7. SIMPLE VOLTAGE AND CURRENT SOURCES

Most of the simple sources are either voltage or current sources defined as a time-dependent function f(t),

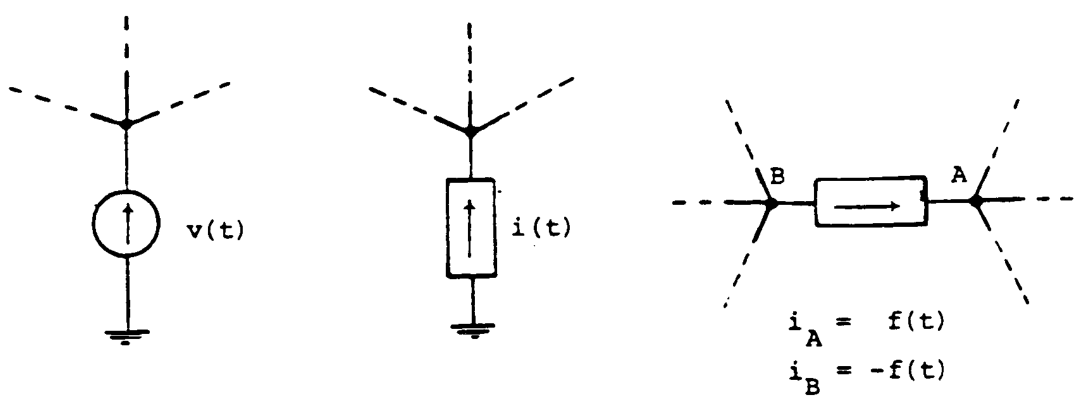
$$v(t) = f(t), \quad or \quad i(t) = f(t) \tag{7.1}$$

Frequently used functions f(t) are built into the EMTP. There is also a current-controlled dc voltage source for simplified HVDC simulations, which is more complicated than Eq. (7.1). In addition to the built-in functions, the BPA version of the EMTP allows the user to define functions through user-supplied FORTRAN subroutines, and to declare TACS output variables as voltage or current source functions. The UBC version of the EMTP does not have these two options, but allows the user to read f(t) step by step in increments at Δt. This option has rarely been used, however.

Note that f(t) = 0 for a current source implies that the source is disconnected from the network (i = 0), whereas for a voltage source it implies that the source is short-circuited (v = 0).

7.1 Connection of Sources to Nodes

If a voltage or current source is specified at a node, it is assumed to be connected between that node and local ground, as shown in Fig. 7.1. A voltage source of v(t) = +1.0 V means that the potential at that node is +1.0 V with respect to local ground, whereas a current source of +1.0 A implies that 1.0 A flows from the local ground into that node.



(a) Voltage source between node and local ground

(b) Current source from local ground into node

(c) Current source between two nodes

Fig. 7.1 - Source connections

7.2 Current Sources Between Two Nodes

Current sources between two nodes, e.g., a current leaving node B and entering into node A as shown in Fig. 7.1(c), must be specified as two current sources, namely as

$$i_A(t) = f(t) \ , \qquad and \quad i_B(t) = -f(t) \tag{7.2}$$

7.3 Voltage Sources Between Two Nodes

Until recently, voltage sources could not be connected between two nodes. With the addition of ideal transformers to the BPA EMTP in 1982 (Section 6.8), voltage sources between two nodes are easy to set up now. In Fig. 6.25, simply ground node $\mathcal{L}$, connect the voltage source from node j to ground, and use a transformer ratio of 1:1. This will introduce a voltage source between nodes k and m. A special input option has been provided for using the ideal transformer for this particular purpose.

The UBC EMTP and older versions of the BPA EMTP do not accept voltage sources between nodes. One could use the equivalent circuit of Fig. 6.27 for the ideal transformer, however, which turns into the circuit of Fig. 7.2. This representation works in the transient solution part of the UBC EMTP, provided the branches of Fig. 7.2 are read in last. In that case, the node "extra" will be forced to the bottom of the equations as shown in Fig. 6.26. The steady-state subroutine in both versions, as well as the transient solution in the BPA version, use optimal re-ordering of nodes, which may not force the row for node "extra" far enough down to assure nonzero diagonal elements during the Gauss elimination. Using Fig. 7.2 may therefore not always work, unless minor modifications are made to the re-ordering subroutine.

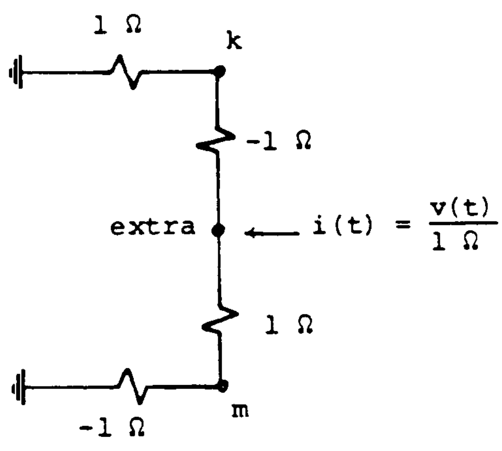


Fig. 7.2 - Equivalent circuit for voltage source v(t) between nodes k and m

In all versions, a voltage source in series with a (nonzero) impedance can always be converted into a current source in parallel with that impedance. The current source between the two nodes is then handled as shown in Eq.

(7.2). The conversion from a Thevenin equivalent circuit (v in series with Z) to a Norton equivalent circuit (i in parallel with Z) is especially simple if the impedance is a pure resistance R, as shown in Fig. 7.3.

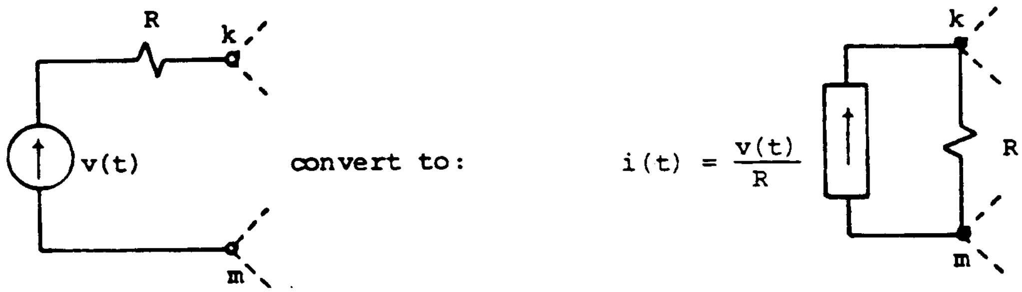


Fig. 7.3 - Conversion of v(t) in series with R into i(t) = v(t)/R in parallel with R

Converting a voltage source in series with an inductance L into a current source with parallel L is slightly more complicated. L is again connected between nodes k and m, in the same way as R in Fig. 7.3. The definition of the current source depends on the initial conditions, however. For example, if

$$v(t) = V_{max} \cos(\omega t + \phi) \tag{7.3}$$

and if the case starts from zero initial conditions, then

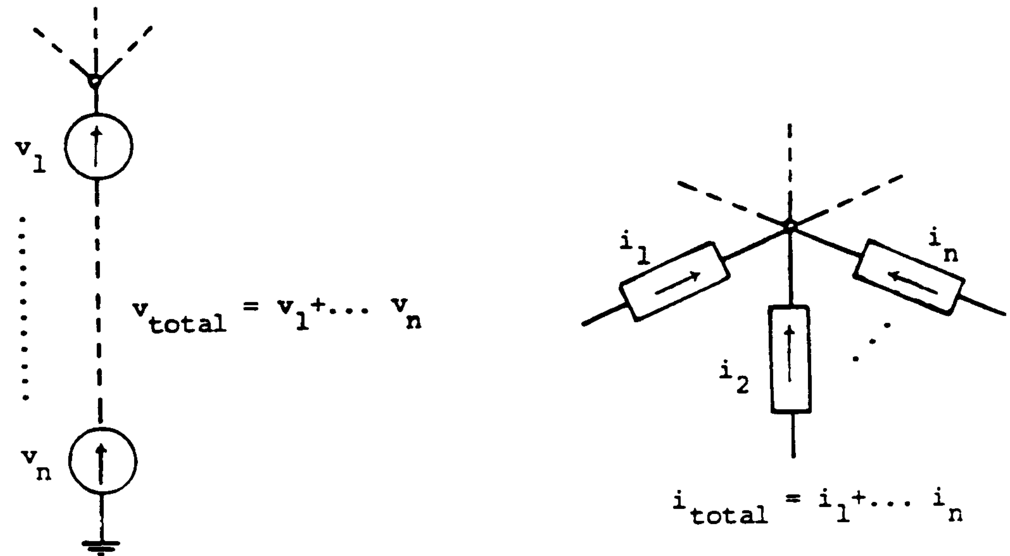
$$i(t) = \frac{V_{max}}{\omega L} [\sin(\omega t + \phi) - \sin\phi] \tag{7.4a}$$

If the case starts from linear ac steady-state conditions, with that voltage source being included in the steady-state solution, then

$$i(t) = \frac{V_{max}}{\omega L} \cos(\omega t + \phi - 90°) \tag{7.4b}$$

7.4 More Than One Source on Same Node

If more than one voltage source is connected to the same node, then the EMTP simply adds their functions $f_1(t), \ldots f_n(t)$ to form one voltage source. This implies a series connection of the voltage sources between the node and local ground, as shown in Fig. 7.4(a).



(a) Series connection of sources

(b) Parallel connection of current sources

Fig. 7.4 - Multiple voltage or current sources on same node

If more than one current source is connected to the same node, then the EMTP again adds their functions $f_1(t),\ldots f_n(t)$ to form one current source. This implies a parallel connection of the current sources, as shown in Fig. 7.4(b).

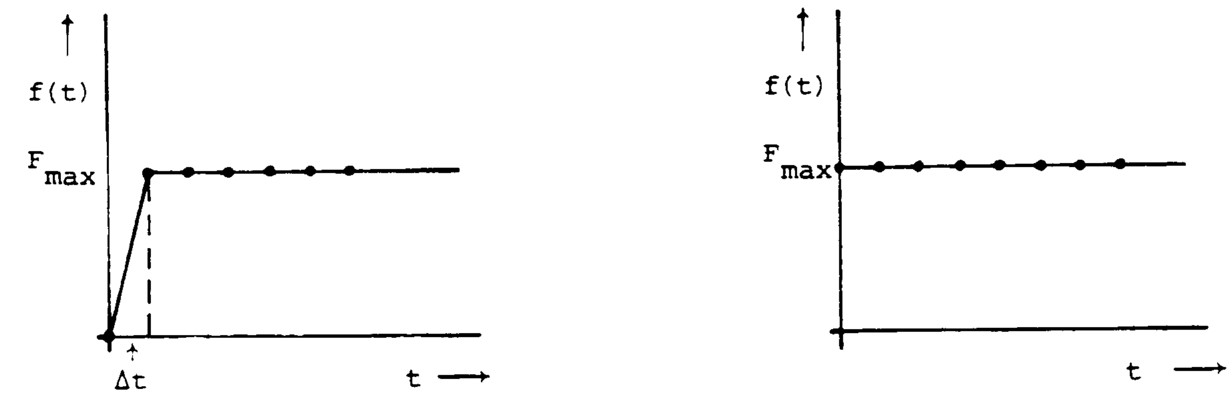
Source functions can be set to zero by using parameters t_{START} and T_{STOP}. The EMTP sets $f(t) = 0$ for $t < T_{START}$ and for $t \geq T_{STOP}$. By using more than one source function at the same node with these parameters, more complicated functions can be built up from the simple functions, as explained in the UBC User's Manual and in the BPA Rule Book.

If voltage and current sources are specified at the same node, then only the voltage sources are used by the EMTP, and the current sources are ignored. Current sources would have no influence on the network in such a case, because they would be directly short-circuited through the voltage sources.

7.5 Built-in Simple Source Functions

Commonly encountered source functions are built into the EMTP. They are:

(a) Step function (type 11). In cases which start from zero initial conditions, the step function is approximate in the sense that the EMTP will see a finite rise time from $f(0) = 0$ to $f(\Delta t) = F_{max}$, as shown in Fig. 7.5.



(a) Starting from zero initial conditions

(b) Starting from initial value F_{max}

Fig. 7.5 - Step function

(b) Ramp function (type 12) with f(t) as shown in Fig. 7.6. The value of the function rises linearly from T_{START} to $T_{START} + T_0$ to a value of F_{max}, and then remains constant until it is zeroed at $t \geq T_{STOP}$.

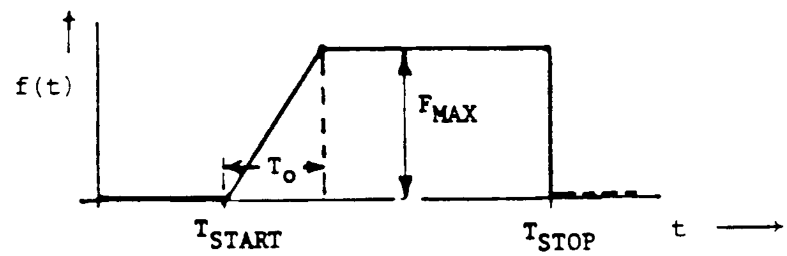


Fig. 7.6 - Ramp function

A modified ramp function (type 13) has the same rise to F_{max} at $T_{START} + T_0$ as in Fig. 7.6, but decays or rises with a linear slope thereafter. By setting $T_{START} = 0$ and $T_0 = 0$, this becomes a step function with a superimposed linear decay or rise.

(c) Sinusoidal function (type 14) with

$$f(t) = F_{\max} \cos(\omega t + \phi) \qquad if \quad T_{START} \leq 0 \tag{7.5a}$$

or

$$f(t) = F_{\max} \cos(\omega (t - T_{START}) + \phi) \qquad if \quad T_{START} > 0 \tag{7.5b}$$

$$with \qquad f(t) = 0 \qquad for \ t < T_{START}$$

This is probably one of the most used source functions. Note that the peak value F_{max} must be specified, rather than the RMS value. To start a case from linear ac steady-state conditions, or to obtain a sequence of steady-state solutions at a number of frequencies, use $T_{START} < 0$ to indicate to the EMTP that this sinusoidal source should be used for the steady-state solution. The value of T_{START} is immaterial as long as its value is negative, and the complex peak phasor used for that source is then

$$V \text{ or } I = F_{max}\, e^{j\phi} \tag{7.6}$$

(d) Impulse function (type 15) of the form

$$f(t) = k\left(e^{-\alpha_1 t} - e^{-\alpha_2 t}\right) \tag{7.7}$$

This function has been provided for the representation of lightning or switching impulses, as used in standard impulse tests on transformers and other equipment. A typical lightning impulse voltage is shown in Fig. 7.7 [126], and a typical switching impulse voltage is shown in Fig. 7.8 [126]. There is no simple relationship between the time constants $1/\alpha_1$ and a/α_2 in Eq. (7.7) and the virtual front time T_1 (or time to crest T_{cr}) and the virtual time to half-value T_2. Table 7.1 shows the values for frequently used waveshapes, as well as values for k which produce a maximum value of $f_{max} = 1.0$ in Eq. (7.7). The time at which the maximum occurs is found by setting the derivative $df/dt = 0$ from Eq. (7.7) and solving for t_{max}. Inserting t_{max} into Eq. (7.7) then produces f_{max}. Note that $1/\alpha_1$ and $1/\alpha_2$ in Table 7.1 are in μs, whereas the EMTP input is usually in s.

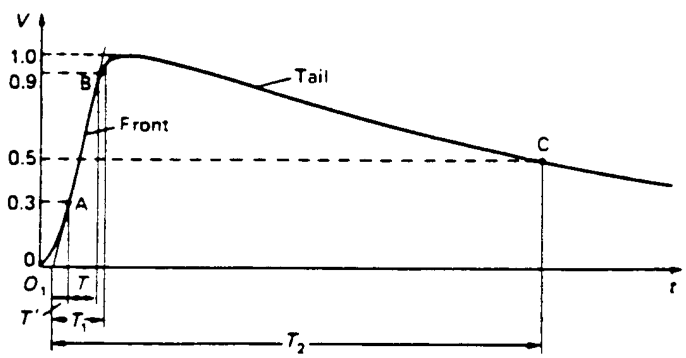


Fig. 7.7 - General shape of lightning impulse voltage (IEC definitions: T_1 = virtual front time, typically 1.2 μs $\pm$ 30%; T_2 = virtual time to half-value, typically 50 μs $\pm$ 20%). Reprinted with permission from [126], © 1984, Pergamon Books Ltd

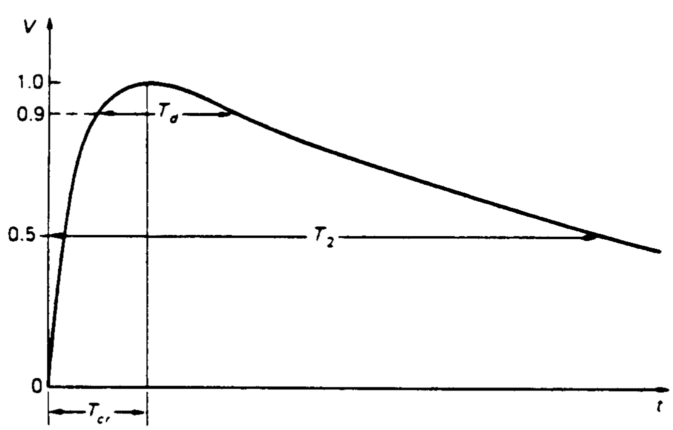


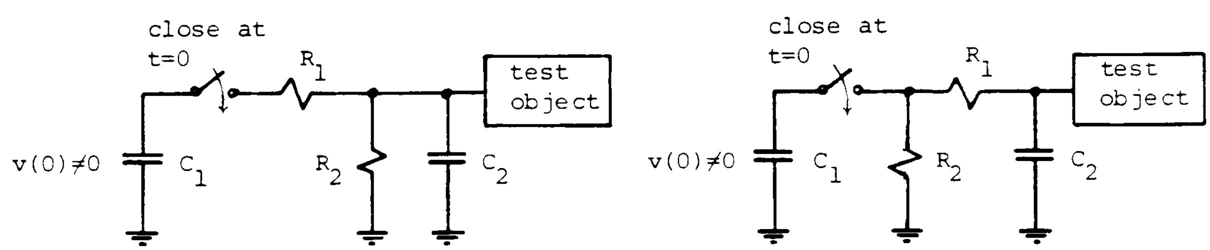
Fig. 7.8 - General shape of switching impulse voltage (IEC definitions: T_{cr} = time to crest, typically 250 μs $\pm$ 20%; T_2 = virtual time to half-value, typically 2500 μs $\pm$ 60%, T_d = time above 90%). Reprinted with permission from [126], © 1984, Pergamon Books Ltd

In impulse testing, the capacitance of the test object is usually much smaller than the capacitance of the impulse generator. It is then permissible to regard the impulse generator as a voltage source with the function of Eq. (7.7). In cases where the impulse generator is discharged into lines, or into other test objects with impedances which can influence the wave

Table 7.1 - Relationship between T_1, T_2, and α_1, α_2. Reprinted with permission from [126], © 1984, Pergamon Books Ltd

T_1/T_2 (μs)	T_{cr}/T_2 (μs)	$\frac{1}{\alpha_1}$ (μs)	$\frac{1}{\alpha_2}$ (μs)	k to produce f_{max} = 1.0
1.2/5	-	3.48	0.80	2.014
1.2/50	-	68.2	0.405	1.037
1.2/200	-	284	0.381	1.010
250/2500	-	2877	104	1.175
-	250/2500	3155	62.5	1.104

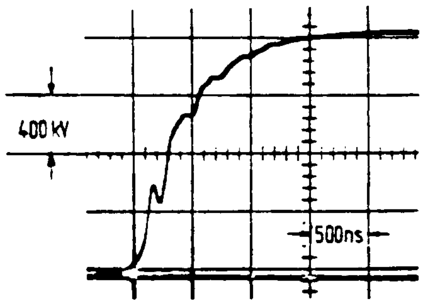
shape, it may be better to simulate the impulse generator as a capacitance and resistance network, as shown in Fig. 7.9 for a simple single-stage impulse generator. The initial voltage across C_1 would be nonzero, and the switch closing would simulate the gap firing. Fig. 7.10 compares measurements against EMTP simulation results for the waveshape of a multistage impulse generator, where the generator was modelled as a network of capacitances, resistances in inductances [127]. The spark gaps were represented as time-dependent resistances based on Toepler's formula.



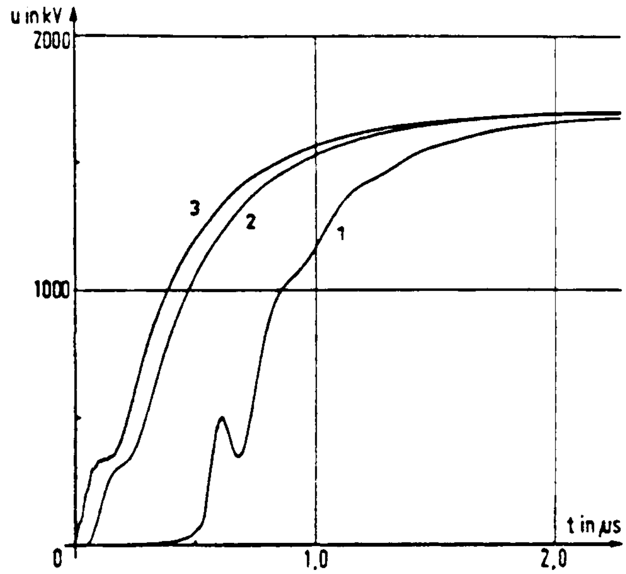
(a) Circuit type a

(b) Circuit type b

Fig. 7.9 - Single-stage impulse generators



(a) Measurement



(b) Simulation results (1 = exact with nonsimultaneous firing of spark gaps, 2 = simultaneous firing, 3 = simultaneous firing with gaps as ideal switches)

Fig. 7.10 - Waveshape of a multistage impulse generator [127]. © 1971 IEEE

7.6 Current-Controlled dc Voltage Source

This source provides a simplified model of an HVDC converter station [128], and produces simulation results which come reasonably close to field tests [129]. The current-dependent voltage source is connected between two nodes (cathode and anode), as indicated in Fig. 7.11. The current can only flow in one direction (from anode to cathode). This is simulated internally with a switch on the anode side, which opens to prevent the current from going negative and closes again at the proper voltage polarity. Spurious voltage oscillations may occur between the anode and cathode side after the switch opens, unless the damping circuits across the valves are also modelled. Good results were obtained in [128] when an RC branch was added between the anode and cathode (R = 900 Ω and C = 0.15 μs in that case).

The current regulator is assumed to be an amplifier with two inputs (one proportional to current bias I_{BIAS}, and the other proportional to measured current i), and with one output e_α which determines the firing angle. The transfer function of the regulator is

$$G(s) = \frac{K(1 + sT_2)}{(1 + sT_1)(1 + sT_3)} \tag{7.8}$$

with limits placed on the output e_α in accordance with rectifier minimum firing angle, or inverter minimum extinction angle.

The current-controlled dc voltage source is a function of e_α,

$$v_{dc} = k_1 + k_2 e_\alpha \tag{7.9}$$

as shown in Fig. 7.12. The current regulator output e_α, minus a bias value (10V in Fig. 7.12) is proportional to $\cos\alpha$. The inverter normally operates at minimum extinction angle at the limit $e_{\alpha min}$, and the rectifier normally operates on constant current control between the limits. The user defines steady-state limits for v_{dc}, which are converted to limits on e_α with Eq. (7.9). If the converter operates at the maximum limit $e_{\alpha max}$ (or at the minimum limit $e_{\alpha min}$), either in initial steady state or later during the transient simulation, it will be back off the limit as soon as the derivative de_α/dt becomes negative (or positive) in the differential equation

$$(T_1 + T_3)\frac{de_\alpha}{dt} = K(I_{BIAS} - i) - kT_2\frac{di}{dt} - T_1 T_3 \frac{d^2 e_\alpha}{dt^2} - e_\alpha \tag{7.10}$$

The value for d^2e_α/dt^2 is zero in Eq. (7.10) as long as the converter operates at the limit.

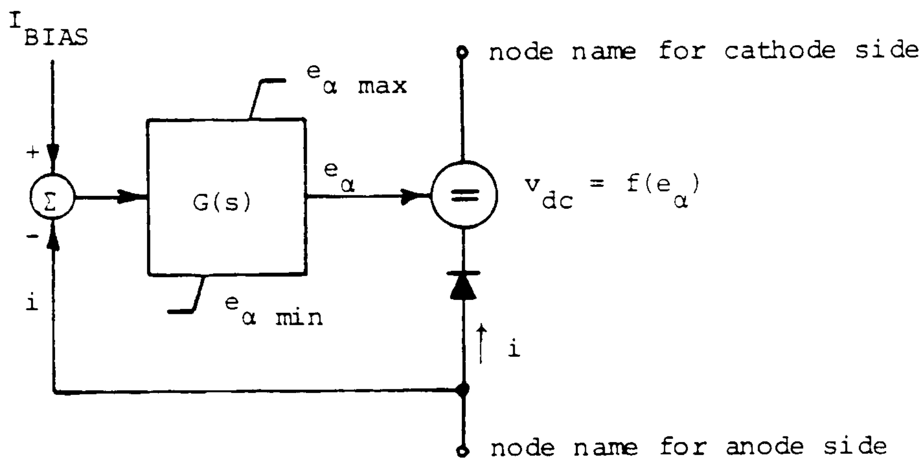


Fig. 7.11 - Current-controlled dc voltage source

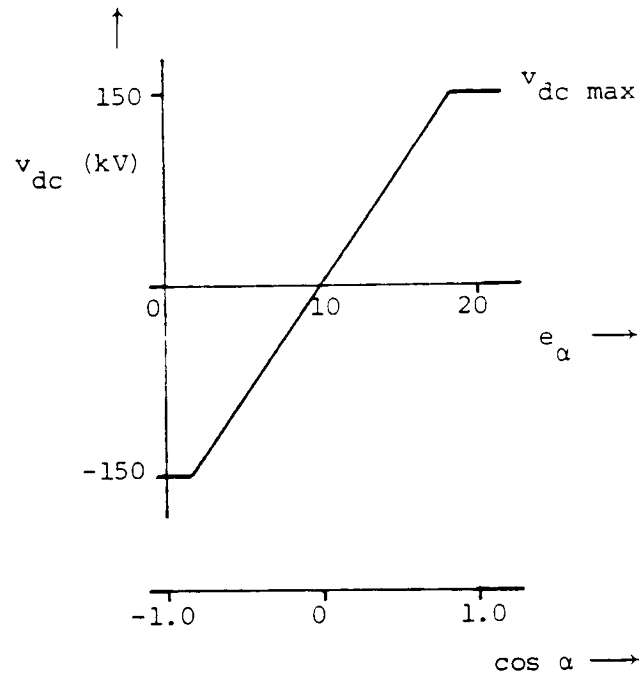


Fig. 7.12 - Relationship between v_{dc} and e_α (k_1 = -150 000, k_2 = 15 000)

7.6.1 Steady-State Solution

Steady-state dc initial conditions are automatically computed by the program with the specified value $v_{dc}(0)$. Since the steady-state subroutine was only written for ac phasor solutions, the dc voltage is actually represented as $v_{dc} = v_{dc}(t) \cos(\omega t)$ with a very low frequency of f = 0.001 Hz. Practice has shown that this is sufficiently close to dc, and still makes reactances ωL and susceptances ωC large enough to avoid numerical problems in the ac steady-state solution. When the current-controlled dc voltage source was added to the EMTP, voltage sources between two nodes were not yet permitted. For the steady-state solution, a resistance R_{equiv} is therefore connected in series with the voltage source, which is then converted into a current source in parallel with R_{equiv}. This produces accurate results if the user already knows what the initial current $i_{dc}(0)$ is, because the specified voltage source of the rectifier is automatically increased by R_{equiv} $i_{dc}(0)$, and that of the inverter is decreased by $R_{equiv}i_{dc}(0)$. The program user should check, however, whether the computed current i_{dc} does indeed agree with what the user thought it would be. This nuisance of having to specify $i_{dc}(0)$, without knowing whether it will agree with the computed value, could be removed by using the methods described in Section 6.3, if this HVDC model is used often enough to warrant the program changes. The value of R_{equiv} is the same as the one used in the transient solution (Section 7.5.2).

The normal steady-state operation of an HVDC transmission link, measured somewhere at a common point (e.g., in the middle of the line) is indicated in Fig. 7.13. For the converter operating between the limits on constant current control (which is normally the rectifier), I_{BIAS} is automatically computed to produce the characteristic A-A' of Fig. 7.13,

$$I_{BIAS} = i(0) + \frac{e_\alpha(0)}{K} , \qquad if \quad e_{\alpha min} < e_\alpha < e_{\alpha max} \tag{7.11}$$

with i(0), $e_\alpha(0)$ being the dc initial conditions. For the converter operating at maximum or minimum voltage (which is normally the inverter), the current setting $I_{SETTING}$ must be given as part of the input, which defines the point where the converter backs off the limit and goes into constant current control. I_{BIAS} is again automatically computed, which in this case is

$$I_{BIAS} = I_{SETTING} + \frac{e_\alpha(0)}{K} \qquad if \quad e_\alpha(0) = e_{\alpha\,max} \quad or \quad e_{\alpha\,min} \tag{7.12}$$

$I_{SETTING}$ is typically 15% lower than the current order I_{ORDER} at the steady-state operating point for inverters (or 15% higher for rectifiers).

7.6.2 Transient Solution

In the transient solution, the dynamics of the current controller in the form of Eq. (7.9) and (7.10) must obviously be taken into account. First, rewrite the second-order differential equation (7.10) as two first-order differential equations,

$$e_\alpha + Tx + P\frac{dx}{dt} = K(I_{BIAS} - i) - KT_2\frac{di}{dt} \tag{7.13a}$$

$$x = \frac{de_\alpha}{dt} \tag{7.13b}$$

with the new variable x and with the new parameters

$$T = T_1 + T_3 \tag{7.13c}$$

$$P = T_1 T_3 \tag{7.13d}$$

After applying the trapezoidal rule of integration to Eq. (7.13a) and (7.13b) (replacing x by [x(t - Δt) + x(t)]/2 and dx/dt by [x(t) - v(t - Δt)]/Δt, etc.), and after eliminating x(t), one linear algebraic equation between $e_\alpha(t)$ and i(t) is obtained. Inserting this into Eq. (7.9) produces an equation of the form

$$v_{dc}(t) = v_0(t) - R_{equiv}\, i(t) \tag{7.14}$$

which is a simple voltage source $v_0(t)$ in series with an internal resistance R_{equiv}. This Thevenin equivalent circuit is converted into a current source $i_0(t)$ in parallel with R_{equiv} (Fig. 7.14).

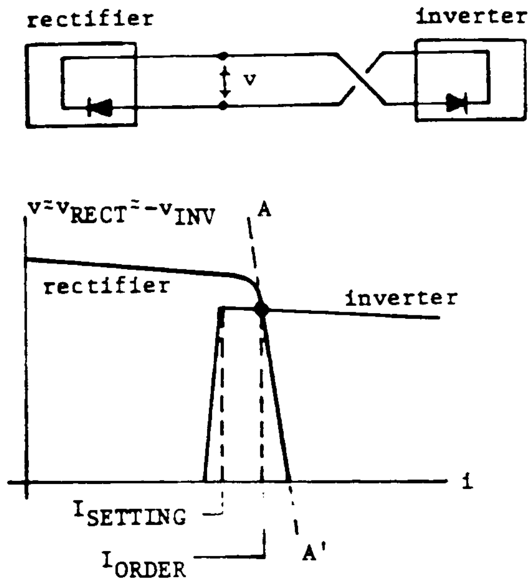


Fig. 7.13 - Normal operation of HVDC transmission link

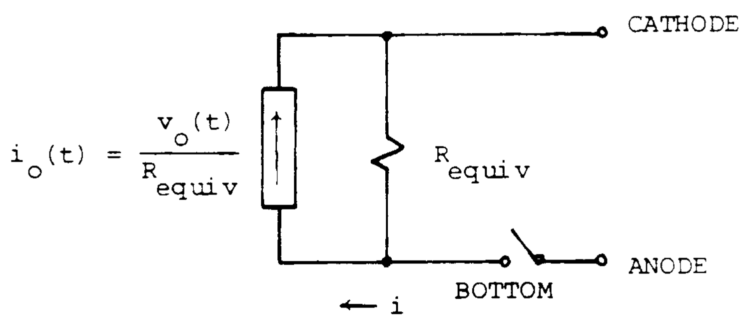


Fig. 7.14 - Norton equivalent circuit

The equivalent resistance R_{equiv} remains constant for a given step size Δt,

$$R_{equiv} = \frac{k_2 K \left(1 + \frac{2T_2}{\Delta t}\right)}{1 + \frac{2T}{\Delta t} + \frac{4P}{(\Delta t)^2}} \tag{7.15}$$

whereas the current source $i_0(t)$ depends on the values $e_\alpha(t - \Delta t)$ and $x(t - \Delta t)$ of the preceding time step. After the complete network solution at each time step, with the converter representation of Fig. 7.14, the current is calculated with Eq. (7.14), and then used to update the variables e_α and x.

If e_α hits one of the limits $e_{\alpha max}$ or $e_{\alpha min}$, it is kept at the appropriate limit in the following time steps, with x and dx/dt set to zero. B.C. Chiu has recently shown, however, that simply setting x and dx/dt to zero at the limit does not represent the true behavior of the current controller [130]. The treatment of limits should therefore be revised, if this current-controlled dc voltage source remains in use. Backing off the limit occurs when the derivative

de_α/dt calculated from Eq. (7.10) becomes negative in case of $e_\alpha = e_{\alpha max}$, or positive in case of $e_\alpha = e_{\alpha min}$.

The switch opens as soon as $i(t) < 0$, and closes again as soon as $V_{ANODE} > v_{BOTTOM}$, to assure that current can only flow in one direction. This updating of the current source $i_0(t)$ from step to step is not influenced by the switching actions.