



# Power System Transient Analysis

Theory and Practice using  
Simulation Programs (ATP-EMTP)

Eiichi Haginomori • Tadashi Koshiduka  
Junichi Arai • Hisatoshi Ikeda



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# Contents

<b>Preface</b>	<b>ix</b>
<b>Part I Standard Course-Fundamentals and Typical Phenomena</b>	<b>1</b>
<b>1 Fundamentals of EMTP</b>	<b>3</b>
1.1 Function and Composition of EMTP	3
1.1.1 Lumped Parameter RLC	3
1.1.2 Transmission Line	4
1.1.3 Transformer	6
1.1.4 Nonlinear Element	6
1.1.5 Arrester	6
1.1.6 Switch	7
1.1.7 Voltage and Current Sources	7
1.1.8 Generator and Rotating Machine	7
1.1.9 Control	7
1.1.10 Support Routines	7
1.2 Features of the Calculation Method	8
1.2.1 Formulation of the Main Circuit	8
1.2.2 Calculation in TACS	12
1.2.3 Features of EMTP	13
References	16
<b>2 Modeling of System Components</b>	<b>17</b>
2.1 Overhead Transmission Lines and Underground Cables	17
2.1.1 Overhead Transmission Line—Line Constants	17
2.1.2 Underground Cables—Cable Parameters	37
2.2 Transformer	46
2.2.1 Single-Phase Two-Winding Transformer	46
2.2.2 Single-Phase Three-Winding Transformer	50
2.2.3 Three-Phase One-Core Transformer—Three Legs or Five Legs	53
2.2.4 Frequency and Transformer Modeling	55
<b>3 Transient Currents in Power Systems</b>	<b>57</b>
3.1 Short-Circuit Currents	57
3.2 Transformer Inrush Magnetizing Current	60
3.3 Transient Inrush Currents in Capacitive Circuits	62

Appendix 3.A:	Example of ATPDraw Sheets—Data3-02.acp	64
	Reference	64
<b>4</b>	<b>Transient at Current Breaking</b>	<b>65</b>
4.1	Short-Circuit Current Breakings	66
4.2	Capacitive Current Switching	71
4.2.1	<i>Switching of Capacitive Current of a No-Load Overhead Transmission Line</i>	72
4.2.2	<i>Switching of Capacitive Current of a Cable</i>	75
4.2.3	<i>Switching of Capacitive Current of a Shunt Capacitor Bank</i>	76
4.3	Inductive Current Switching	78
4.3.1	<i>Current Chopping Phenomenon</i>	78
4.3.2	<i>Reignition</i>	79
4.3.3	<i>High-Frequency Extinction and Multiple Reignition</i>	80
4.4	TRV with Parallel Capacitance in SLF Breaking	80
Appendix 4.A:	Current Injection to Various Circuit Elements	84
Appendix 4.B:	TRV Calculation, Including ITRV—Current Injection is Applied for TRV Calculation	91
Appendix 4.C:	550 kV Line Normal Breaking	97
Appendix 4.D:	300 kV, 150 MVA Shunt Reactor Current Breaking—Current Chopping—Reignition—HF Current Interruption	100
	References	103
<b>5</b>	<b>Black Box Arc Modeling</b>	<b>105</b>
5.1	Mayr Arc Model	106
5.1.1	<i>Analysis of Phenomenon of Short-Line Fault Breaking</i>	106
5.1.2	<i>Analysis of Phenomenon of Shunt Reactor Switching</i>	110
5.2	Cassie Arc Model	112
5.2.1	<i>Analysis of Phenomenon of Current Zero Skipping</i>	113
Appendix 5.A:	Mayr Arc Model Calculating SLF Breaking, 300 kV, 50 kA, L90 Condition	118
Appendix 5.B:	Zero Skipping Current Breaking Near Generator—Fault Current Lasting	124
Appendix 5.C:	Zero Skipping Current Breaking Near Generator—Dynamic Arc Introduced, Still Nonbreaking	131
<b>6</b>	<b>Typical Power Electronics Circuits in Power Systems</b>	<b>135</b>
6.1	General	135
6.2	HVDC Converter/Inverter Circuits	135
6.3	Static Var Compensator/Thyristor-Controlled Inductor	140
6.4	PWM Self-Communicated Type Inverter Applying the Triangular Carrier Wave Shape Principle—Applied to SVG (Static Var Generator)	142
Appendix 6.A:	Example of ATPDraw Picture	147
	Reference	148



<b>Part II</b>	<b>Advanced Course-Special Phenomena and Various Applications</b>	<b>149</b>
<b>7</b>	<b>Special Switching</b>	<b>151</b>
7.1	Transformer-Limited Short-Circuit Current Breaking	151
7.2	Transformer Winding Response to Very Fast Transient Voltage	152
7.3	Transformer Magnetizing Current under Geomagnetic Storm Conditions	156
7.4	Four-Armed Shunt Reactor for Suppressing Secondary Arc in Single-Pole Rapid Reclosing	159
7.5	Switching Four-Armed Shunt Reactor Compensated Transmission Line	162
	References	163
<b>8</b>	<b>Synchronous Machine Dynamics</b>	<b>165</b>
8.1	Synchronous Machine Modeling and Machine Parameters	165
8.2	Some Basic Examples	167
8.2.1	<i>No-Load Transmission Line Charging</i>	167
8.2.2	<i>Power Flow Calculation</i>	169
8.2.3	<i>Sudden Short-Circuiting</i>	172
8.3	Transient Stability Analysis Applying the Synchronous Machine Model	176
8.3.1	<i>Classic Analysis (Equal-Area Method) and Time Domain Analysis (EMTP)</i>	176
8.3.2	<i>Detailed Transients by Time Domain Analysis: ATP-EMTP</i>	180
8.3.3	<i>Field Excitation Control</i>	183
8.3.4	<i>Back-Swing Phenomenon</i>	186
Appendix 8.A:	Short-Circuit Phenomena Observation in d-q Domain Coordinate	190
Appendix 8.B:	Starting as an Induction Motor	193
Appendix 8.C:	Modeling by the No. 19 Universal Machine	195
Appendix 8.D:	Example of ATPDraw Picture File: Draw8-111.acp (Figure D8.1).	197
	References	198
<b>9</b>	<b>Induction Machine, Doubly Fed Machine, Permanent Magnet Machine</b>	<b>199</b>
9.1	Induction Machine (Cage Rotor Type)	199
9.1.1	<i>Machine Data for EMTP Calculation</i>	200
9.1.2	<i>Zero Starting</i>	201
9.1.3	<i>Mechanical Torque Load Application</i>	204
9.1.4	<i>Multimachines</i>	206
9.1.5	<i>Motor Terminal Voltage Change</i>	208
9.1.6	<i>Driving by Variable Voltage and Frequency Source (VVVF)</i>	209
9.2	Doubly Fed Machine	212
9.2.1	<i>Operation Principle</i>	212
9.2.2	<i>Steady-State Calculation</i>	213
9.2.3	<i>Flywheel Generator Operation</i>	213
9.3	Permanent Magnet Machine	215
9.3.1	<i>Zero Starting (Starting by Direct AC Voltage Source Connection)</i>	217
9.3.2	<i>Calculation of Transient Phenomena</i>	217
Appendix 9.A:	Doubly Fed Machine Vector Diagrams	218
Appendix 9.B:	Example of ATPDraw Picture	219

<b>10</b>	<b>Machine Drive Applications</b>	<b>221</b>
10.1	Small-Scale System Composed of a Synchronous Generator and Induction Motor	221
10.1.1	<i>Initialization</i>	221
10.1.2	<i>Induction Motor Starting</i>	223
10.1.3	<i>Application of AVR</i>	225
10.1.4	<i>Inverter-Controlled VVVF Starting</i>	226
10.2	Cycloconverter	233
10.3	Cycloconverter-Driven Synchronous Machine	237
10.3.1	<i>Application of Sudden Mechanical Load</i>	237
10.3.2	<i>Quick Starting of a Cycloconverter-Driven Synchronous Motor</i>	242
10.3.3	<i>Comparison with the Inverter-Driven System</i>	245
10.4	Flywheel Generator: Doubly Fed Machine Application for Transient Stability Enhancement	248
10.4.1	<i>Initialization</i>	249
10.4.2	<i>Flywheel Activity in Transient Stability Enhancement</i>	254
10.4.3	<i>Active/Reactive Power Effect</i>	254
10.4.4	<i>Discussion</i>	258
Appendix 10.A:	Example of ATPDraw Picture	260
	Reference	266
<b>Index</b>		<b>267</b>

# Preface

The development of the EMTP (Electro-Magnetic Transient Program) has contributed to a revolution in analysis of switching phenomena and insulation coordination, which are critical issues in modern electric power systems. The authors of this book have been engaged in the development of Japan's electric power system, which is one of the most reliable in the world, as engineers of research and development and in universities for 30–50 years. In their careers, they have used EMTP for solving problems. The contents of this book come from their experiences. Although fundamental examples are displayed, they will definitely be practical for existing power systems.

Some of the contents of the book have been used to teach students in universities and engineers in industry. Those students and engineers all gained a splendid skill that proved useful in their jobs. Electric supply companies and manufacturers need skilled engineers; without them, the modern electric power system cannot operate reliably and safely.

The electric power system is changing rapidly and will change in the future both to cope with the growth of electricity demand and to keep the sustainability of modern society. Designers of today's complicated system configurations and operations need the knowledge in this book more than ever before.

The authors strongly hope that young engineers in the field study this book and use it to contribute to society's future.



# **Part I**

## **Standard Course- Fundamentals and Typical Phenomena**



# 1

## Fundamentals of EMTP

The Electromagnetic Transients Program (EMTP) is a powerful analysis tool for circuit phenomena in power systems. Both steady state voltage and current distribution in the fundamental frequency and surge phenomena in a high-frequency region can be solved using EMTP. Selection of suitable models and appropriate parameters is required for getting correct results. Many comparisons of calculation results and actual recorded data are carried out, and accuracy of EMTP is discussed. Through such applications, EMTP is used widely in the world. EMTP can treat not only main equipment but also control functions. ATP-EMTP is a program that came from EMTP. After ATPDraw (which provides an easy, simple, and powerful graphical user interface) was developed, ATP-EMTP was able to expand its user ability.

### 1.1 Function and Composition of EMTP

Built-in models in EMTP are listed in Tables 1.1 and 1.2. Table 1.1 shows a main circuit model and Table 1.2 shows a control model. There are two ways to simulate control; one is TACS (Transient Analysis of Control Systems) and the other is MODELS. MODELS is a flexible modeling language and permits more complex calculations than TACS. All statements in MODELS must be written by the user. MODELS is not covered in this book, but TACS is explained for representing control.

#### 1.1.1 Lumped Parameter RLC

The Series RLC Branch model is prepared for representing power system circuits. Load, shunt reactor, shunt capacitor, filter, and other lumped parameter components are represented using this model.

**Table 1.1** Main circuit model.

Main Circuit Equipment	Built-in Model
Lumped parameter RLC	Series RLC branch
Transmission line, cable	Mutually coupled RLC element, Multiphase PI equivalent (Type 1, 2, 3) Distributed parameter line with lumped R (Type-1, -2, -3) Frequency dependent distributed parameter line, JMARTI (Type-1, -2, -3) Frequency dependent distributed parameter line, SEMLYEN (Type-1)
Transformer	Single-phase saturable transformer Three-phase saturable transformer Three-phase three-leg core-type transformer
Nonlinear element	Mutually coupled RL element (Type 51, 52) Multiphase time varying resistance (Type 91) True nonlinear inductance (Type 93) Pseudo nonlinear hysteretic inductor (Type 96) Staircase time varying resistance (Type 97) Pseudo nonlinear inductor (Type 98) Pseudo nonlinear resistance (Type 99) TACS controlled resistance for arc model (Type 91)
Arrester	Multiphase time-varying resistance (Type 91) Exponential ZnO (Type 92) Multiphase piecewise linear resistance with flashover (Type 92)
Switch	Time-controlled switch Voltage-controlled switch Statistical switch Measuring switch
TACS controlled switch	Diode, thyristor (Type 11) Purely TACS-controlled switch (Type 13)
Voltage source, current source	Empirical data source (Type 1–9) Step function (Type 11) Ramp function (Type 12) Two slopes ramp function (Type 13) Sinusoidal function (Type 14) CIGRE surge model (Type 15) Simplified HVDC converter (Type 16) Ungrounded voltage source (Type 18) TACS controlled source (Type 60)
Generator	Three-phase synchronous machine (Type 58, 59) Universal machine module (Type 19)
Rotating machine	Universal machine module (Type 19)
Control	TACS MODELS

### 1.1.2 Transmission Line

The multiphase PI-equivalent circuit model, Type 1, 2, and 3, is used as a simple line model. It has mutual coupling inductors and is applicable to a transposed or nontransposed three-phase transmission line.



**Table 1.2** Control model.

Control Element	Built-in Function in TACS
Transfer function	$\frac{K}{s}, Ks, \frac{K}{1+Ts}, \frac{Ks}{1+Ts},$ $G \frac{1+N_1s+N_2s^2+\dots+N_7s^7}{1+D_1s+D_2s^2+\dots+D_7s^7}$
Devices	Frequency sensor (50) Relay operated switch (51) Level triggered switch (52) Transport delay (53) Pulse transport delay (54) Digitizer (55) Point-by-point nonlinear (56) Time sequence switch (57) Controlled integrator (58) Simple derivative (59) Input-If selector (60) Signal selector (61) Sample and track (62) Instantaneous min/max (63) Min/max tracking (64) Accumulator and counter (65) RMS meter (66)
Algebraic and logical expression	+, −, *, /, AND, OR, NOT, EQ, GE, SIN, COS, TAN, ASIN, ACOS, ATAN, LOG, LOG10, EXP, SQRT, ABS Free format FORTRAN
Signal source	DC level (Type 11) Sinusoidal signal (Type 14) Pulse (Type 23) Ramp (Type 24)
Input signal from main circuit	Node voltage (Type 90) Switch current (Type 91) Synchronous machine internal signal (Type 92)
Output signal to main circuit	Switch state (Type 93) On/off signal for TACS-controlled switch Signal for TACS-controlled source Torque and field voltage signals for synchronous machine

The distributed parameter line model with lumped resistance, Type-1, -2, and -3, consists of a lossless distributed parameter line model and constant resistances. The resistance is inserted into the lossless line in the mode. Normally the resistance corresponding to the fundamental frequency is used, then this model is applicable to phenomena from the fundamental frequency to the harmonic frequency, in the 1–2 kHz region.

The frequency-dependent distributed parameter line model developed by J. Marti, Semlyen, takes into account line losses at high frequency, even in an untransposed line. It enables the

production of detailed and precise simulation for surge analysis. The required data for use of the model can be obtained using support routine Line Constants or Cable Constants, explained later. Height of transmission line tower, conductor configuration, and necessary data are inputted to the support routine, and the input data for EMTP are calculated by the support routine. Both cables and overhead lines are treated by these support routines.

### 1.1.3 Transformer

A single-phase saturable transformer model is a basic component that permits a multiwinding configuration. The two- or three-winding model is used in many study cases. A pseudo nonlinear inductor is included in this model for saturation characteristics. Input data are resistance and inductance of each winding. A three-phase saturable transformer model also is prepared. The three-phase three-leg transformer is applied for a core type transformer that has a path for air gap flux generated by a zero sequence component. When a hysteresis characteristic is desired, the pseudo nonlinear hysteretic inductor, Type 96, should be used instead of the incorporated pseudo nonlinear inductor. In such a case, the Type 96 branch will be connected outside of the transformer model. The mutually coupled RL element is used for representing a multiwinding transformer; however, self and mutual inductances of all windings are required for input data. This is used for transition voltage analysis in the transformer, which requires a multiwinding model.

### 1.1.4 Nonlinear Element

True nonlinear inductance, Type 93, has a limit on the number of elements one circuit can hold. When the true nonlinear is included, an iterative convergence calculation is carried out at each time step. Therefore, one element is permitted in one circuit. If more than two elements are needed, these elements must be in separate circuits or be separated by a distributed parameter line. The distributed parameter line separates the network internally as explained in the next section; it is a marked advantage of the EMTP calculation algorithm.

Pseudo-nonlinear elements are prepared that can be used without such constraints. An iterative convergence calculation is not applied for the pseudo nonlinear element, but a simple method is applied. That is, after one time step is calculated, a new value on the nonlinear characteristic curve is adopted for the next time step. Then if the pseudo-nonlinear element is used, a small time step must be selected, suppressing a larger change of voltage or current in the circuit during one time step. The pseudo-nonlinear reactor, Type 98, is the same as the element included in the saturable transformer model. A residual flux in an iron core is simulated by use of the pseudo-nonlinear hysteretic inductor, Type 96.

For use of TACS controlled resistance for the arc model, Type 91, the arc equation must be composed by TACS functions.

### 1.1.5 Arrester

In the model Type 92, two models are available: one is the exponential ZnO and the other is the multiphase piecewise linear resistance with flashover. The pseudo-nonlinear resistance is also used as an arrester.

### *1.1.6 Switch*

A time-controlled switch is used for normal open/close operation or fault application. The open action is completed after the current crosses the zero point. A voltage-controlled switch is used as a flashover switch or gap. A statistical switch is used for statistical overvoltage studies.

A measuring switch is always closed, along with current value, though the switch is transferred to TACS for control. The TACS-controlled switch, Type 11, simulates a diode without a firing signal or thyristor with a firing signal, as defined in the TACS controller. A purely TACS-controlled switch, Type 13, closes when the open/close signal becomes 1 and opens when the signal becomes 0, even if the current is flowing. The IGBT (insulated gate bipolar transistor) or self-extinguishing power electronics element is simulated by this switch.

### *1.1.7 Voltage and Current Sources*

Many pattern sources are available and a combination of these sources is applicable.

Sinusoidal function, Type 14, is used for a 50 or 60 Hz power source. If the start time of the source, T-start, is specified in negative, EMTP calculates steady state condition and sets initial values of voltage and current to all branches. The ungrounded voltage source consists of voltage source and ideal transformer without grounding on the circuit side. The TACS-controlled source, Type 60, transfers the calculated signal in TACS to the main circuit as a source.

### *1.1.8 Generator and Rotating Machine*

The three-phase synchronous machines, Type 58 and 59, are modeled by Park equations and permit transient calculations. Three-phase circuits in the machine are assumed to be balanced circuits. Values of internal variables of the machine can be transferred to TACS, and torque and field voltage can be connected from TACS as input signals for the machine. In this model, a mechanical system of shaft with turbines and generators represented by a mass-spring equivalent equation is included and it permits analysis of sub-synchronous resonance phenomena.

The universal machine module, Type 19, is used for modeling of an induction machine or DC machine.

### *1.1.9 Control*

TACS simulates a control part. Input signals for TACS are node voltages, switch currents, internal variables of the rotating machine, and switch status. Output signals from TACS are the on/off signal for the TACS-controlled switch and torque and field voltage for the synchronous machine. Sufficient signal sources, transfer functions, many devices, and algebraic expressions have been prepared, and free-format FORTRAN expression is permitted in addition. Only TACS calculation without the main circuit is accepted.

### *1.1.10 Support Routines*

Support routines are listed in Table 1.3. These support routines are included in EMTP. In the first step the support routine is used and calculated output is obtained. Second, the obtained data are used as input data for EMTP calculation.

**Table 1.3** Support routine.

Support Routine	Function
Cable Constants, Line Constants, Cable Parameters	Calculation of data for frequency-dependent distributed parameter line for overhead line and cable from geometric data and resistivity of the earth
Xformer, Bctran	Calculation of self and mutual inductance of transformer windings from capacity and percentage impedance
Saturation	Calculation of peak value saturation curve from RMS saturation data
Hysteresis	Calculation of hysteresis curve from RMS saturation data

## 1.2 Features of the Calculation Method

The trapezoidal rule is applied in EMTP for numerical integration [1–3]. A simultaneous differential equation is converted to a simultaneous equation with real number coefficient by the trapezoidal rule. The circuit is represented by a nodal admittance equation. The time step for simulation is fixed and ranges from  $t=0$  [s] to T-max [s].

### 1.2.1 Formulation of the Main Circuit

#### 1.2.1.1 Inductance

Figure 1.1 shows an inductance  $L$  between node  $k$  and  $m$ . The basic equation for this circuit is Equation (1.1).

$$e_k - e_m = L \frac{di_{km}}{dt} \quad (1.1)$$

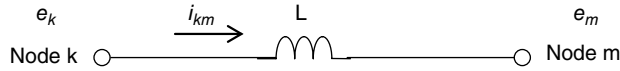
$i_{km}$  at  $t$  is obtained by integration from  $t - \Delta t$ ,

$$i_{km}(t) = i_{km}(t - \Delta t) + \frac{1}{L} \int_{t-\Delta t}^t (e_k - e_m) dt \quad (1.2)$$

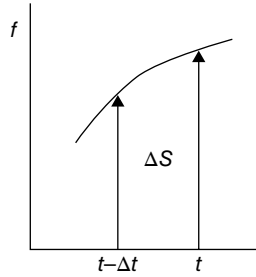
The trapezoidal rule is applied to a time function of  $f$  to get area  $\Delta S$  as shown in Figure 1.2. We get Equation (1.3).

$$\begin{aligned} \Delta S &= \int_{t-\Delta t}^t f(t) dt \\ \Delta S &= \frac{\Delta t}{2} (f(t) + f(t - \Delta t)) \end{aligned} \quad (1.3)$$

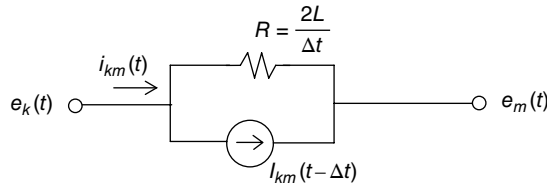
Here  $f(t) = e_k(t) - e_m(t)$  is substituted and Equation (1.2) is replaced by Equations (1.4) and (1.5).



**Figure 1.1** Inductance.



**Figure 1.2** Function  $f$  and area  $\Delta S$ .



**Figure 1.3** Equivalent circuit of inductance.

$$i_{km}(t) = \frac{\Delta t}{2L} (e_k(t) - e_m(t)) + I_{km}(t - \Delta t) \quad (1.4)$$

$$I_{km}(t - \Delta t) = i_{km}(t - \Delta t) + \frac{\Delta t}{2L} (e_k(t - \Delta t) - e_m(t - \Delta t)) \quad (1.5)$$

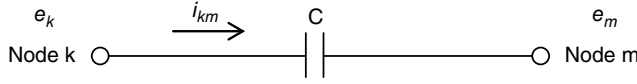
Equation (1.4) is represented by Figure 1.3.

Equation (1.5) is the value of the previous step and is a known value at calculation of time  $t$ . Figure 1.3 shows that the inductance is represented by parallel connection of an equivalent resistance  $R$  and the known current source. Resistance  $R$  is calculated once before time step calculation.

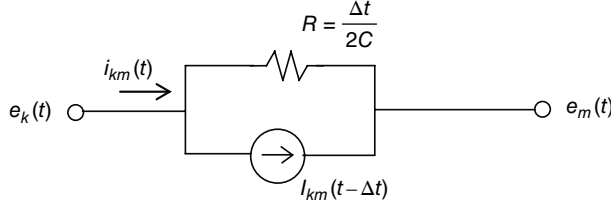
### 1.2.1.2 Capacitance

Capacitance  $C$  between nodes  $k$  and  $m$  is shown in Figure 1.4. The basic equation for this circuit is Equation (1.6).

$$i_{km} = C \frac{d(e_k - e_m)}{dt} \quad (1.6)$$



**Figure 1.4** Capacitance.



**Figure 1.5** Equivalent circuit of capacitance.

By applying the trapezoidal rule to Equation (1.6), Equations (1.7) and (1.8) are obtained and equivalent circuit is shown as in Figure 1.5; that means the capacitance is represented by an equivalent resistance  $R$  and a known current source.

$$i_{km}(t) = \frac{2C}{\Delta t} (e_k(t) - e_m(t)) + I_{km}(t - \Delta t) \quad (1.7)$$

$$I_{km}(t - \Delta t) = -i_{km}(t - \Delta t) - \frac{2C}{\Delta t} (e_k(t - \Delta t) - e_m(t - \Delta t)) \quad (1.8)$$

### 1.2.1.3 Resistance

The resistance shown in Figure 1.6 is represented as it appears.

### 1.2.1.4 Distributed Parameter Line

The distributed parameter line connecting node  $k$  and node  $m$  is shown in Figure 1.7.

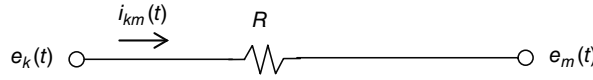
If resistance is ignored, relationships between voltage and current as functions of distance and time are described in differential equations, Equation (1.9).

$$\begin{aligned} -\frac{\partial e}{\partial x} &= L' \left( \frac{\partial i}{\partial t} \right) \\ -\frac{\partial i}{\partial x} &= C' \left( \frac{\partial e}{\partial t} \right) \end{aligned} \quad (1.9)$$

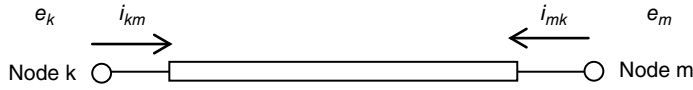
where  $L'$  and  $C'$  are inductance and capacitance per unit length, respectively. The solution is shown in Equation (1.10),

$$\begin{aligned} e_k(t - \tau) + Z * i_{km}(t - \tau) &= e_m(t) - Z * i_{mk}(t) \\ e_k(t) - Z * i_{km}(t) &= e_m(t - \tau) + Z * i_{mk}(t - \tau) \end{aligned} \quad (1.10)$$

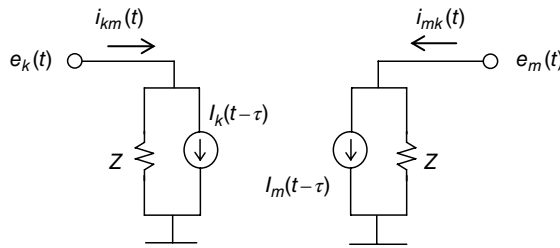
$$Z = \sqrt{L'/C'}, \quad v = 1/\sqrt{L'*C'}, \quad \tau = 1/v$$



**Figure 1.6** Resistance circuit.



**Figure 1.7** Distributed parameter line.



**Figure 1.8** Equivalent circuit for distributed parameter line.

where  $Z$  is surge impedance,  $v$  is propagation velocity, and  $\tau$  is travel time. Equation (1.10) can be represented in Figure 1.8.

At node  $k$ , voltage and current are expressed by Equation (1.11). This means the current  $i_{km}(t)$  is represented by voltage at self node  $k$  and a known current before travel time  $\tau$ . As a result, the two nodes can be treated as separated circuits.

$$\begin{aligned} i_{km}(t) &= \frac{1}{Z} e_k(t) + I_k(t-\tau) \\ I_k(t-\tau) &= -\frac{1}{Z} e_m(t-\tau) - i_{mk}(t-\tau) \end{aligned} \quad (1.11)$$

### 1.2.1.5 Nodal Equation

The nodal equation of the circuit is formulated in Equation (1.12) by applying the trapezoidal rule.

$$[Y] * [e(t)] = [i(t)] - [I] \quad (1.12)$$

where  $Y$  = node conductance matrix (real value),  $i(t)$  = injection current vector, and  $I$  = known current vector.

Equation (1.12) is represented as Equation (1.13) by dividing it into unknown and known values. Finally, the unknown value is solved as in Equation (1.14).

$$Y_{AA} = \begin{bmatrix} \text{shaded} & 0 & 0 & 0 \\ 0 & \text{shaded} & 0 & 0 \\ 0 & 0 & \text{shaded} & 0 \\ 0 & 0 & 0 & \text{shaded} \end{bmatrix} \quad \text{0 is null matrix}$$

**Figure 1.9** Admittance matrix with distributed parameter lines.

$$\begin{bmatrix} Y_{AA} & Y_{AB} \\ Y_{BA} & Y_{BB} \end{bmatrix} \begin{bmatrix} e_A(t) \\ e_B(t) \end{bmatrix} = \begin{bmatrix} i_A(t) \\ i_B(t) \end{bmatrix} - \begin{bmatrix} I_A \\ I_B \end{bmatrix} \quad (1.13)$$

Unknown      Known  
 ↙                      ↘  
 Known              Unknown

$$[e_A(t)] = [Y_{AA}]^{-1} * \{[i_A(t)] - [I_A] - [Y_{AB}] * [e_B(t)]\} \quad (1.14)$$

In EMTP voltage,  $e_A(t)$  is calculated at each time step until T-max is reached.

If a distributed parameter line is used in the circuit, the admittance matrix  $Y_{AA}$  is divided into a small size matrix as shown in Figure 1.9, due to Figure 1.8. It contributes a short computation time and error reduction.

### 1.2.2 Calculation in TACS

The trapezoidal rule is also applied in TACS. A general transfer function,  $G(s)$  of Equation (1.15), is taken for explanation.

$$X(s) = G(s) * U(s)$$

$$G(s) = \frac{N_0 + N_1 s + N_2 s^2 + \dots + N_m s^m}{D_0 + D_1 s + D_2 s^2 + \dots + D_n s^n} \quad (1.15)$$

$U$  is input,  $X$  is output, and  $s$  is a Laplace operator.

Laplace operator  $s$  is replaced by  $d/dt$  for transient analysis, then Equation (1.15) is represented by differential Equation (1.16).

$$D_0 x + D_1 \frac{dx}{dt} + D_2 \frac{d^2 x}{dt^2} + \dots + D_n \frac{d^n x}{dt^n} = N_0 u + N_1 \frac{du}{dt} + N_2 \frac{d^2 u}{dt^2} + \dots + N_m \frac{d^m u}{dt^m} \quad (1.16)$$

New variables are introduced as follows:

$$x_1 = \frac{dx}{dt}, x_2 = \frac{dx_1}{dt}, \dots, x_n = \frac{dx_{(n-1)}}{dt}$$



$$u_1 = \frac{du}{dt}, u_2 = \frac{du_1}{dt}, \dots, u_n = \frac{du_{(n-1)}}{dt}$$

The trapezoidal rule is applied for  $x_1 = \frac{dx}{dt}$ ,

$$x_1 = \frac{2}{\Delta t} x(t) - \left\{ x_1(t - \Delta t) + \frac{2}{\Delta t} x(t - \Delta t) \right\}$$

The second term on the right hand side is the known value. Finally, Equation (1.15) is represented by simultaneous linear equations.

$$c * x(t) = d * u(t) + Hist(t - \Delta t) \quad (1.17)$$

where  $c$  and  $d$  are coefficients. They are calculated uniquely by time step  $\Delta t$  and parameters of transfer function. The calculation of these coefficients is required once before transient calculation.

### 1.2.3 Features of EMTP

#### 1.2.3.1 Relationship between the Main Circuit and TACS

Although the main circuit and TACS part must be solved essentially simultaneously, EMTP calculates them independently [4]. The main circuit at time  $t$  is calculated initially. Voltage and current signals are transferred to TACS and calculation of TACS is carried out. The output of TACS is used in the main circuit calculation of the next time,  $t + \Delta t$ . The output of TACS is on/off pulse signal for TACS-controlled switch or exciter voltage for synchronous generator. In most cases, the controller has a delay at the input and output stages, so selection of a reasonably small time step will make the error negligible. If a large time step is selected, attention should be given to the calculation error.

#### 1.2.3.2 Initial Setting

Initial values on all branches are set automatically if a negative T-start of the sinusoidal source is specified. EMTP calculates the steady state condition by complex plane and the value of the real part is set to each branch. The steady state calculation permits only one frequency. In TACS, the initial DC value can be inputted by the user.

#### 1.2.3.3 Nonlinear Branch

Only one true nonlinear branch is accepted due to performing the iterative convergence calculation. There is no such restriction for a pseudo-nonlinear branch.

#### 1.2.3.4 Floating Circuit

A floating circuit must be avoided due to calculation error at the inverse calculation of the admittance matrix. This is measured by connecting the stray capacitance to the ground.

### 1.2.3.5 Calculation Order in TACS

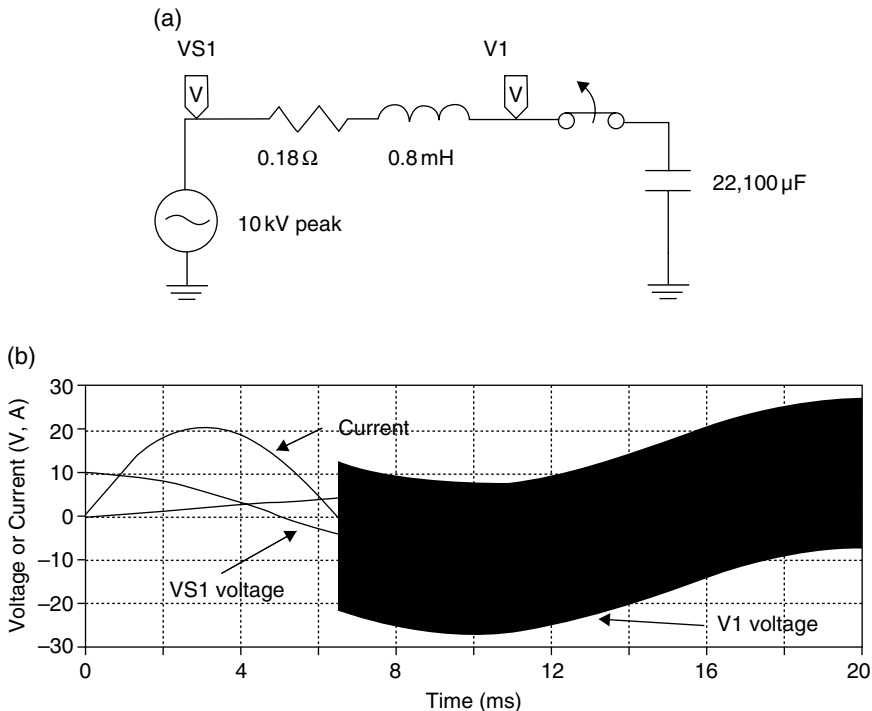
Calculation order of control elements is determined automatically. When the device in Table 1.2 is used, EMTP cannot determine its order. The user must specify its order by indicating the place, in input side, in output side, or internal position between transfer functions.

### 1.2.3.6 Switch and Apparent Oscillation

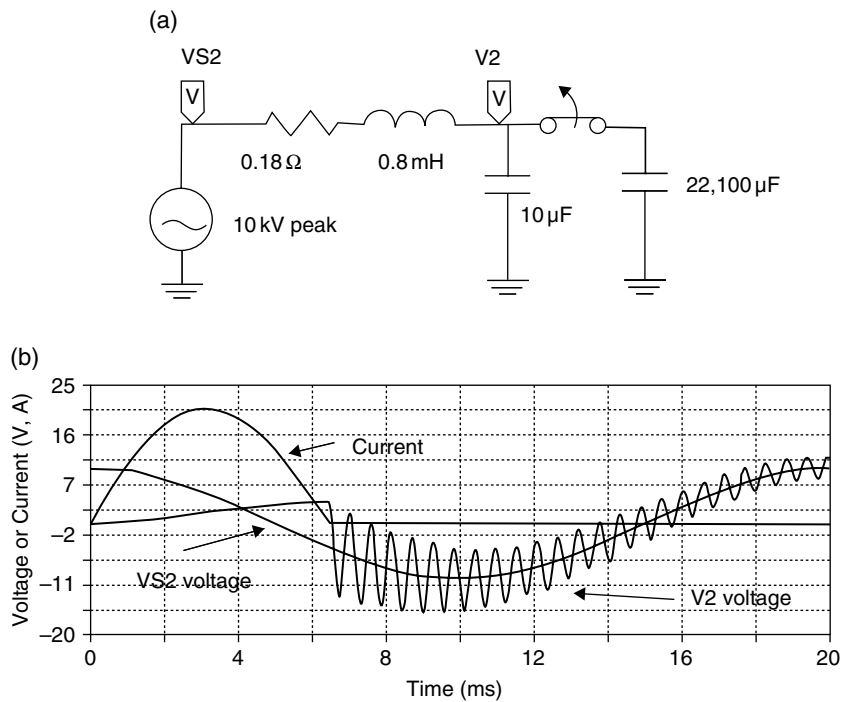
In normal use of the time switch when the open order is given to the switch, the switch memorizes the current direction and opens after the current changes the sign, that is, from plus to minus, or from minus to plus. EMTP adopts the fixed time step calculation, so then the switch current is not zero at the opened time. Due to this algorithm, apparent oscillation appears on the voltage at the terminal of inductance, as shown in Figure 1.10a, b. Figure 1.10a shows the interruption of pure inductance current and voltage at node V1. At node V1 there is no branch to the ground and apparent voltage oscillation is obtained. This oscillation appears at each time step. In an actual system there is no such condition; part of the branch exists as a stray capacitor. In Figure 1.11a, b a small capacitance,  $10\mu\text{F}$ , is connected at node V2, and the apparent oscillation disappears. This problem that causes current oscillation when pure capacitance is closed by the switch can be solved by adding reactance in series.

### 1.2.3.7 ATPDraw

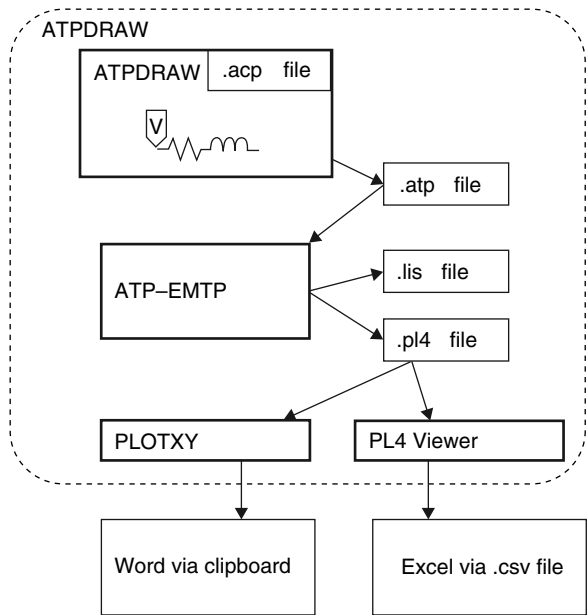
ATPDraw is a graphical preprocessor for ATP-EMTP [5], and it allows execution of ATP-EMTP and PLOTXY. Figure 1.12 shows a simple outline and relating files for normal use.



**Figure 1.10** Reactor current interruption. (a) Circuit. (b) Current and voltages.



**Figure 1.11** Reactor current interruption with capacitor modification. (a) Circuit. (b) Current and voltages.



**Figure 1.12** Outline of ATPDraw.

## References

- [1] H. W. Dommel (1969) Digital computer solution of electromagnetic transients in single- and multiphase network, *IEEE Transactions on Power Apparatus and Systems*, **PAS-88**, 4, 388–399.
- [2] H. W. Dommel, W. S. Meyer (1974) Computation of electromagnetic transients, *Proceeding of the IEEE*, **62** (7), 983–993.
- [3] H.W. Dommel (1986) *Electromagnetic Transients Program Reference Manual (EMTP Theory Book)*, BPA.
- [4] W. Scott Meyer, T.-H. Liu (1992) *Alternative Transients Program (ATP) Rule Book*, Canadian/American EMTP User Group.
- [5] L. Prikler, H. K. Hoidalén (2002) *ATPDRAW Version 3.5 for Windows 9x/NT/2000/XP Users' Manual*, SINTEF.

# 2

## Modeling of System Components

### 2.1 Overhead Transmission Lines and Underground Cables

#### 2.1.1 Overhead Transmission Line—Line Constants

##### 2.1.1.1 General

##### 2.1.1.1.1 Inductance of Single Conductor over the Earth

When a single conductor is located over the Earth's surface, the magnetic images are as shown in Figure 2.1 and self-inductance is written as in Equation (2.1). Table 2.1 shows the self-inductances in the case of changing  $H_e$ . The self-inductance increases with  $H_e$ .

$$L = \frac{\mu_0}{2\pi} \left( 1 + 2 \ln \frac{2H_e}{r} \right) \quad (2.1)$$

##### 2.1.1.1.2 Capacitance of Single Conductor over the Earth

A conductor with a radius  $r$  (m) is located at  $h$  (m) high over the Earth and has an electric charge  $+q$  (c) per unit length, as shown in Figure 2.2. Generally, the permittivity of Earth,  $\epsilon e$ , is quite large compared with the permittivity of air,  $\epsilon a$ . The electric field lines from the conductor will flow into the Earth vertically. The voltage distribution of Earth's surface will be flat. We can treat the Earth as a conductor. The electric field in the air will be treated as shown in Figure 2.3.

The voltage between two conductors is expressed by Equation (2.2).

$$v_{11} = \frac{q}{\pi \epsilon_0} \ln \frac{2h}{r} \quad (2.2)$$