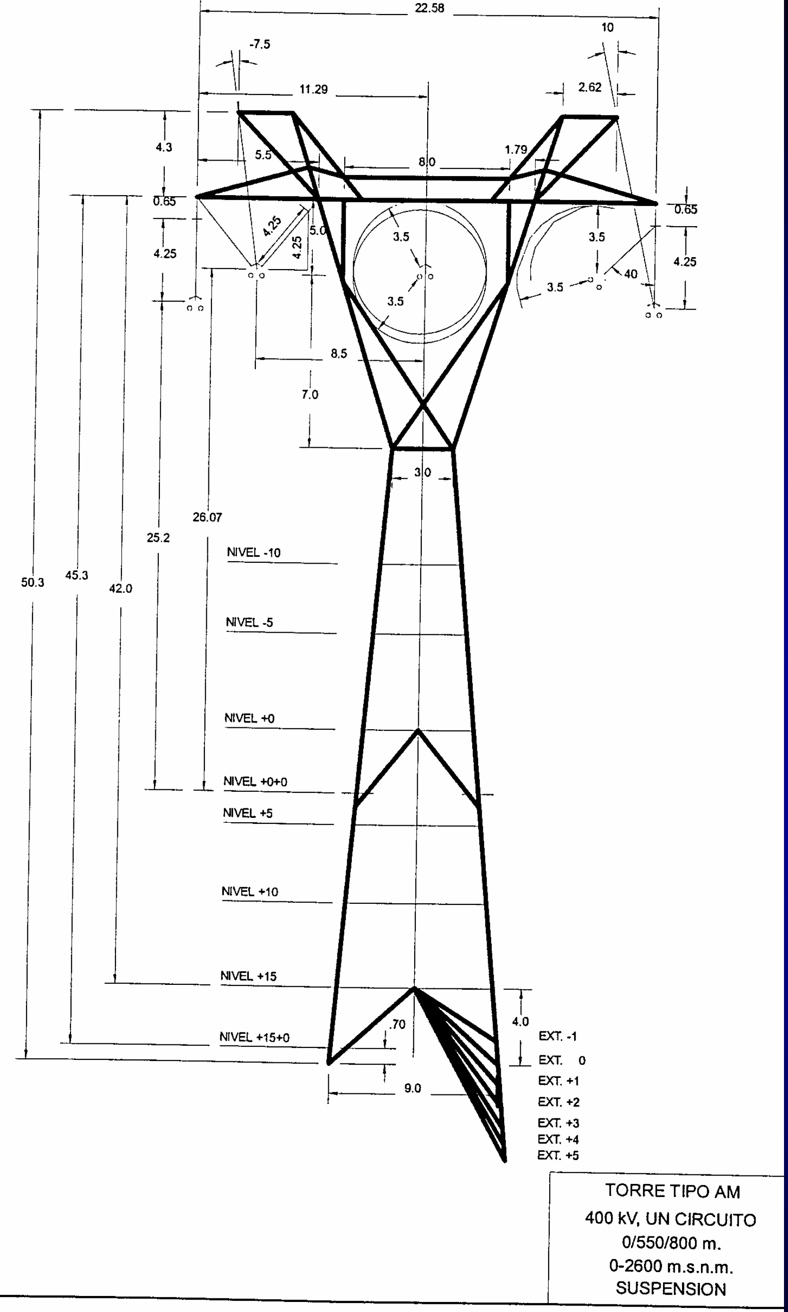


Figura IV.A.2. Torre tipo AM. Adaptada de [5].

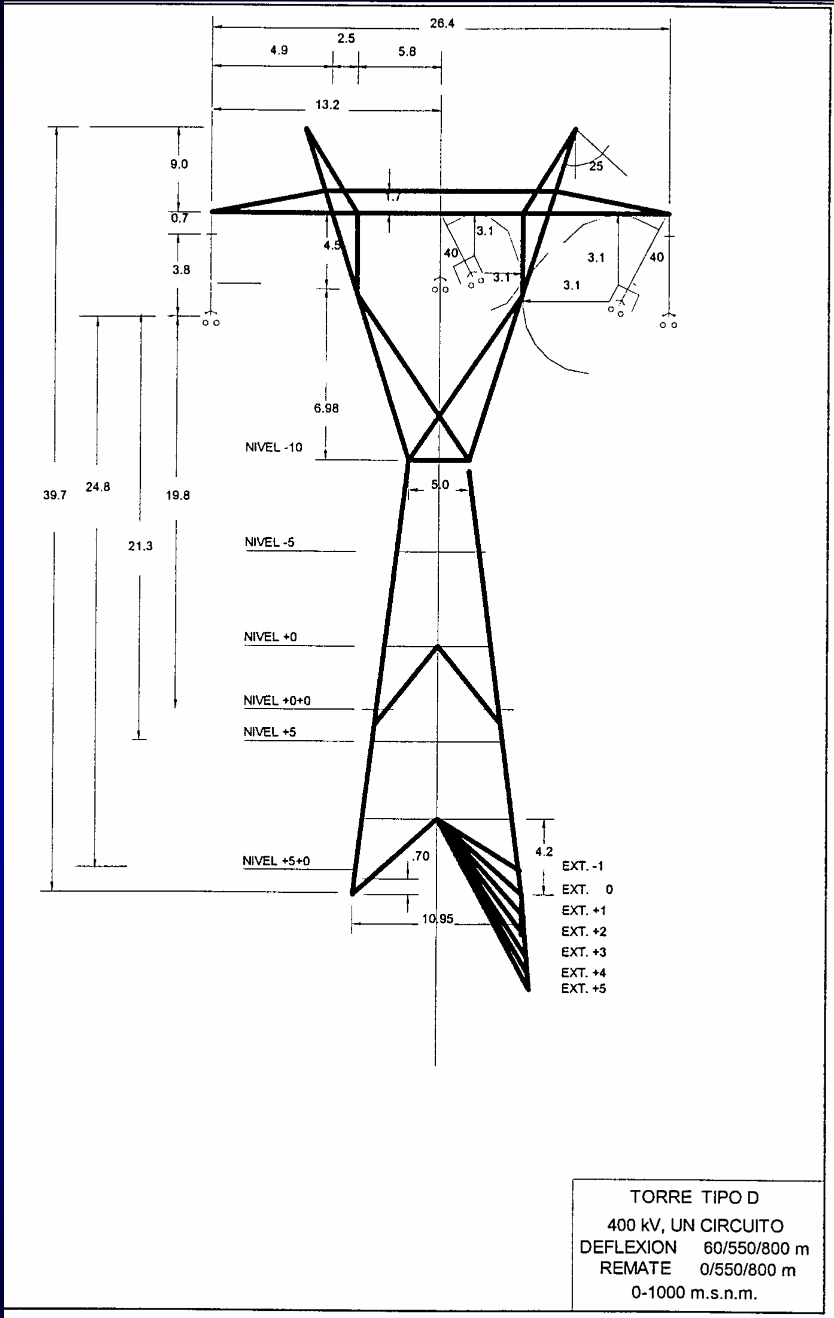


Figura IV.A.7. Torre tipo D. Adaptada de [5].

D

Calculated No. of outages/100 km/year, resulting from shielding failures in 400 kV transmission towers

Tower type:	A	AM	4BC1	4BA1	C	CM	D	DM
Shielding failure index:	0.001	0	0	0.015	0	0	0.073	0

ANEXO III.B "Cálculo de la Distancia Crítica"

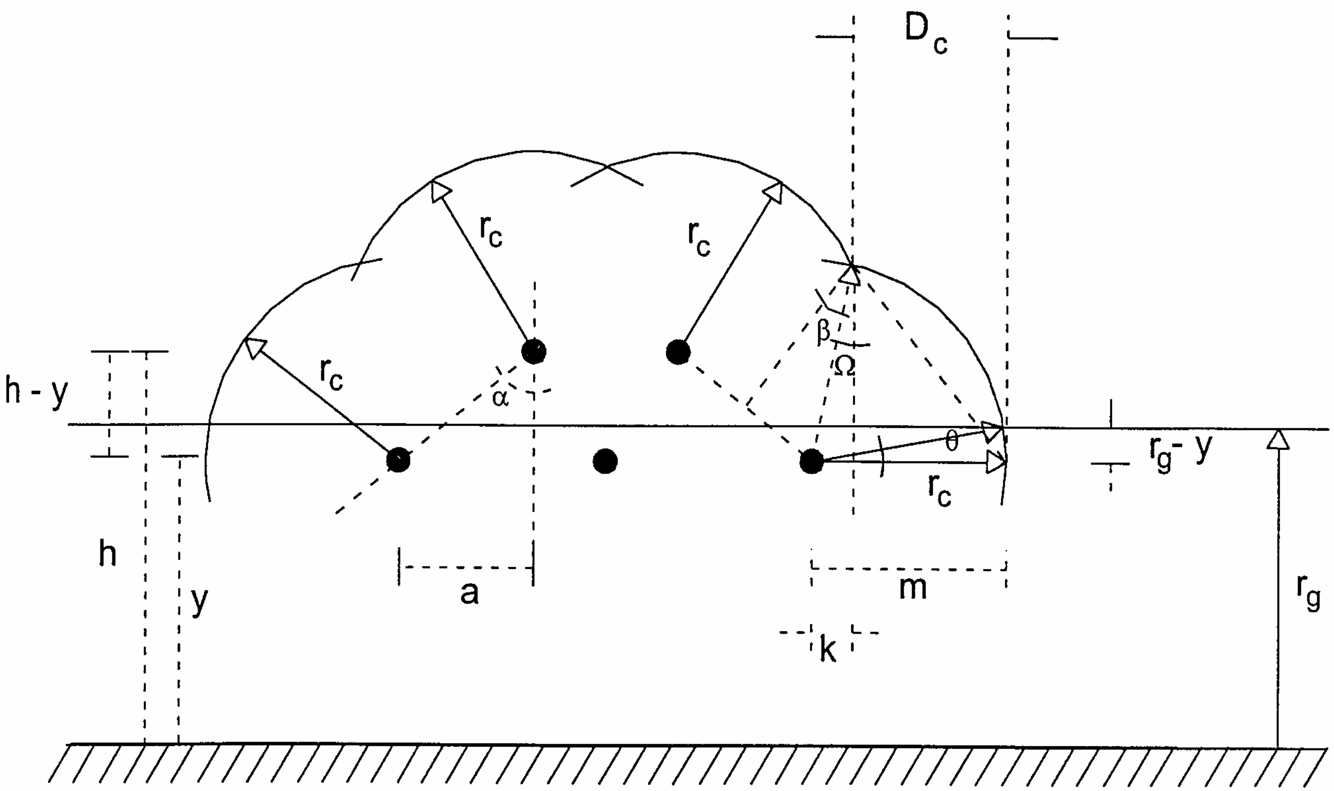
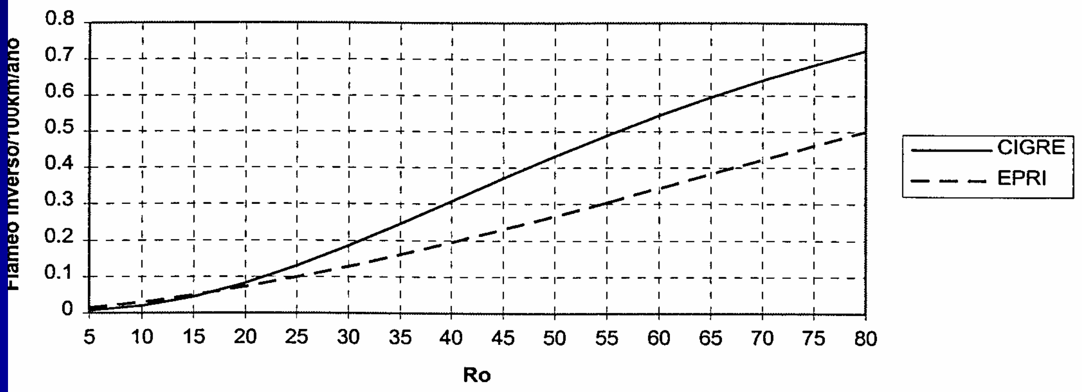


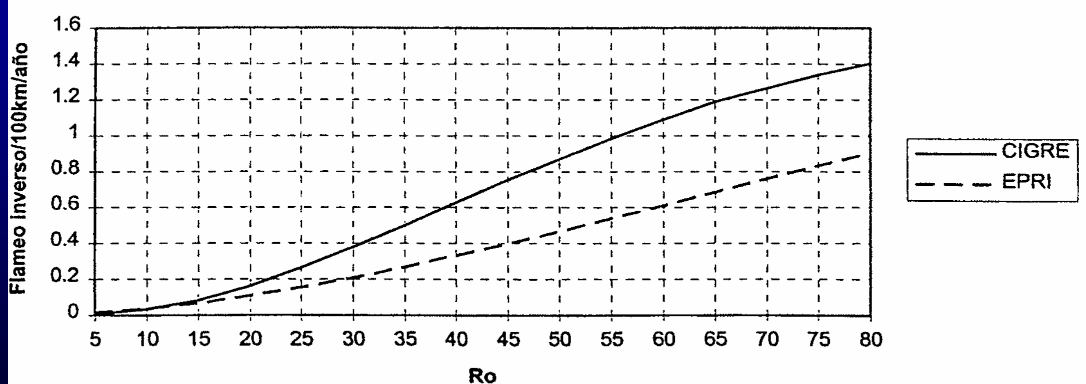
Figura III.B.1. Calculo de la distancia crítica. Modelo Electrogeométrico. Adaptada de [7].

Calculated Backflashover index (per 100 km per year) for 400 kV tower types AM and D. Cigre method refers to:

$$BFR = 2(Ng/10) \int_{Imin}^{Im} D_c \, p(i) \, dI \ \textit{flashovers/100km/year}$$

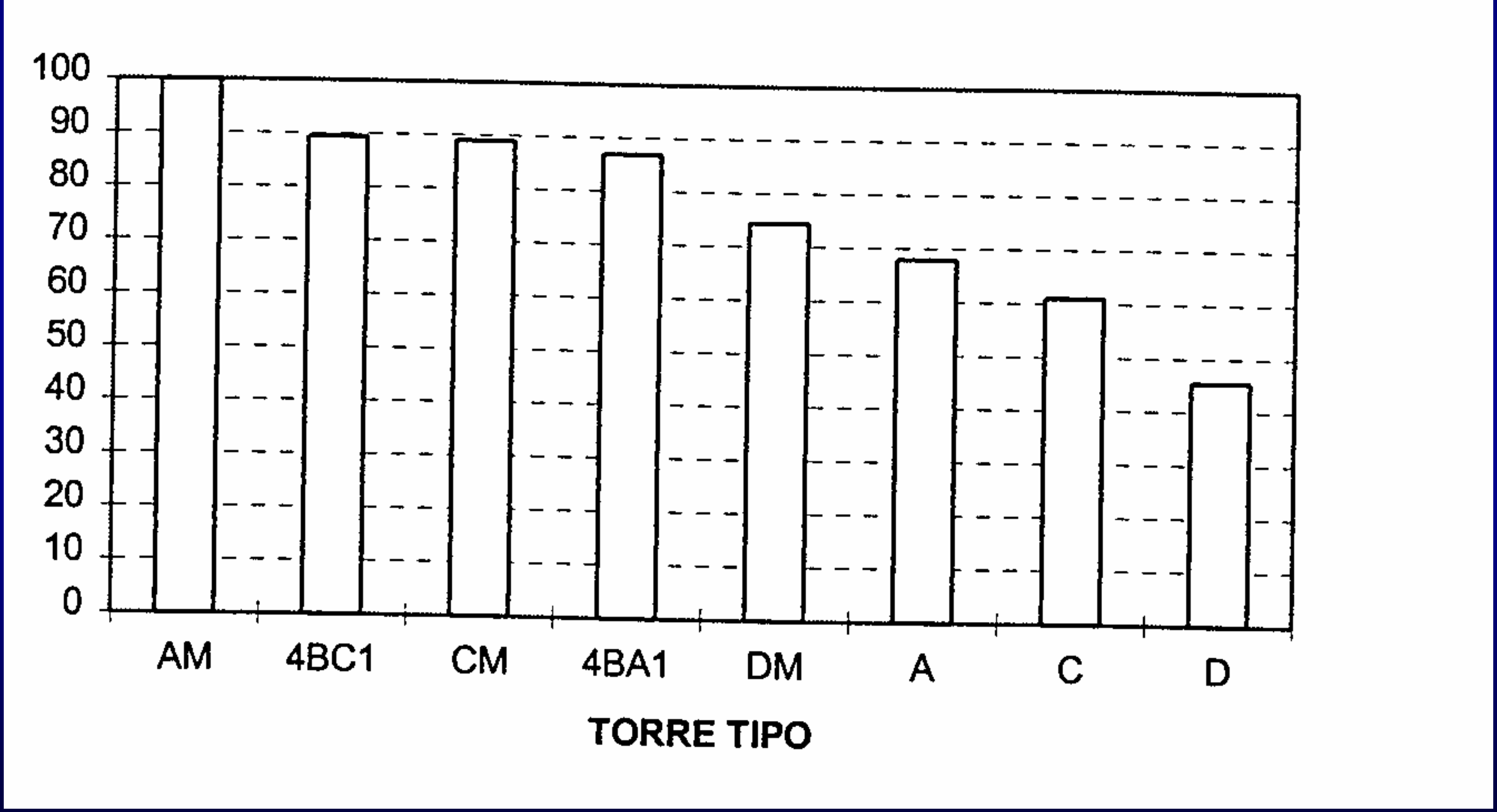


Gráfica IV.2. Índice de flameo inverso vs. resistencia al pie de la torre
Torre tipo AM



Gráfica IV.7. Índice de flameo inverso vs. resistencia al pie de la torre
Torre tipo D

Relative reliability for different types of 400 kV tower designs



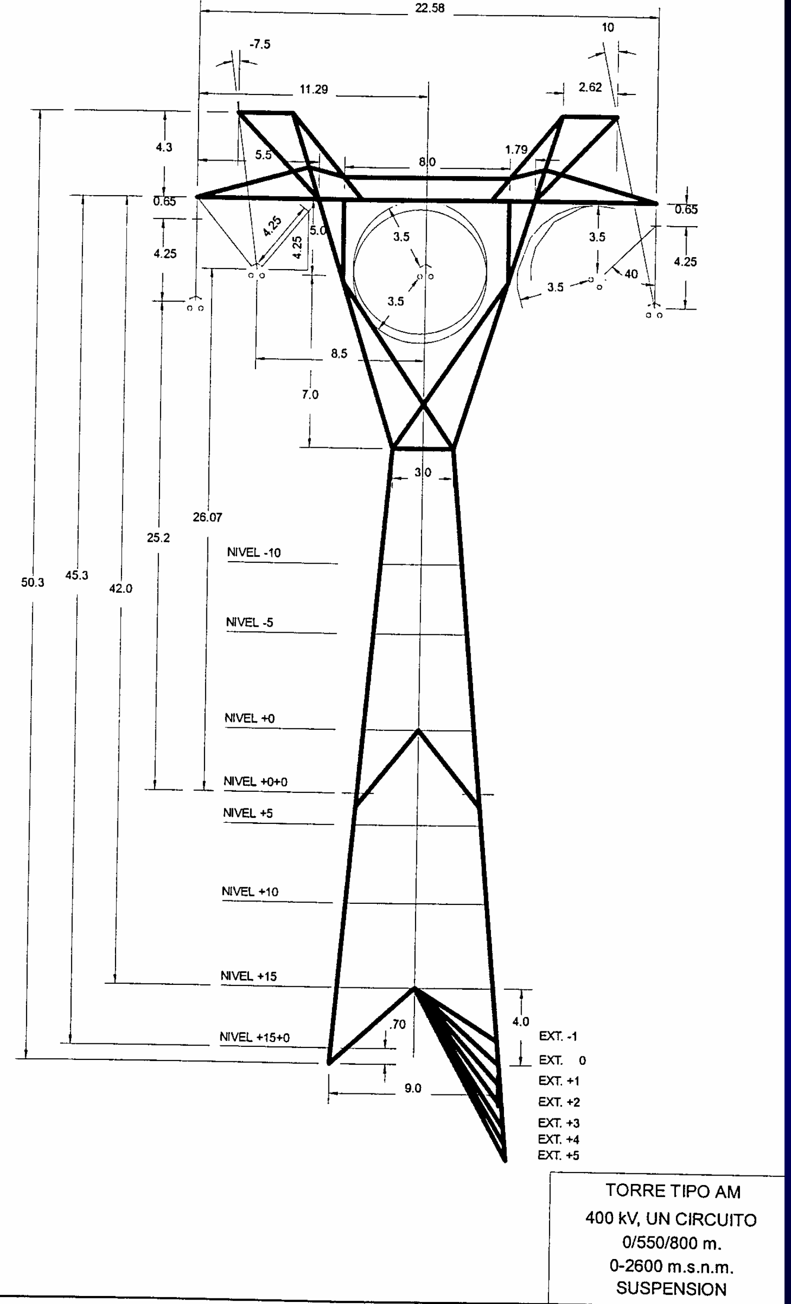


Figura IV.A.2. Torre tipo AM. Adaptada de [5].

AM

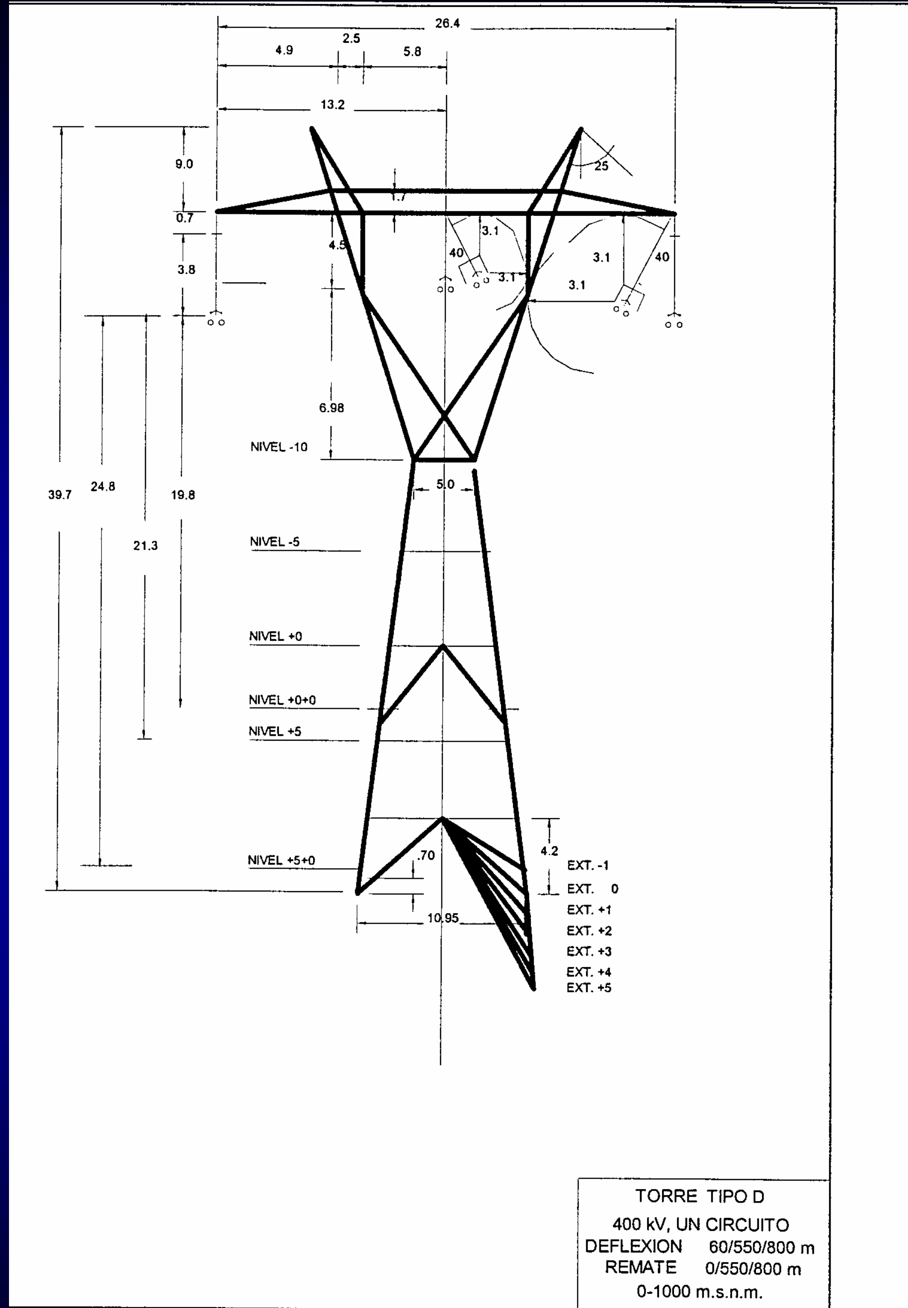


Figura IV.A.7. Torre tipo D. Adaptada de [5].

D

Simplified relationship between relevant parameters to account for ionization phenomena in soil resistivity calculations, after Oettlé

El factor que tomará en cuenta la geometría de los electrodos de aterrizamiento puede ser determinado como:

$$h = \sqrt{h_1^2 + h_2^2 + d^2} \tag{5.4}$$

donde

d	profundidad de aterrizamiento (m)
h_1	máxima distancia horizontal del arreglo de electrodos (m)
h_2	máxima distancia vertical del arreglo de los electrodos (m)

De acuerdo a la realización de diversas pruebas [18], es posible obtener la relación entre P_1 y P_2 ajustando una curva a estos resultados. La figura V.1 nos muestra ésta relación:

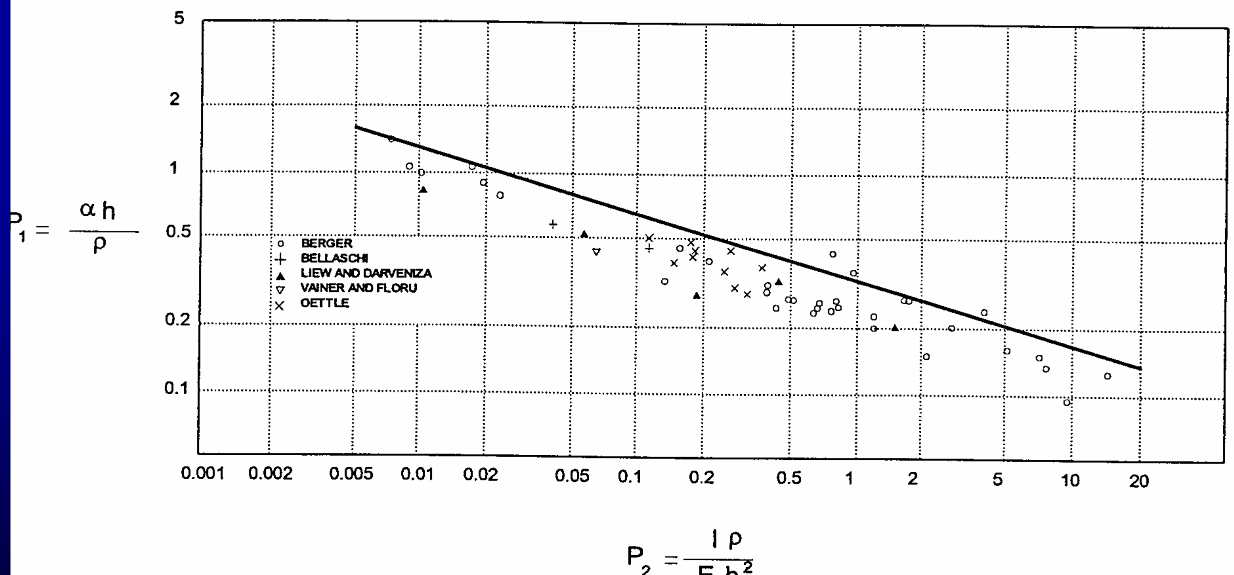


Figura V.1. Resultados de pruebas de impedancia al impulso en términos de P_1 y P_2. Adaptada de [18].

La ecuación 5.5 describe la recta trazada en la figura V.1:

$$(\text{Log } P_1) = -0.3\,(\text{Log } P_2) - 0.49 \tag{5.5}$$

Impulse impedance calculation from the simplified Oettlé approach

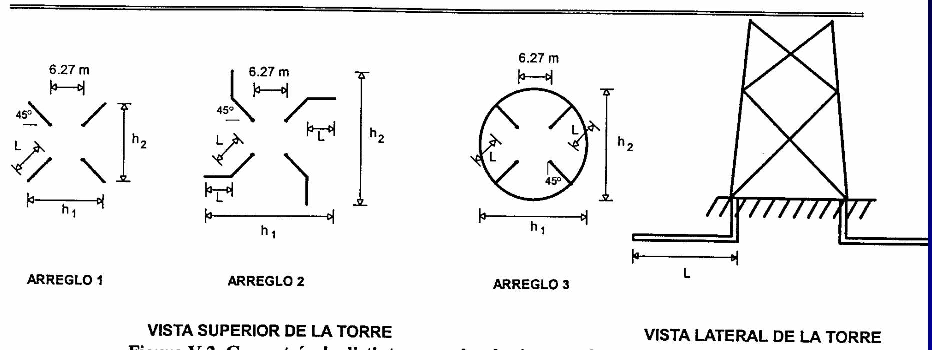


Figura V.2. Geometría de distintos arreglos de sistemas de aterrizamiento.

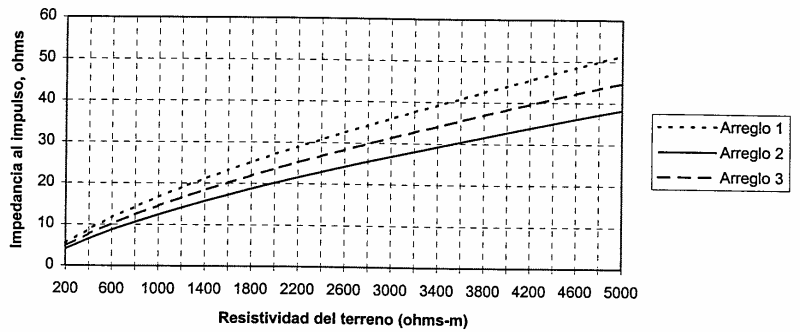
De la figura:

h_1	máxima distancia horizontal
h_2	máxima distancia vertical
d	profundidad de los electrodos
L	longitud individual de los electrodos

El análisis se realiza considerando, para todos los arreglos las siguientes, consideraciones:

- Amplitud de la corriente de rayo — 150 kA
- Gradiente de rompimiento del suelo[1] — 1000 kV/m
- Profundidad del aterrizamiento — 1 y 2 m
- longitud de los electrodos — 15 y 30 m

Entonces, a continuación se muestran los valores de impedancia al impulso para diversos valores de resistividad del terreno.



Gráfica V.1. Impedancia al impulso vs. resistividad para distintos arreglos. Profundidad del los electrodos 1 m. Longitud de los electrodos 15 m.

LIGHTNING ARRESTER PROTECTION IN A 115 kV LINE IN SOUTHERN MEXICO

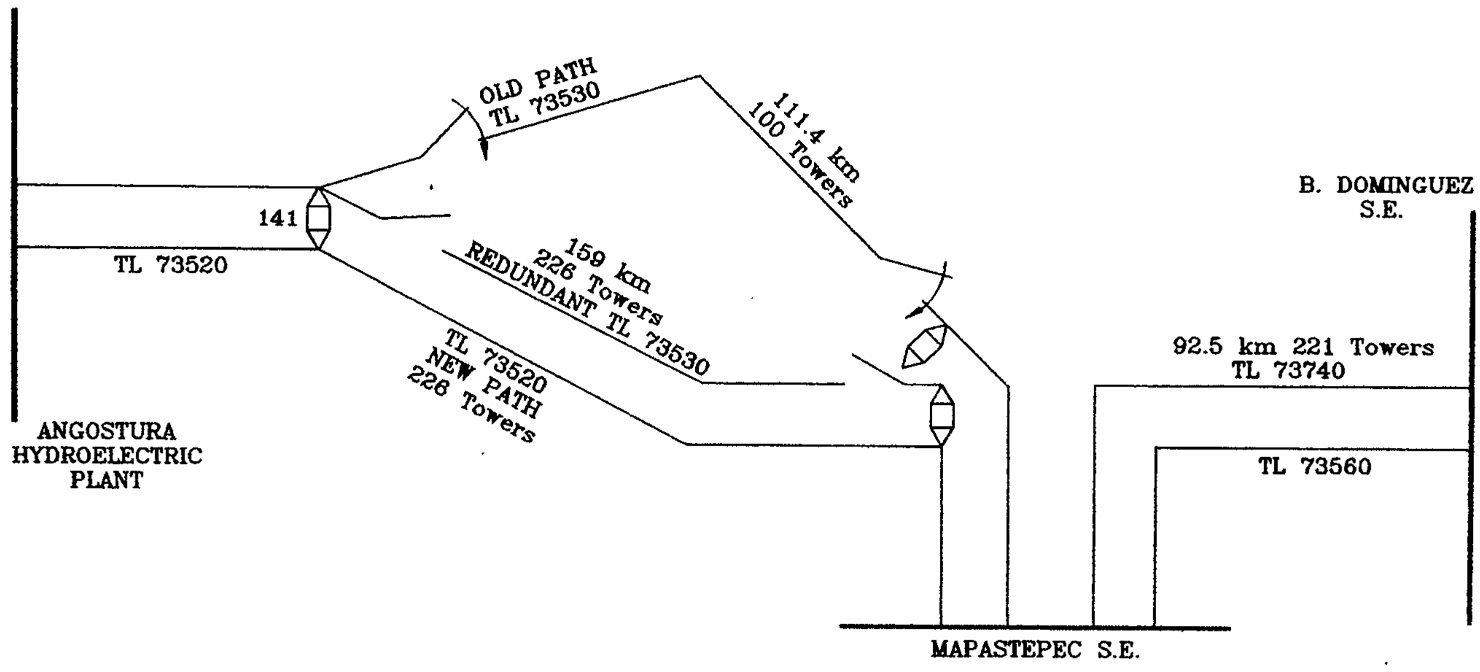
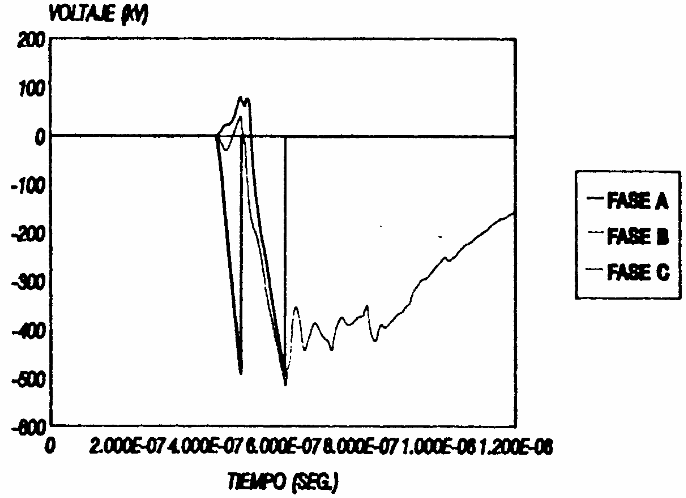


Figure 3. 115 kV Angostura-B. Domínguez line



Rt = 10 OHMS
Ir = 30 kA

Figura 4. Simulación de un rayo en la fase A a medio claro, con CIAH's en fases A y C. No se produce flameo en fase B.

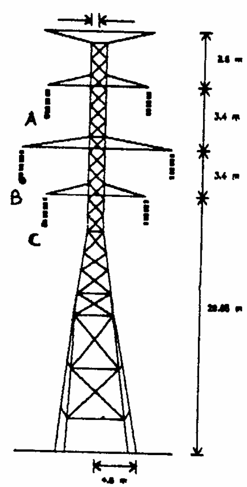


Figura 5. Torre de suspensión tipo "A", utilizada en la línea de 115 kV Angostura-Belisario Domínguez

RESULTS OF SURGE ARRESTER APPLICATION IN THE 115 kV LINE

Table 2
Behaviour of 115 kV line Angostura- B. Domínguez
before and after installation of ZnO arresters

Circuit No.	Avg. No. of outages for period 1984-1992	No. of outages 1993 (MOSA's installed)	No. of outages 1994 (MOSA's installed)	Type of MOSA installed
73530	14.55	6	4	External-series gap
73520	14.5	8	4	Gapless
73560	14.88	8	5	Gapless

LIGHTNING ARRESTER PROTECTION IN A 115 kV LINE IN SOUTHERN MEXICO

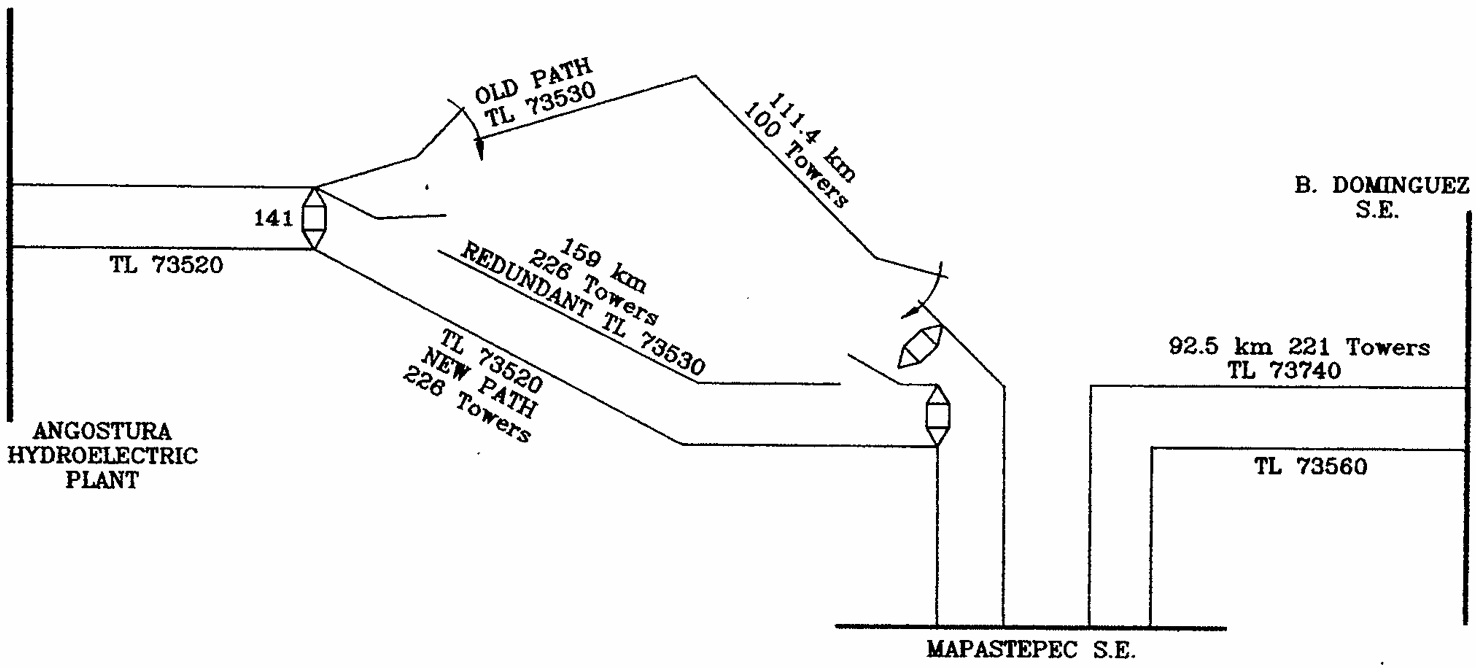


Figure 3. 115 kV Angostura-B. Domínguez line

CONCLUSIONS

- Reliability of a number of presently used tower designs for 115, 230 and 400 kV CFE transmission lines in Mexico was performed.
- This was possible with the aid of EGM concepts taking Eriksson´s attractive radius formula, to determine shielding failures , and CIGRE recommended formula for backflashover.
- A simplified approach used to account for soil ionization allowed us to determine the most effective layout of grounding electrodes for the transmission towers.
- Length of electrodes more than their buried depth was found to be the dominant performance factor.

CONCLUSIONS….cont.

- From the first two years of MOSA operation in 115 kV transmission lines, outage reduction to around 60 % and less of the average values experienced in the past 8 years was obtained.
- Selective protection was largely based on:
  - statistical data to pinpoint the towers most exposed to lightning damage (outage reports from crews)
  - lightning incidence along the line (from LFC´s)
  - EMTP simulations to decide the phases to protect

ANY QUESTIONS?