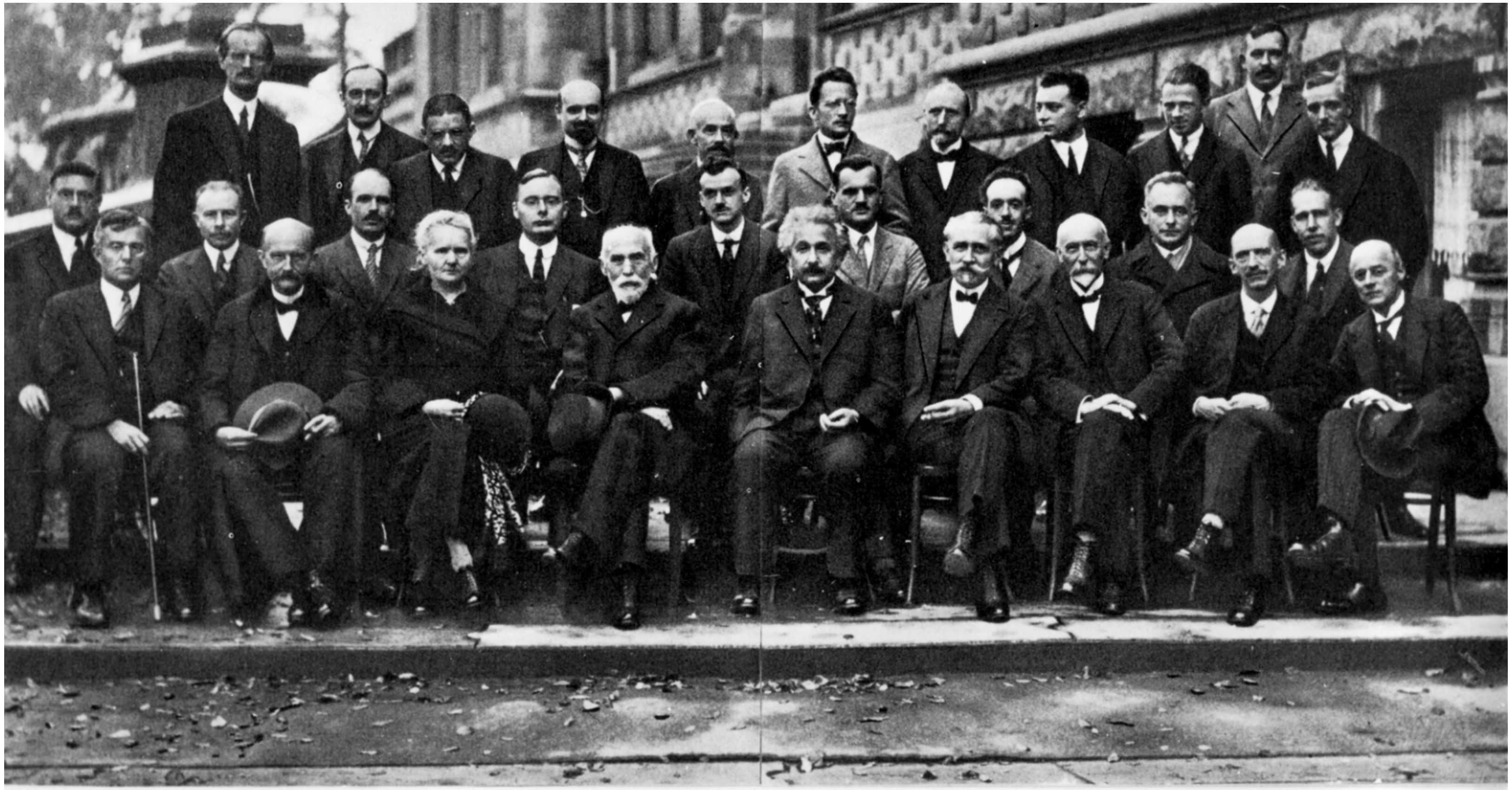
IPST 2015 / Dubrovnik
15-18 June 2015

History of Transient Analysis, EMTP Development and IPST

A. Ametani, Ecole Polytechnique Montreal, Canada

1. Background of transient analysis
2. Computer simulations
3. EMTP
4. Numerical Electromagnetic Analysis
5. IPST



Photographie Benjamin Couprie — 28, Avenue Louise, Bruxelles

R. H. FOWLER

A. PICCARD E. HENRIOT ED. HERZEN TH. DE DONDER E. SCHROEDINGER W. PAULI W. HEISENBERG L. BRILLOUIN

P. EHRENFEST E. VERSCHAFFELT

P. DEBYE M. KNUDSEN W. L. BRAGG H. A. KRAMERS P. A. M. DIRAC A. H. COMPTON L.V. DE BROGLIE M. BORN N. BOHR

I. LANGMEIR M. PLANCK MADAME CURIE H. A. LORENTZ A. EINSTEIN P. LANGEVIN CH. E. GUYE C.T.R. WILSON

O.W. RICHARDSON

History Related to Electrical Engineering

1831	Faraday	Electromagnetic induction
1864	Maxwell	Maxwell’s equation
1880	Edisson	Electric bulb
1882	Edisson	DC transmission in New York
1884	AIEE established	
1886	WH founded	
1892	GE founded	
1896	Niagara Falls AC generation station 11kV/40km	
1921	CIGRE founded	
1933	US President Roosevelt New Deal	

1. Background of Transient Analysis

(1) Trans - Atlantic tele - communication cable

・Kelvin arrival curve in 1854

・ wave (signal) distortion → Heaviside (Laplace) transform in 1900s

・ transient analysis in a lumped-parameter circuit

(2) US 220kV transmission line in 1923

・ transformer failure due to lightning to the transmission line : lightning overvoltage analysis

→ Heaviside transform to a transformer

traveling wave theory to a transmission line

・ transient analysis in a distributed-parameter circuit

(3) Fault surge (temporary overvoltage)

→ symmetrical component theory in 1930s

・ modal analysis of a multi-phase line

(4) Telephone line interference in 1930s

→ accurate impedance / admittance required

・conductor internal impedance by Schelknoff

earth - return impedance by Pollaczeck and Carson

earth - return admittance by Wise

History of Transient Analysis

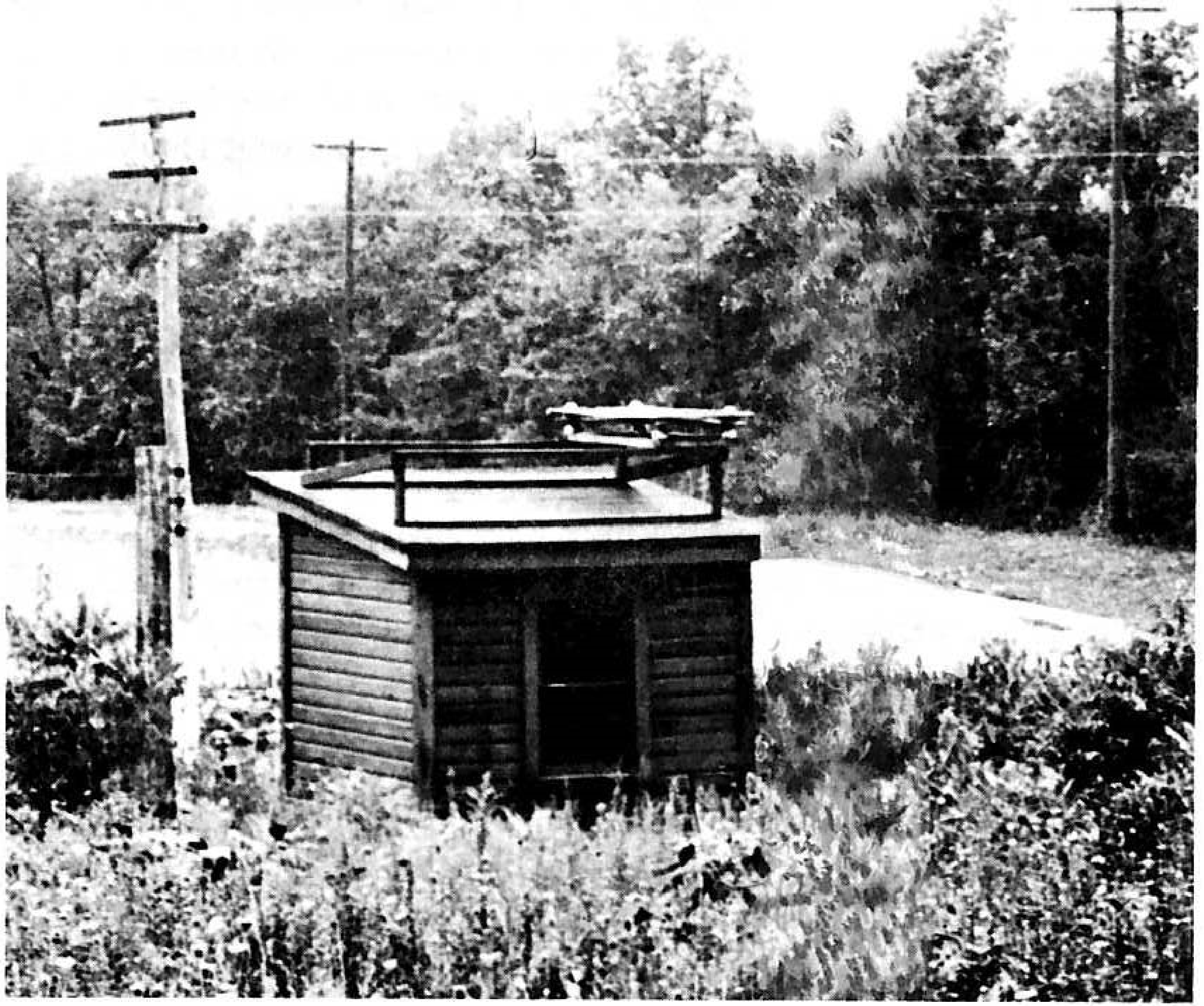


FIG. 1·5. View of air capacitor for field-intensity recorder, mounted on top of wooden house in which recorder is located.

FIG. 5·8. Interior of oscillograph room in Wallenpaupack laboratory, 1929, showing two cathode-ray oscillographs, one for connection to transmission line and one for connection to antenna.

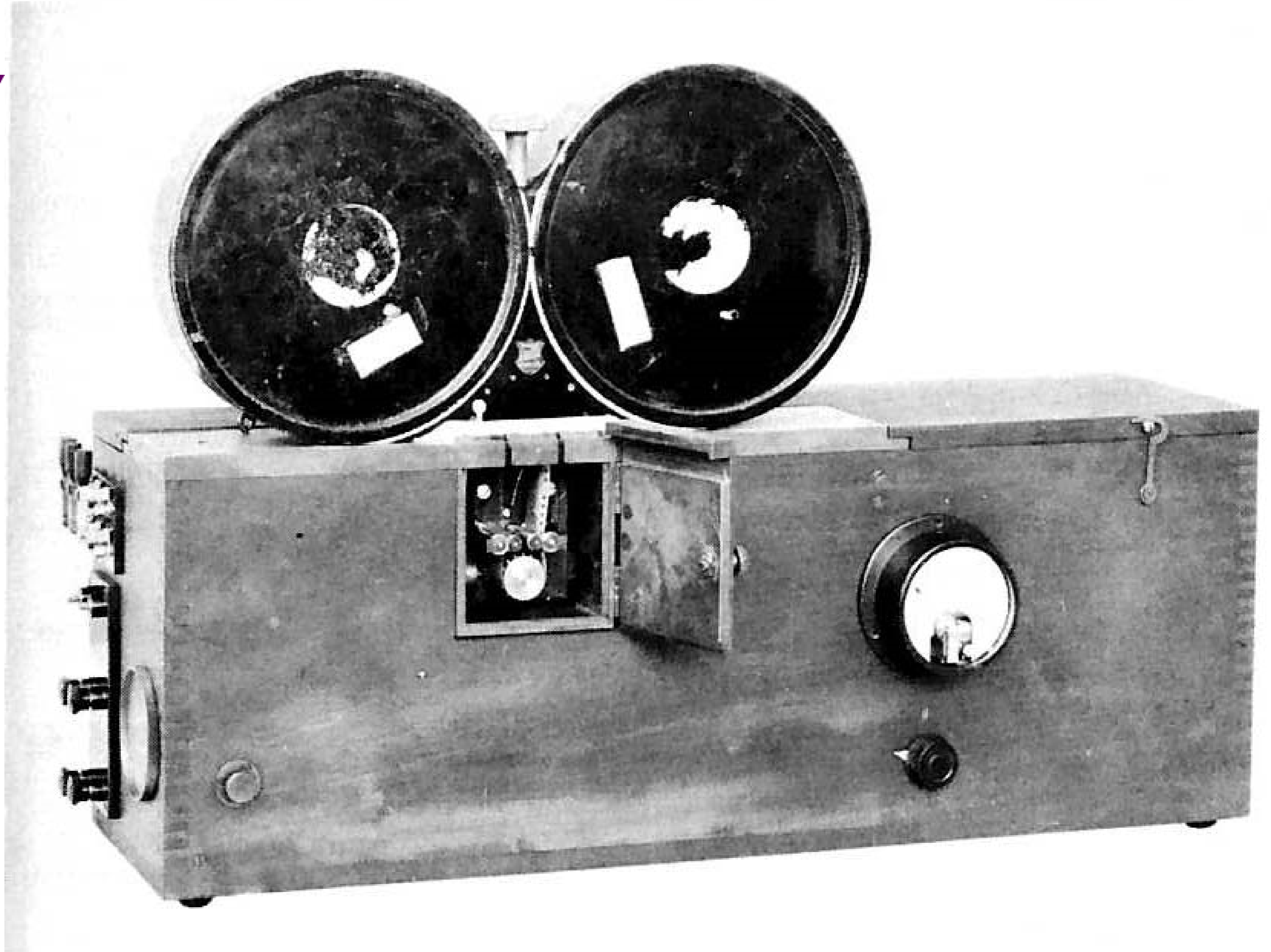


FIG. 1·6. The field-intensity recorder.

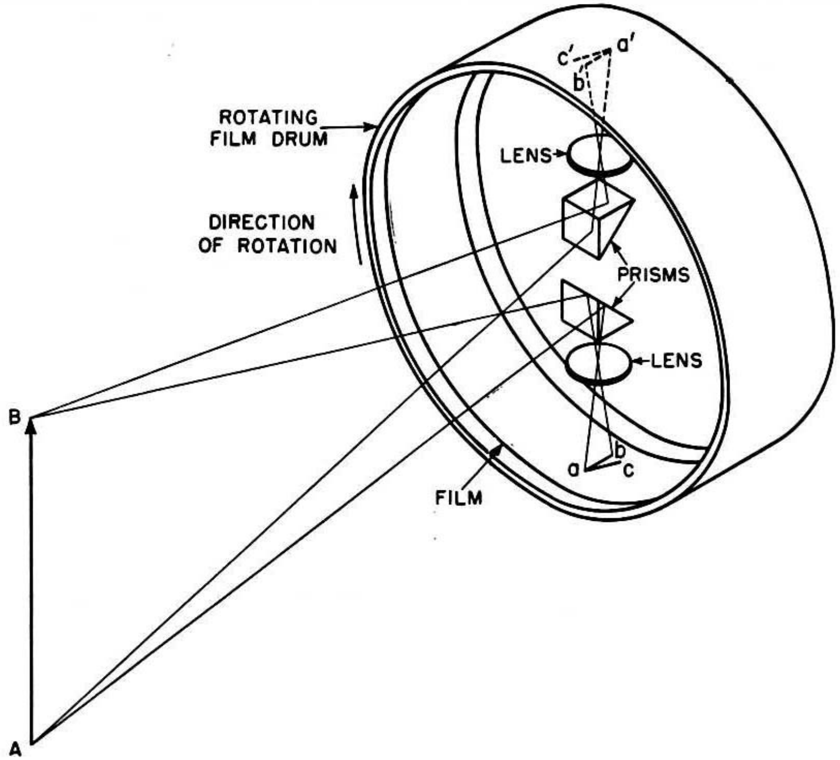


FIG. 2·1. Schematic diagram of a Boys camera with moving film and stationary optical system.[3]

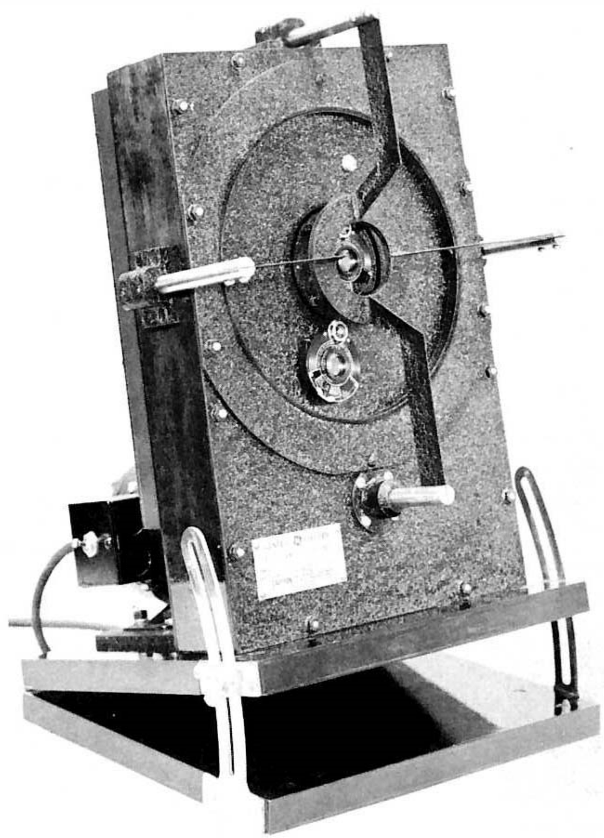


FIG. 2·6. One type of Boys camera with middle lens stationary and outside lens rotating at 120 rpm.[19]

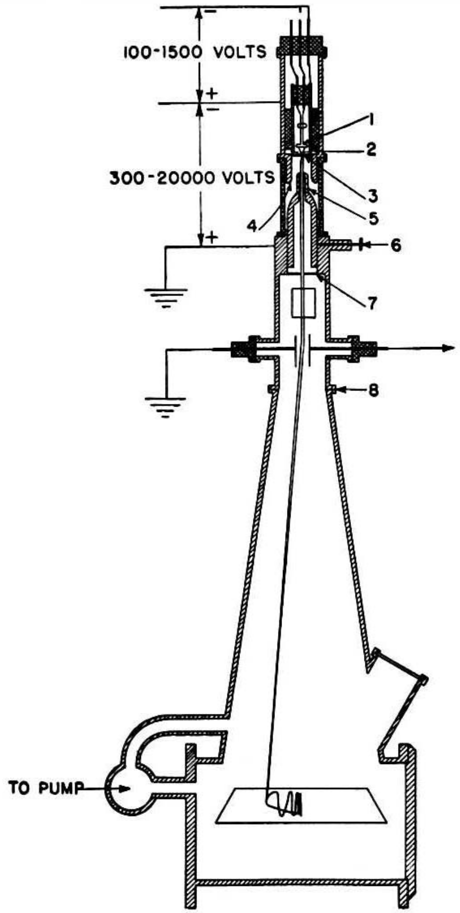


FIG. 5·3. Diagram of automatic cathode-ray oscillograph of the hot-cathode type.[7] 1. Ribbon filament. 2. Filament shield. 3. Positive plate. 4. Cup-shaped cathode. 5. Cylindrical anode. 6. Screw for raising and lowering anode. 7. Diaphragm for cutting off stray emission. 8. Section of Bakelite to prevent eddy currents when using deflecting coils.

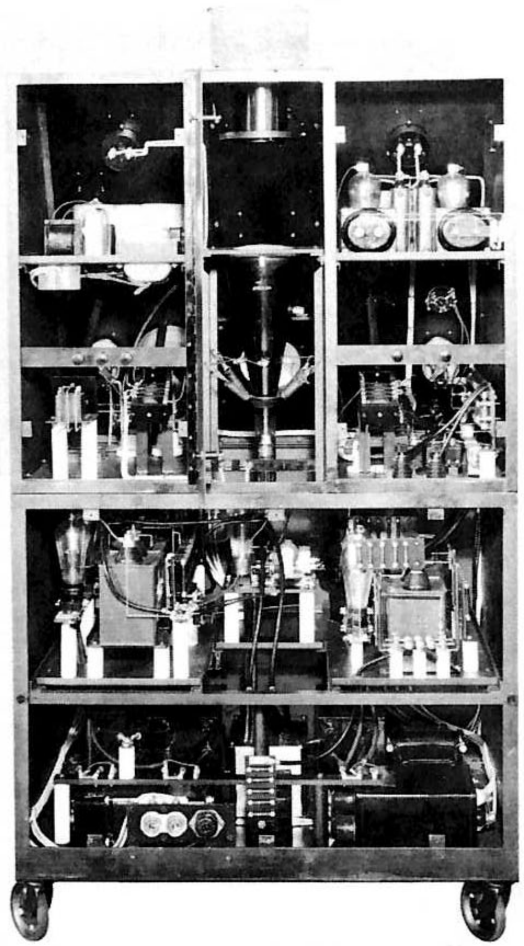


FIG. 5·5. Rear view of high-speed hot-cathode oscillograph.[8]

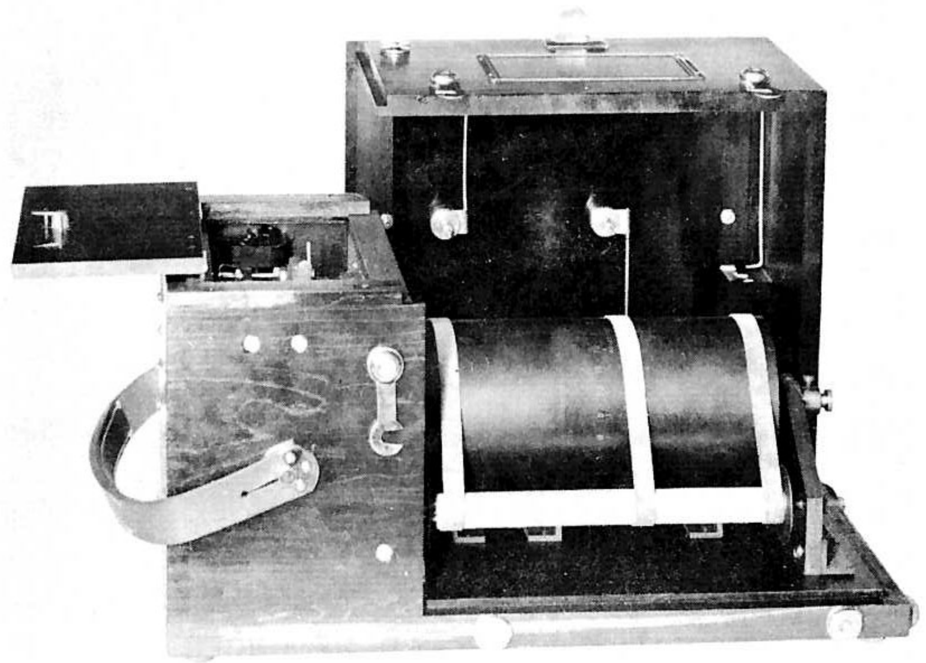


Fig. 3·5. Surge-voltage recorder of the moving-film type, shown with the film and clock compartments open.

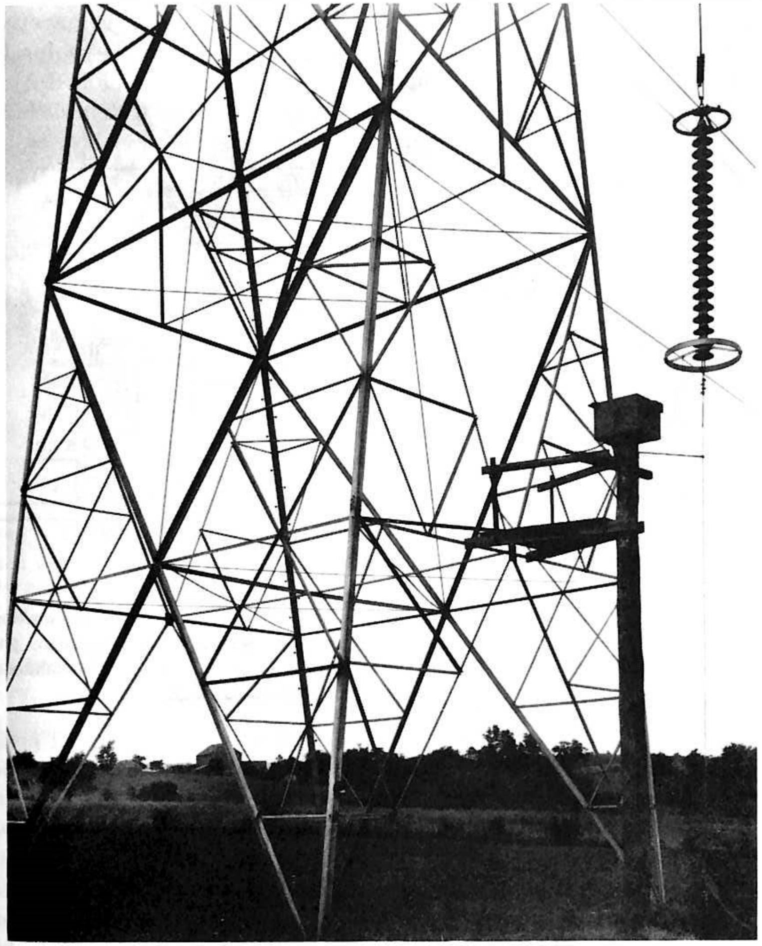


Fig. 3·14(*b*). Field installation on 220-kv system, showing surge-voltage recorder and voltage divider.

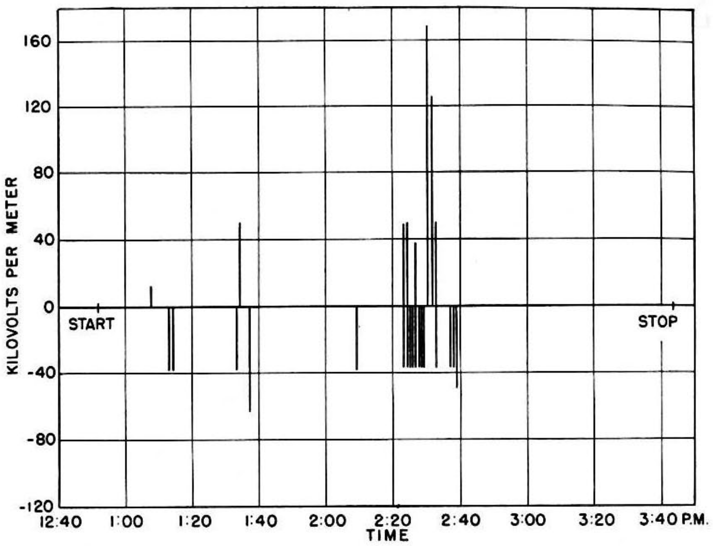


FIG. 1·8. Field-intensity data obtained by the field-intensity recorder during storm of June 19, 1929.[21]

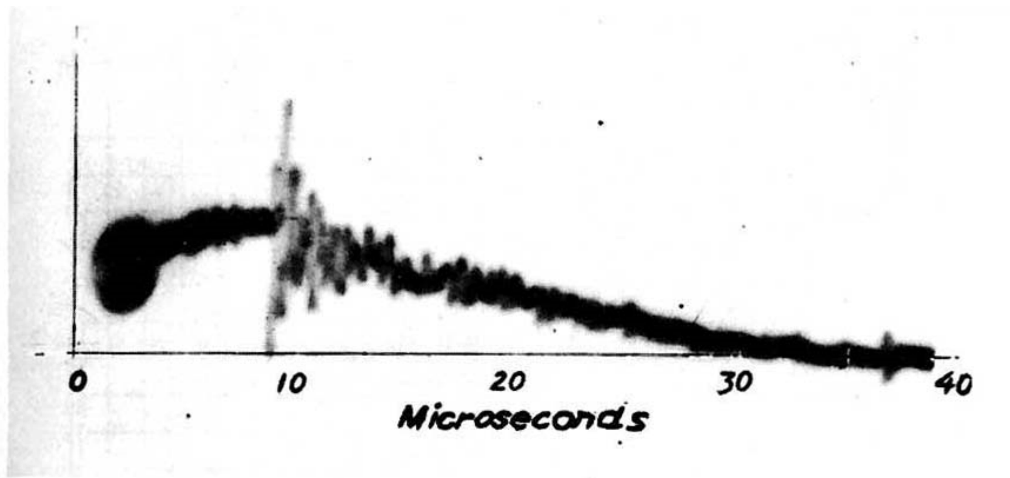


FIG. 3·19. Cathode-ray oscillogram of surge on 220-kv line on July 27, 1928. See profile of voltage, Fig. 3·17.[17, 19]

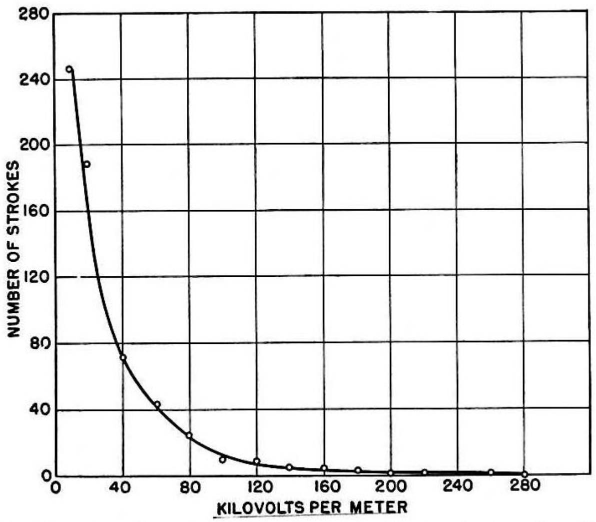


FIG. 1·9. Curve showing cloud-field potential gradient against number of strokes as obtained by the field-intensity recorder during the 1929 season. Ordinates represent number of strokes giving intensity greater than specified value.[21]

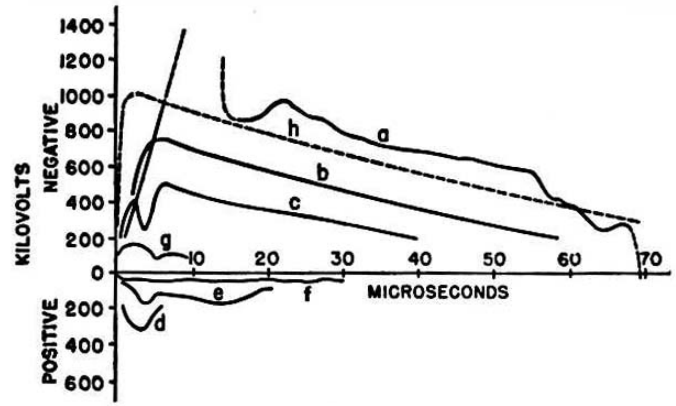


FIG. 5·6. Reproduction of typical lightning surges recorded with Norinder oscillograph in 1929 in New Jersey, Tennessee, and West Virginia.[10] See Table 5·1 for data.

History of Transient Analysis

years	field	name
1900	Heaviside transform	Heaviside
1910	lightning observation, measuring instrument	Boys, Peters, Dufour
1920～1940	lightning phenomena, surge measurement	Lewis, Schonland
	transformer, machinery	Blume, Rudenberg
	traveling wave	Bewley
	countermeasures, protection	
	surge / transient over voltages	Bewley, Rudenberg, Hayashi
	symmetrical component theory	Fortescue, Clark
	line impedance / admittance	Carson, Pollaczek, Wise, Sunde
	grounding	Bewley, Sunde, Tagg

一人の技術者（研究者）が、実験、理論、解析全てを把握

2. Computer Simulations－History 1950-1980

(1)1950-1969

Surge analyzer (artificial line)
TNA
Analog computer

Digital computer
(a) Frequency domain
(b)Time domain
(c) Modal theory

---

(2) 1970

a) Frequency domain method
(1) computation time
(2) accuracy: Laplace transform
(3) dis-continuity/ non-linear: piece-wise linear
(4) wind-band freq.: exponential / logarithmic transform

b) Time-domain method
(1) recursive convolution
(2) TACS (MODELS)
(3) element models

Simulation Tools Available: 1980～

(a)Circuit-Theory Based Approaches

EMTP→ATP, EMTDC, RTDS,

EMTP-RV,   XTAP, SPICE

(b) Numerical Electromagnetic Analysis

NEC, CDEGS, VSTL

(c) Supporting Tools

MATLAB, SIMULINK, SAVER

(1) Frequency - domain approach

- analytical Laplace transform → numerical transform
  to solve ordinary / partial differential equations

- modified Fourier (=Laplace) transform
  to overcome numerical instability
  due to descritization and finite integral

- piece - wise linear transform
  to solve discontinuity (switching) and nonlinear elements

(2) Time-domain approach

・traveling wave theory based on Schnyder - Bergeron method to solve partial differential equations (method of characteristics)

・real-time convolution to deal with frequency-dependent parameters

3. EMTP

(1) History of the EMTP

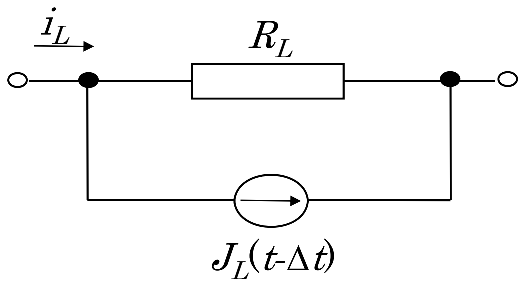
1961	Schnyder-Bergeron method by Frey and Athammer.
1964	Dommel's Ph. D. thesis in Tech. Univ. Munich.
1966	Dommel started EMTP development in BPA.
1968	Transients Program (TP=EMTP Mode 0), 4000 statements.
1973	Dommel moved to Univ. British Columbia. Scott-Meyer succeeded EMTP Development.
1976	Universal Transients Program File (UTPF) and Editor / Translator Program (E/T) completed by Scott-Meyer. UTPF and E/T made EMTP could be used in any computers because those solve machin-dependent problems, and prepared a platform for any researchers able to join EMTP development, not necessary to visit BPA. Japanese EMTP Committee founded.
1976-1982	Semlyen, Ametani, Brandwajn, Dube and later Marti joined EMTP development.
1978	First EMTP Workshop during IEEE PES Meeting.

1981	First EMTP Tutorial Course during IEEE PES Meeting. Development Coordination Group (DCG) proposed by BPA.
1982	DCG 5 years project started, Chairman Vithyathil of BPA. Members: BPA, Ontario Hydro, Quebec, US Bereaue of Realamation, WAPA
1983	EPRl joined DCG, DCG / EPRI started. Gopyright of EMTP to be given to EPRI / DCG. EMTP Mode 39 completed and distributed.
1984	EMTP development in BPA terminated. Final version EMTP Mode 42. Scott-Meyer started to develop ATP-EMTP independently on BPA and EPRI / DCG.
1985	ATP development transferred to Leuven EMTP Center (LEC) in Belgium. ATP ver. 2 completed. BPA joined LEC.
1986	DCG / EPRI EMTP Ver.1 completed
1987	DCG / EPRI 5 years project to be terminated, but DCG / EPRI project continued. BPA resigned from DCG / EPRI.
1991	ATP copyright transferred to Can / Am ATP Users Group. BPA joined Can / Am User Group. DCG / EPRI Ver.2 completed.

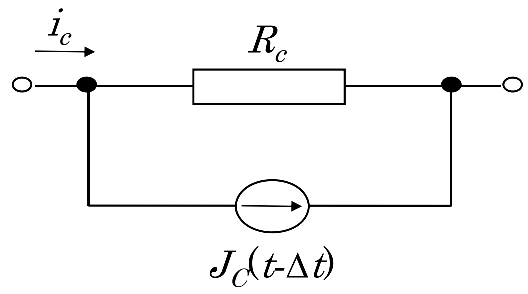
EMTP until 1981

1. Basic structure: Dommel
2. Platform for development: Scott-Meyer
3. Overhead line parameters: Dommel
4. Cable parameters: Ametani
5. Frequency-dependent line: Semlyen, Ametani, Marti
6. Machineries: Dommel, Bandwajn, Lon
7. Control circuits: Dube

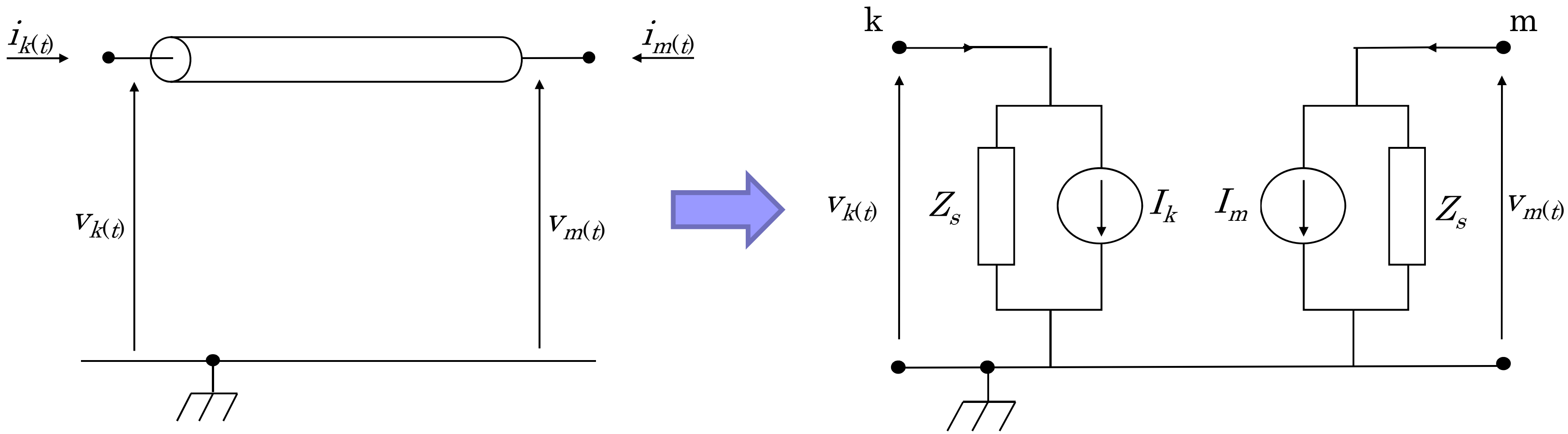
(2) Basic Theory



(a) Inductance



(b) Capacitance



(c) Distributed line

All the circuit elements → *R* and current source

Representation of circuit elements by a resistance and a current source

$$v = L \cdot di/dt$$

Integrating the above equation from time $t = t - \Delta t$ to t,

$$\int_{t-\Delta t}^{t} v(t) \cdot dt = L \int_{t-\Delta t}^{t} (di/dt) \cdot d_t = L[i(t)]_{t-\Delta t}^{t} = L\{i(t) - i(t - \Delta t)\}$$

By applying Tropezoidal rule to the left-hand side of the equation,

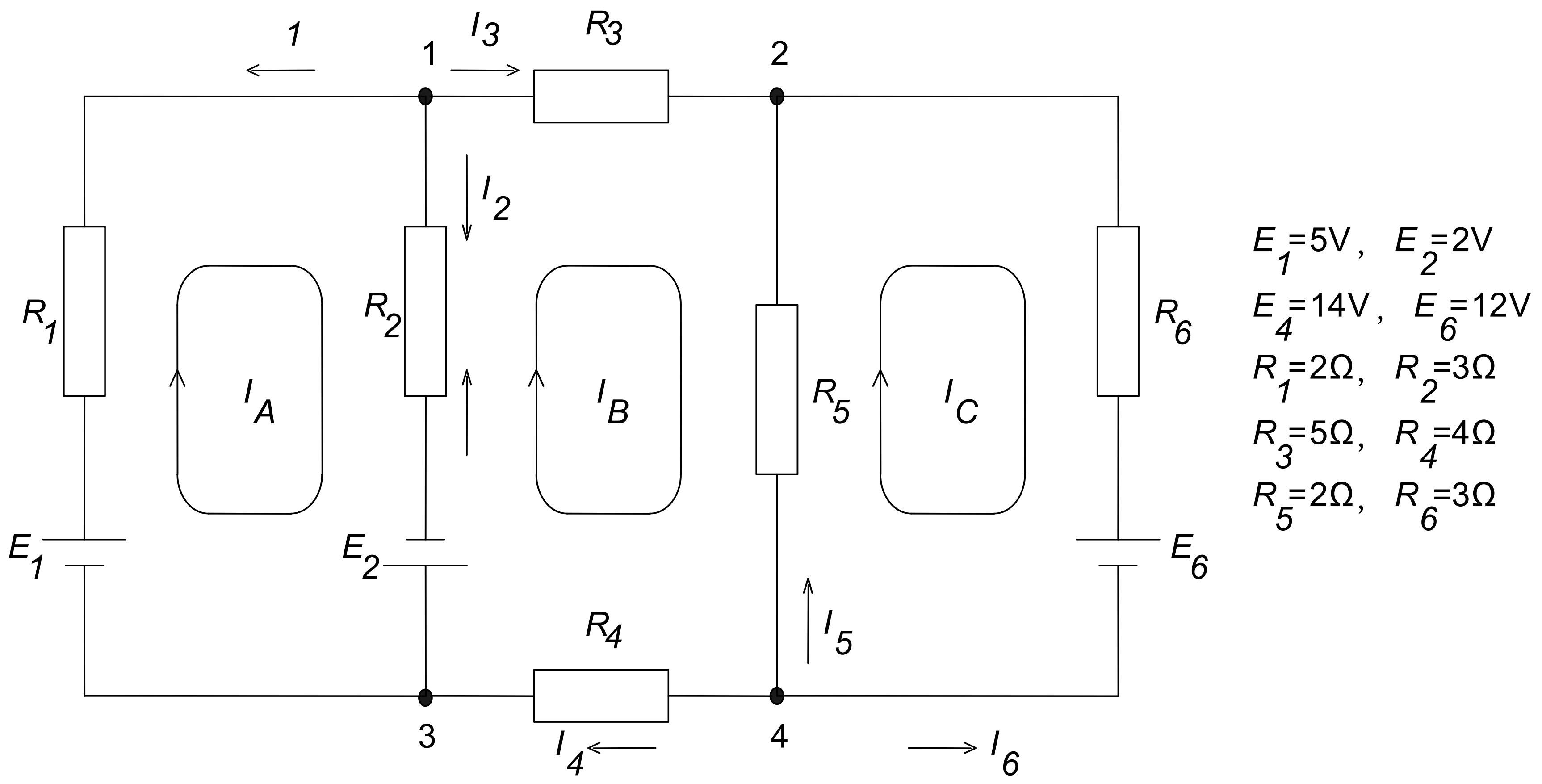
$$\int v(t) \cdot dt = \{v(t) + v(t - \Delta t)\}\Delta t/2$$

From the above two equations,

$$i(t) = (\Delta t/2L)\{v(t) + v(t - \Delta t)\} - i(t - \Delta t) = v(t)/\mathrm{R_L} + J(t - \Delta t)$$

where $J(t - \Delta t) = v\,(t - \Delta t)/R_L + i(t - \Delta t)$

$R_L = 2L/\Delta t$, Δt : time step



Nodal analysis — only conductance matrix [G] at node 1 : $G_1(V_1-E_1-V_3)+G_2(V_1+E_2-V_3)+G_3(V_1-V_2) = 0$

at node 2 : $G_3(V_1-V_2)+G_5V_2+G_6(V_2-E_6) = 0$

at node 3 : $G_4(V_3-E_4)+G_2(V_3-E_2-V_1)+G_1(V_3+E_1-V_1) = 0$

where $G_i = 1/R_i$, $i = 1$ to 6

Rearranging the above equation and writing in a matrix form,

$$\begin{bmatrix} G_1+G_2+G_3 & G_2 & -G_1 - G_2 \\ -G_3 & G_3+G_5+G_6 & 0 \\ -G_1 - G_2 & 0 & G_1+G_2+G_4 \end{bmatrix} \begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix} = \begin{pmatrix} J_1 - J_2 \\ J_6 \\ -J_1+J_2+J_4 \end{pmatrix}$$

or,

$[G](V) = (J)$

where $J_i = G_iE_i$, $i = 1, 2, 4, 6$

$[G]$: node conductance matrix

(3) Circuit elements and subroutines prepared in the EMTP

(a) Circuit elements

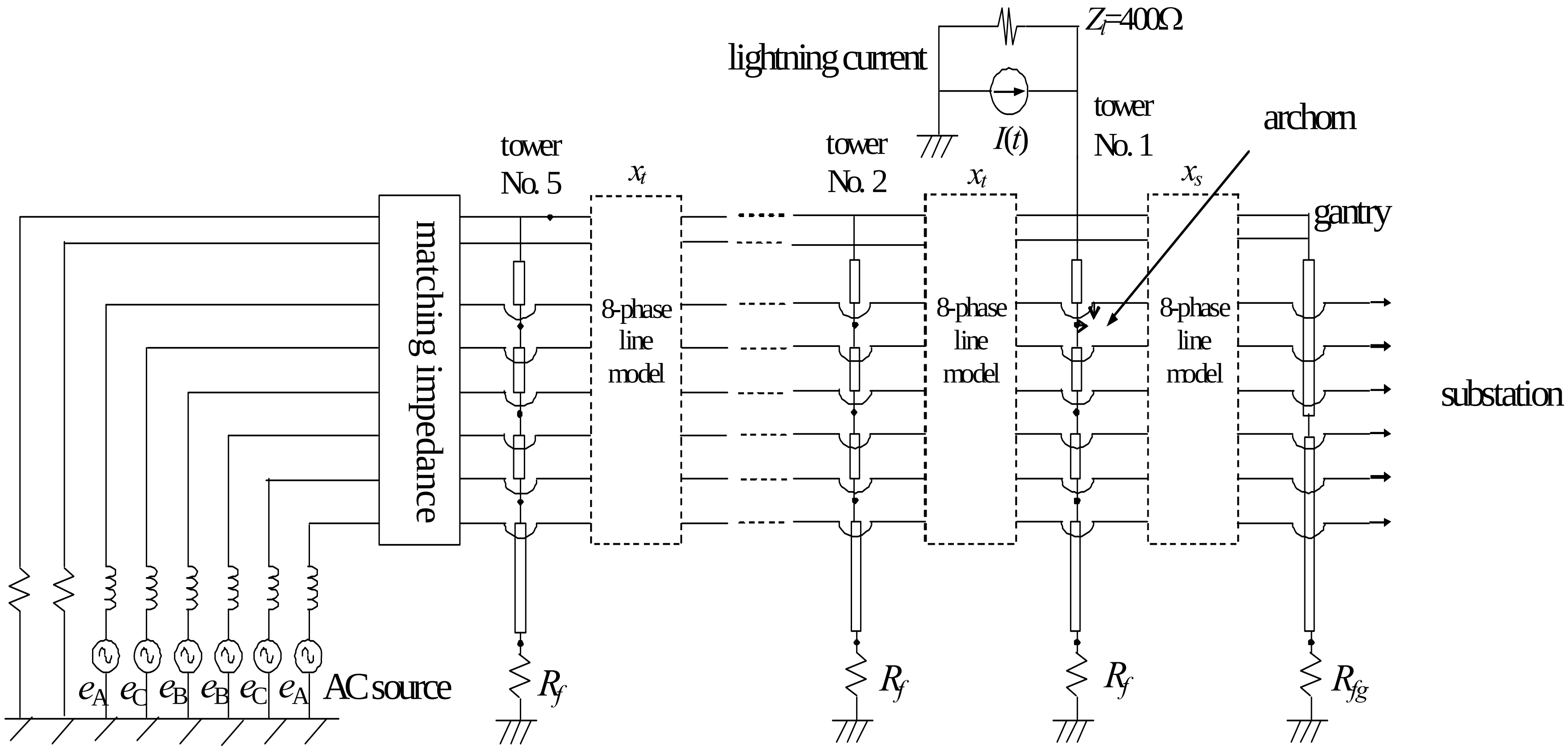
element	model	remark
lumped *R*, *L*, *C*	series, parallel	
line / cable	multi-phase π circuit distributed line with constant parameters frequency-dependent line	transposed, untransposed overhead, underground Semlyen, Marti, Noda
transformer	mutually coupled *R*-*L* element N winding, single-phase 3-phase shell-type 3-phase・3-leg・core-type	single-phase, three-phase saturation, hysteresis
load, nonlinear	starecase *R*(*t*) (type-97) piece-wise time varying *R* (type-91,94) pseudo-nonlinear *R* (type-99) pseudo-nonlinear *L* (type-98) pseudo-nonlinear hysteretic *L* (type-96)	
arrester	exponential function Z_n0 flashover type multi-phase *R* TACS controlled arc model	with gap, gapless
source	step-like (type-11) piece-wise linear (type-12,13) sinusoidal (type-14) impulse (type-15) TACS controlled source	voltage source current source
rotating machine	synchronous generator (type-59) universal machine	synchronous, induction, dc
switch	time-controlled switch flashover switch statistic / systematic switch measuring switch TACS controlled switch (type-12, 13)	circuit breaker
semi-conductor	TACS controlled switch (type-11)	diode, thyristor
control circuit	TACS MODELS	transfer function arithmetics, logics

(b) Supporting routines

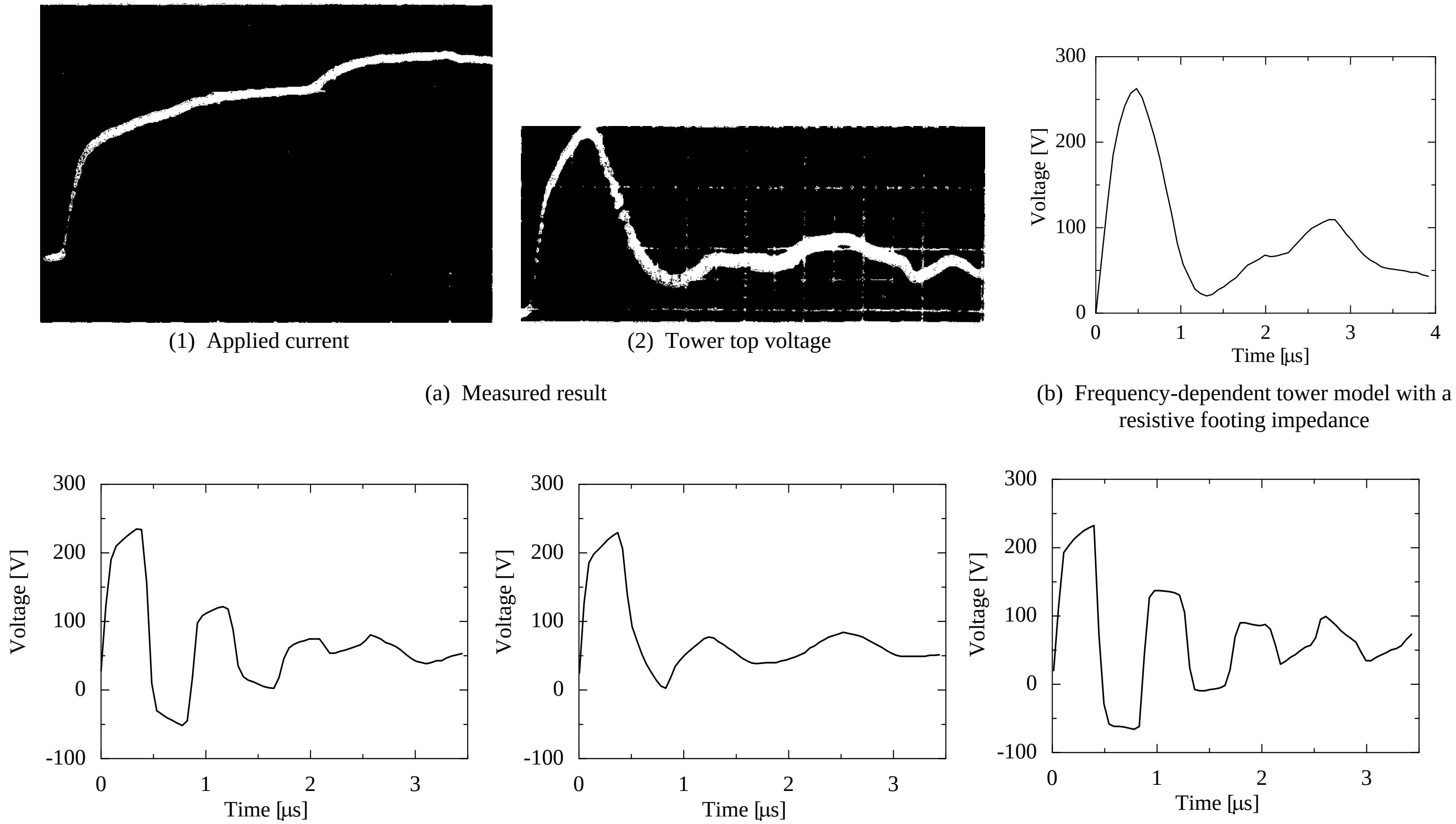
name	function	input data
LINE CONSTANTS	overhead line parameters	frequency, configuration, physical parameters
CABLE CONSTANTS	overhead / underground cable parameters	frequency, configuration, physical parameters
CABLE PARAMETERS	overhead / underground cable parameters distributed Y, snaking	frequency, configuration, physical parameters
XFORMER	transformer parameters	configuration, rating, %*Z*
BCTRAN	transformer parameters	configuration, rating, %*Z*
SATURATION	saturation characteristics	configuration, rating, %*Z*
HYSTERESIS	hysteresis characteristics (type-96)	configuration, rating, %*Z*
NETEQV	equivalent circuit	circuit configuration, *Z*, *Y*, frequency

(4) Application Examples

(a) JEC-0102-1994 High-Voltage Testing Standard



A representative model circuit



(1) Applied current

(2) Tower top voltage

(a) Measured result

(b) Frequency-dependent tower model with a resistive footing impedance

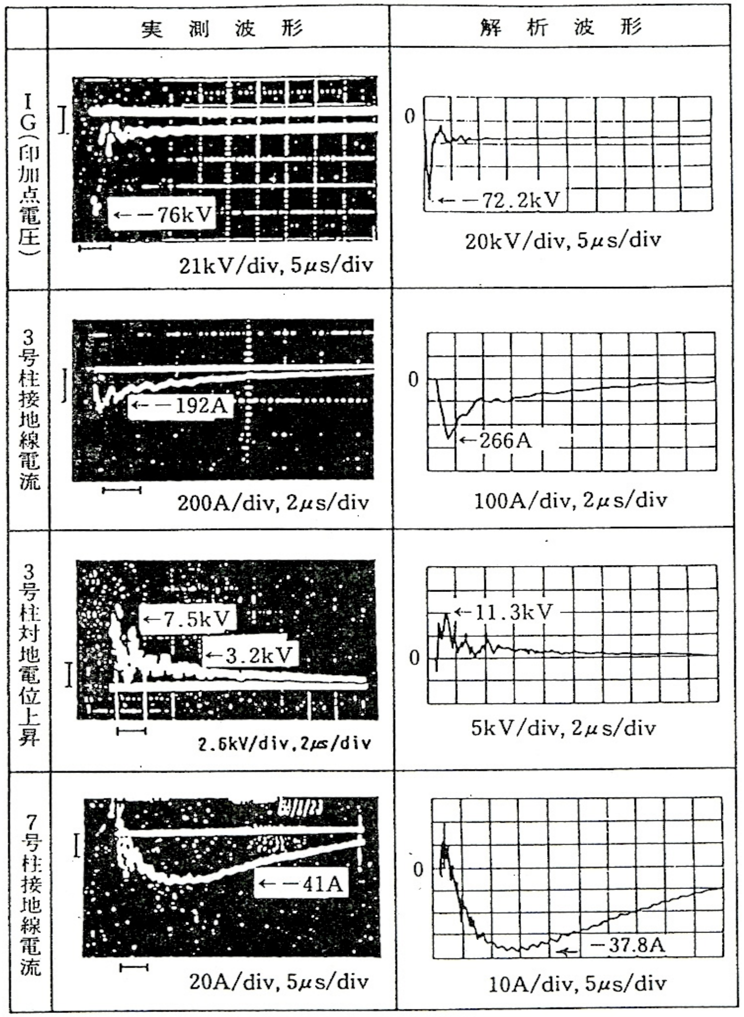
(1) Resistive footing impedance

(2) Inductive footing impedance

(3) Capacitive footing impedance

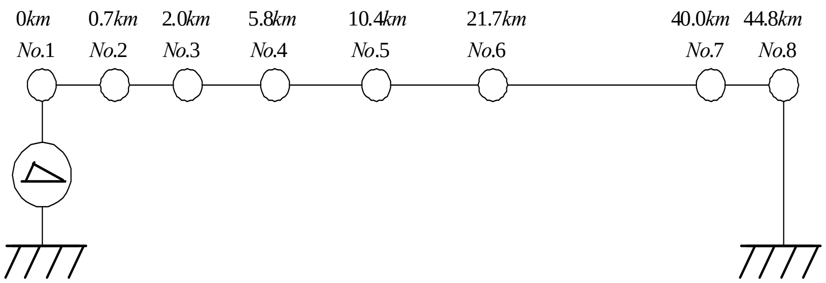
(c) Distributed-line tower model with various footing impedances

Transient response of a tower

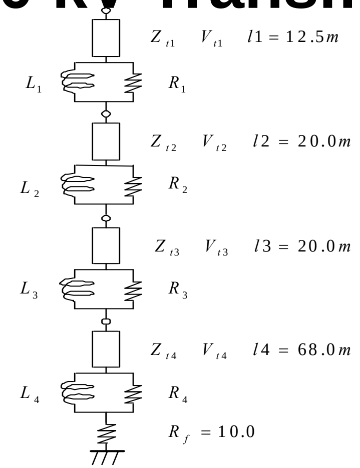


Lighting surges on a distribution line

(b) Design of Japanese 1100 kV Transmission Line

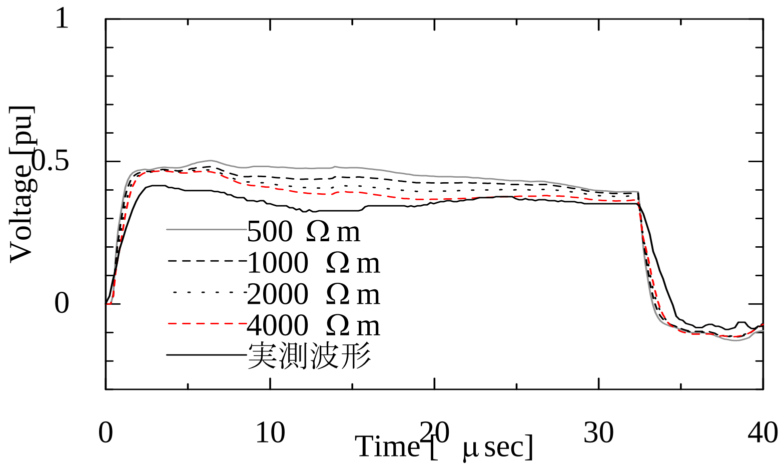


(a) Tested 1100kV transmission line

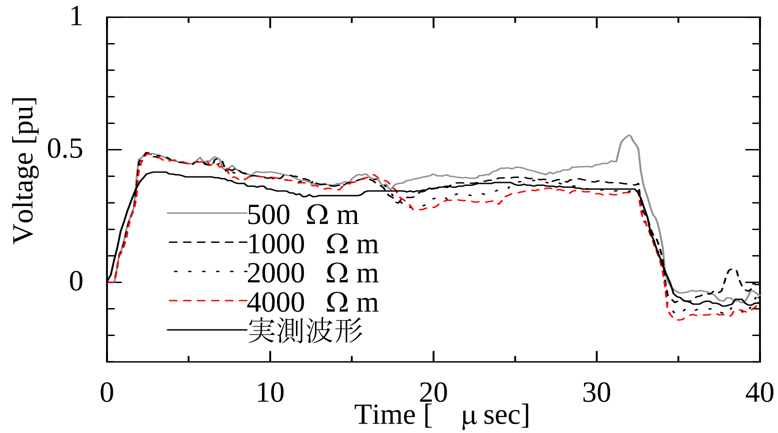


$Z_{t1-3}[\Omega]$	120
$Z_{t4}[\Omega]$	120
$V_{t1-4}[m/\mu s]$	300
$R_1[\Omega]$	10.19
$L_1[\mu H]$	8.186
$R_{2-3}[\Omega]$	16.31
$L_{2-3}[\mu H]$	13.10
$R_4[\Omega]$	42.80
$L_4[\mu H]$	34.38

(b) 1100kV transmission tower



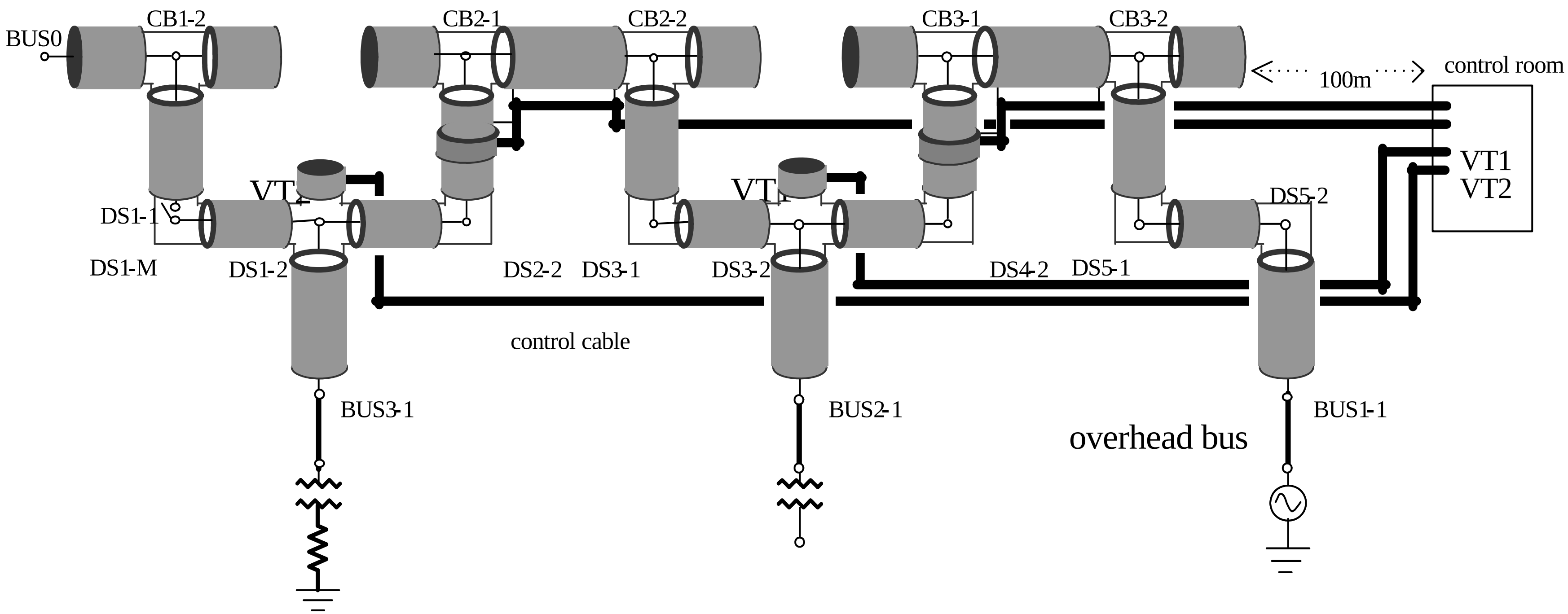
(c) Simulation results by Marti model



(d) Simulation results by Dommel model. (f=3.348kHz)

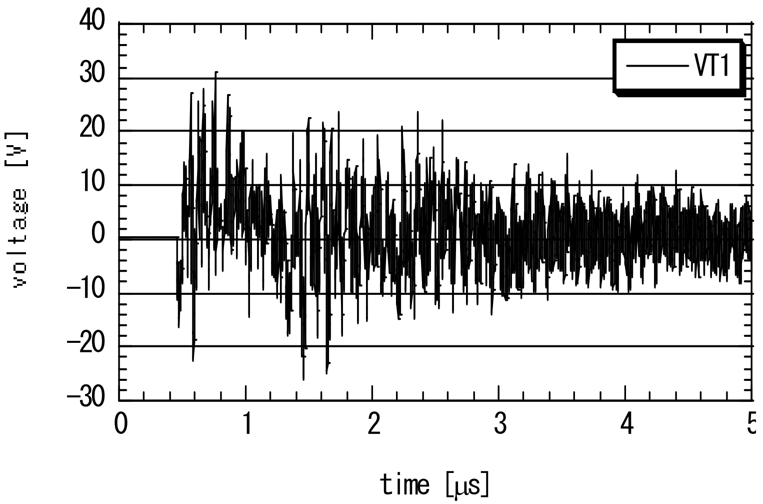
Waveform deformation on Japanese 1100kV transmission line

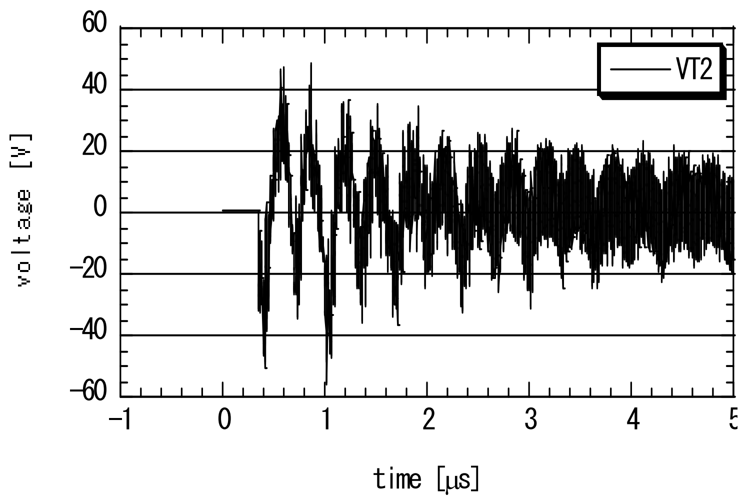
(c) JEC-0103-2005 Standard for Testing Low-Voltage Control Circuits



(a) A model circuit of a 500kV GIS

Switching surges in a gas insulated substation
— Electromagnetic interference





(1) DS3 operation with CB2 open (2) DS1 operation

(b) Induced voltages at the remote end of the control cables

Switching surges in a gas insulated substation
— Electromagnetic interference

(d) JEC-3408-2015 High Voltage Testing Standard of Cables

公称電圧・導体断面積	絶縁厚 mm	絶縁体内径 $2r_1$ mm	絶縁体外径 $2r_2$ mm	ケーブル最高電圧 kV	ケーブル最高電圧/$\sqrt{3}$ V_B kV	回転楕円体長軸半径 a μm
11kV 60mm^2	4	11.3	19.3	12	6.93	843
22 kV 60mm^2	6	11.3	23.3	24	13.86	498
33 kV 60mm^2	8	11.3	27.3	36	20.78	374
66 kV 80mm^2	9	12.8	30.8	72	41.57	162
77 kV 80mm^2	11	12.8	34.8	84	48.50	156
110 kV 100mm^2	17	14.0	48.0	120	69.28	143
154 kV 200mm^2	23	19.0	65.0	168	96.99	136
187 kV 400mm^2	23	26.1	72.1	204	117.78	122
220 kV 200mm^2	23	19.0	65.0	240	138.56	76
275 kV 600mm^2	27	31.5	85.5	300	173.21	86
500 kV 800mm^2	27	38.0	92.0	550	317.54	33

(5) Application Limits / Problems

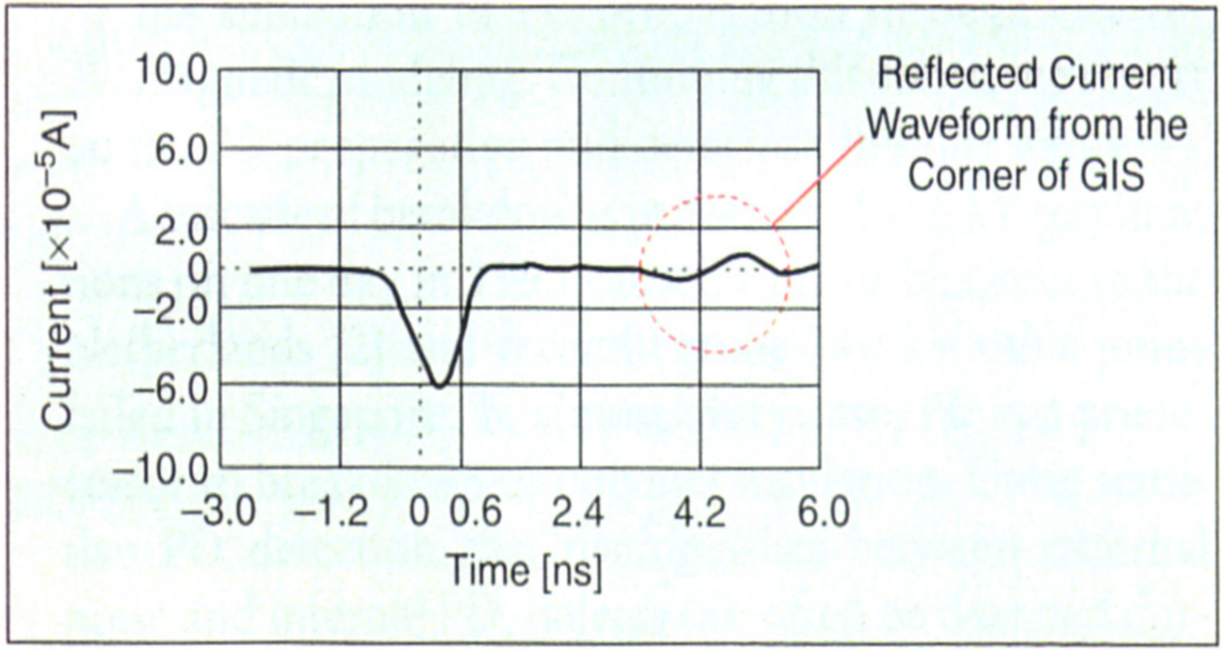
- Any circuit – theory based approach is within TEM mode propagation of electromagnetic waves.

- Impedance / Admittance formulas used in the approach assume :
  length x >> height h >> radius r .

- Unknown parameters :
  earth resistivity along a line and depth
  frequency / temperature – dependent permittivity
  stray capacitance / residual inductance of equipment
  semiconducting layer parameters

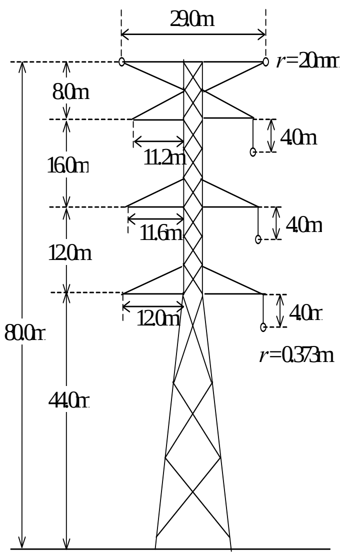
4. Numerical Electromagnetic Analysis

<table>
<tr><td>partition</td><td colspan="5">space</td><td>boundary</td></tr>
<tr><td>discretization/ domain</td><td colspan="2">finite difference</td><td colspan="2">boundary length</td><td>finte element</td><td></td></tr>
<tr><td>time-domain</td><td>FDTD</td><td>TD-FI</td><td>3D circuit</td><td>TLM</td><td>TD-FEM</td><td>MOM (TWTDA)</td></tr>
<tr><td>frequency</td><td>—</td><td>FI</td><td>—</td><td>—</td><td>FEM</td><td>MOM</td></tr>
<tr><td>base equation</td><td>Maxwell diffrential</td><td>Maxwell integral</td><td>Maxwell characteristic</td><td>D’Alembert solution</td><td></td><td>field integral</td></tr>
<tr><td rowspan="2">feature</td><td rowspan="2">easy programing</td><td rowspan="2">multi media</td><td colspan="2">circuit theory extension</td><td rowspan="2">wide application</td><td rowspan="2">Small CPU nonlinear in time domain</td></tr>
<tr><td>hard program.</td><td>easy program.</td></tr>
</table>

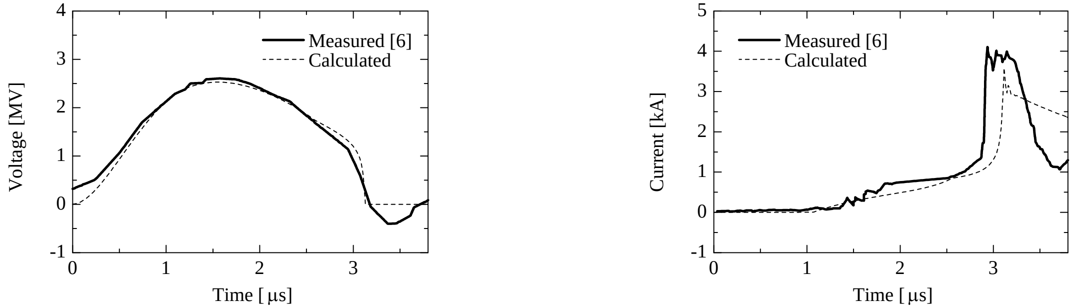


Simulation of partial-discharge pulse propagation in a gas-insulated switchgear by MoM

Comparison with EMTP

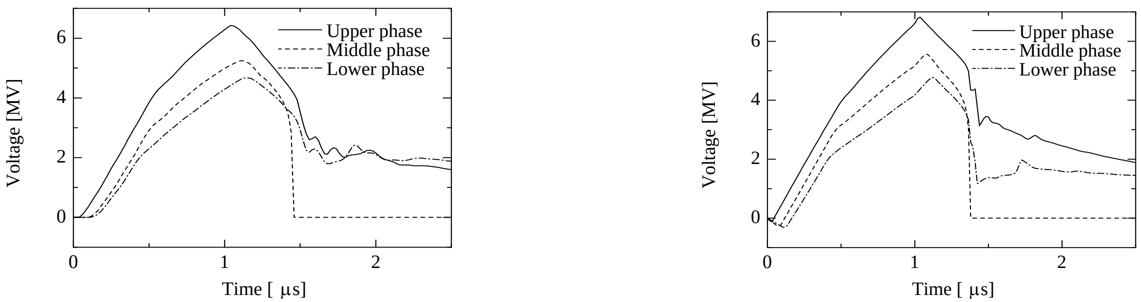


(a) The structure of a model tower subject to analysis.



(1) (2)

(b) Measured waveforms of the voltage of a 3 m gap and the current flowing through it [2], and those computed with the TWTDA code including Motoyama's flashover model. (1) Voltage. (2) Current.



(1) (2)

(c) Waveforms of archorn voltages computed by (1) TWTDA and by (2) EMTP, in the case of a middle-phase back-flashover. (150 kA, 1.0 μs ramp current injection)

5. IPST
(1) History of IPST

0) 1993 Lisbon − European Conference on Power System Transients
1) 1995 Lisbon − International Conference on Power System Transients
2) 1997 Seattle 3) 1999 Budapest
4) 2001 Rio de Janeiro
5) 2003 New Orleans (Due to SARS, originally to be H. K)
6) 2005 Montreal 7) Lyon
8) 2009 Kyoto 9) 2011 Delft
10) 2013 Vancouver 11) 2015 Dubrovnik
12) 2017 Asia?

- Place： Europe→American Continent→Asia/Pacific
- Technical Committee Co-chair： from another continent
- Papers 100～120 in average, participants 200～400

(2) IPST Records

- **IPST '97 June 22-26, Seattle (3.5 days)**

  registration fee US$ 495- on site US$ 585-

  participants 84, papers 74 (Abst. 217), 23 sessions, 1 session 90 min / 3 papers

  LOC Chairman + Committee Members 2 + Conference Management 3

- **IPST 1999 June 20-24, Budapest (3.5 days)**

  US$ 390- (before March 31), US$ 470- (after March 31), on site US$ 550-, papers 109, 22 sessions, 3 parallel,1 session 100min / 5 papers, LOC: 5

- **IPST 2001 June 24-28, Rio de Janeiro (3.5 days)**

  papers 122 (Abst. 270), 23 sessions, 3 parallel,1 session 100 min / 5 papers, LOC: 4

- **IPST 2003 September 28- October 2, New Orleans (3.5 days)**

  US$ 375- before August 31 / after US$ 400-

  participants 92, papers 97, 15 sessions, 1 session 100 min / 4 to 5 papers, LOC: 3

- **IPST 2005 June 19-23, Montreal (3.5 days)**

  papers 129/26 sessions , 1 ses./100

  registration fee CA$ 600 before May 1, after $725 IEEE Member

  CA$ 725 before May 1, after $ 800 Non-member

  CA$ 300 before May 1, after $ 250 Student

  lunch for 3 days

  LOC: 11, Regional Supporting Staffs: 3
- **IPST 2007 4-6 July, Leon (3 days)**
- **IPST 2009, June 2-6, Kyoto (4 days)**

  papers 111, participants 242,

  registration fee early bird ¥70,000-, regular ¥90,000- (€690-)

  lunch for 3 days

  LOC: 8, supporting staffs: 6

(3) Trends

a) IPST expands into

  Power systems, stability, control

  Relaying, fault location

  Power Electronics

b) Real-time simulators

  Application vs development

  Hardware in the loop testing

c) Integration of various tools: MatLab, FEM

d) Numerical Electromagnetic Analysis