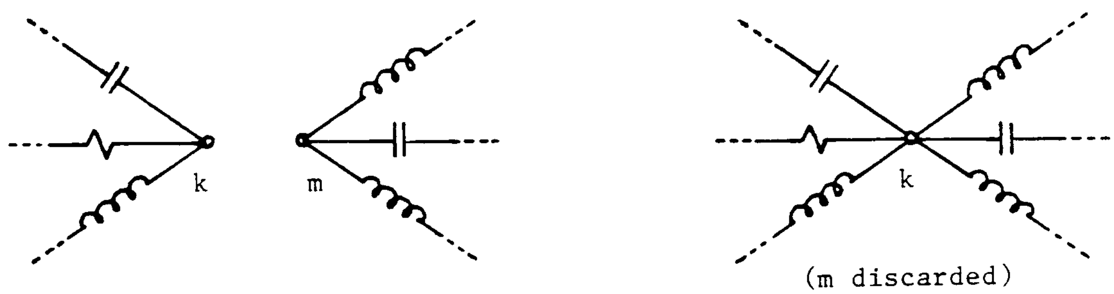
10. SWITCHES

Any switching operation in a power system can potentially produce transients. For the simulation of such transients, it is necessary to model the various switching devices, such as

circuit breakers,
load breakers,
dc circuit breakers,
disconnectors,
protective gaps,
thyristors, etc.

So far, all these switching devices are represented as ideal switches in the EMTP, with zero current ($R = \infty$) in the open position and zero voltage ($R = 0$) in the closed position. If the switch between nodes k and m is open, then both nodes are represented in the system of nodal equations, whereas for the closed switch, both k and m become one node (Fig. 10.1). It is



(a) open (b) closed

Fig. 10.1 - Representation of switches in the EMTP

possible, of course, to add other branches to the ideal switch, to more closely resemble the physical behavior, e.g., to add a capacitance from k to m for the representation of the stray capacitance or the R-C grading network of an actual circuit breaker. The characteristics of the arc in the circuit breaker are not yet modelled, but work is in progress to include them in future versions.

Switches are not needed for the connection of voltage and current sources if they are connected to the network at all times. The source parameters T_{START} and T_{STOP} can be used in place of switches to have current sources temporarily connected for $T_{START} \leq t \leq T_{STOP}$, as explained in Section 7. For voltage sources, this definition would mean that the voltage is zero for $t < T_{START}$ and for $t > T_{STOP}$, which implies a short-circuit rather than a disconnection. Therefore, switches are needed to disconnect voltage sources.

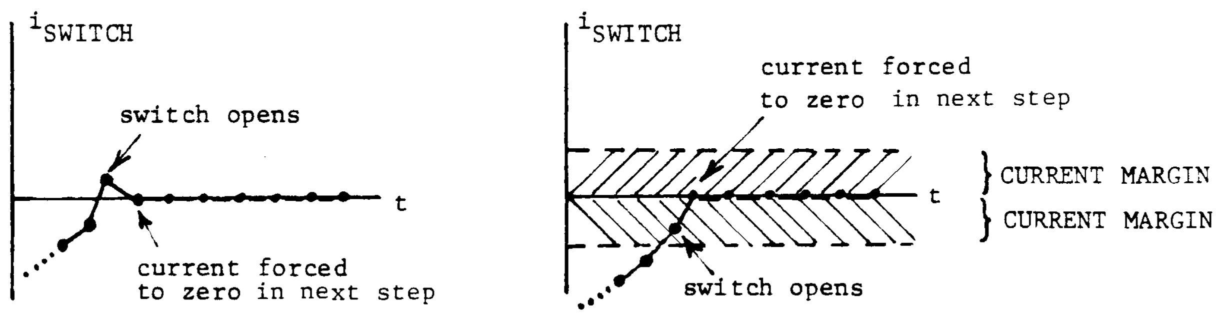
Switches are also used to create piecewise linear elements, as discussed in Section 12.

10.1 Basic Switch Types

There are five basic switch types in the EMTP, which are all modelled as ideal switches. They differ only in the criteria being used to determine when they should open or close.

10.1.1 Time-Controlled Switch

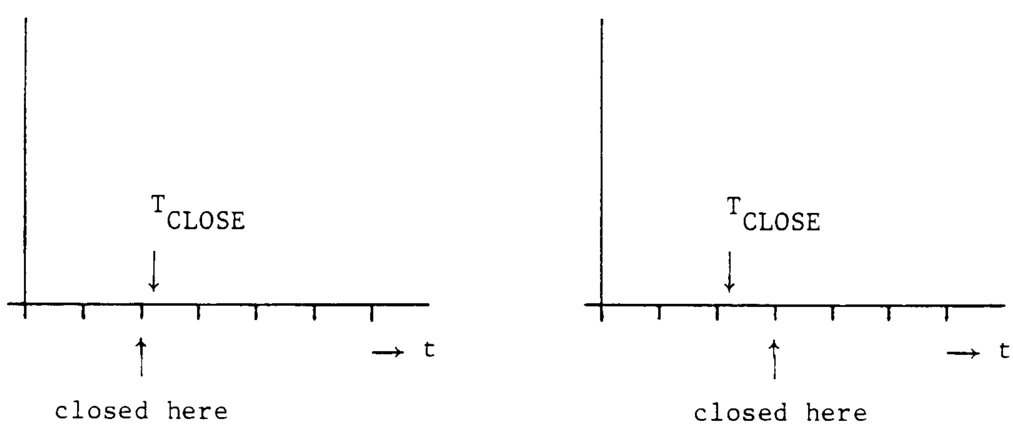
This type is intended for modelling circuit breakers, disconnectors, and similar switching devices, as well as short-circuits. The switch is originally open, and closes at T_{CLOSE}. It opens again after T_{OPEN} (if $< t_{max}$), either as soon as the absolute value of the switch current falls below a user-defined current margin, or as soon as the current goes through zero (detected by a sign change), as indicated in Fig. 10.2 For the simulation of circuit breakers, the latter criterion for opening should normally be used. The time between closing and opening can be delayed by a user-defined time delay.



(a) current going through zero (b) current less than margin

Fig. 10.2 - Opening of time-controlled switch

The closing takes place at the time step nearest to T_{CLOSE} in the UBC version (Fig. 10.3(a)), and at the time step where $t \geq T_{CLOSE}$ for the first time in the BPA version (Fig. 10.3(b)).



(a) UBC version (b) BPA version

Fig. 10.3 - Closing of time-controlled switch

$T_{CLOSE} < 0$ signals to the EMTP that the switch should be closed from the very beginning. If the simulation starts from automatically calculated ac steady-state conditions, then the switch will be recognized as closed in the steady-state phasor solution.

The BPA EMTP has an additional time-controlled switch type (TACS-controlled switch type 13), in which the closing and opening action is controlled by a user-specified TACS variable from the TACS part of the EMTP. With that feature it is easy to build more complicated opening and closing criteria in TACS.

10.1.2 Gap Switch

This switch is used to simulate protective gaps, gaps in surge arresters, flashovers across insulators, etc. It is always open in the ac steady-state solution. In the transient simulation, it is normally open, and closes as soon as the absolute value of the voltage across the switch exceeds a user-defined breakdown or flashover voltage. For this checking procedure, the voltage values are averaged over the last two time steps, to filter out numerical oscillations. Opening occurs at the first current zero, provided a user-defined delay time has already elapsed. This close-open cycle repeats itself whenever the voltage exceeds the breakdown or flashover voltage again, as indicated in Fig. 10.4

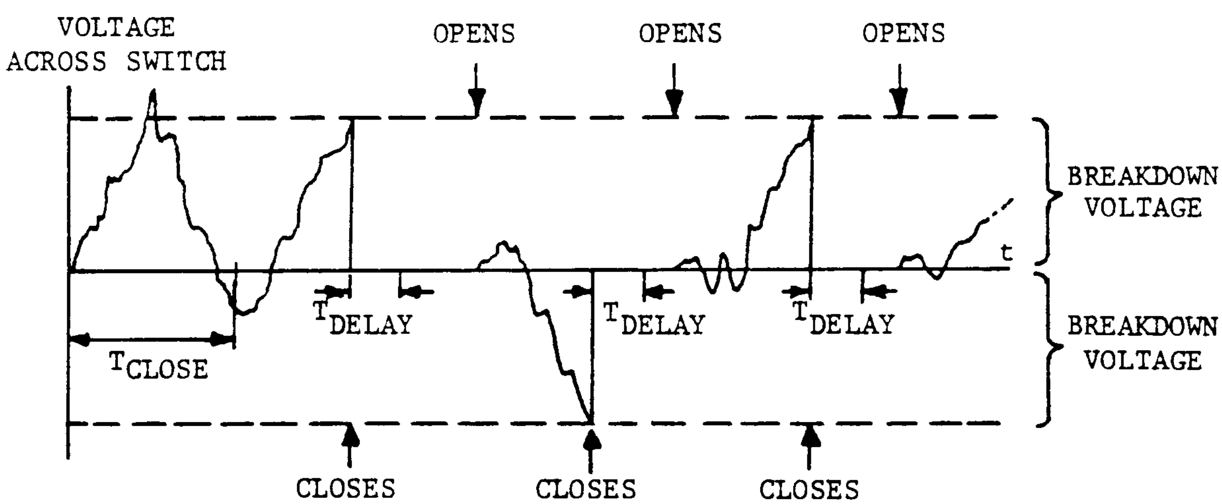


Fig. 10.4 - Repetition of close-open operation for gap switch

It is well known that the breakdown voltage of a gap or the flashover voltage of an insulator is not a simple constant, but depends on the steepness of the incoming wave. This dependence is usually shown in the form of a voltage-time characteristic (Fig. 10.5), which can be measured in the laboratory for standard impulse waveshapes. Unfortunately, the waveshapes of power system transients are usually very irregular, and voltage-time characteristics can seldom be used, therefore. Analytical methods based on the integration of a function

$$F = \int_{t_1}^{t_2} (v(t) - v_0)^k \, dt \tag{10.1}$$

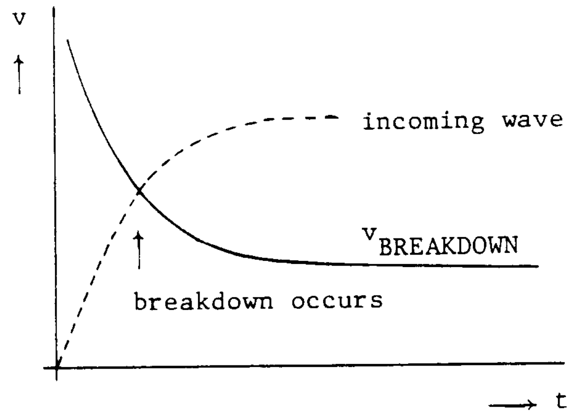


Fig. 10.5 - Voltage-time characteristic of a gap

could easily be implemented. In Eq. (10.1), v_o and k are constants, and breakdown occurs at instant t_2 where the integral value F becomes equal to a user-defined value [8]. For k = 1, this is the "equal-area criterion" of D. Kind [172]. Neither the voltage-time characteristic nor Eq. (10.1) has been implemented so far.

The BPA EMTP has an additional gap switch type (TACS-controlled switch type 12), in which the breakdown or flashover is controlled by a firing signal received from the TACS part of the EMTP (Section 13). With that feature, voltage-time characteristics or criteria in the form of Eq. (10.1) can be simulated in TACS by skilled users.

10.1.3 Diode Switch

This switch is used to simulate diodes where current can flow in only one direction, from anode m to cathode k (Fig. 10.6). The diode switch closes whenever $v_m \geq v_k$ (voltage values averaged over two successive time steps to filter out numerical oscillations), and opens after the elapse of a user-defined time delay as soon as the current i_{mk} becomes negative, or as soon as its magnitude becomes less than a user-defined margin.

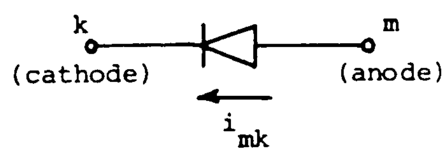


Fig. 10.6 - Diode switch

In the ac steady-state solution, the diode switch can be specified as either open or closed.

10.1.4 Thyristor Switch (TACS Controlled)

This switch is the building block for HVDC converter stations. It behaves similarly to the diode switch, except that the closing action under the condition of $v_m \geq v_k$ only takes place if a firing signal has been received from the TACS part of the EMTP (Section 13).

10.1.5 Measuring Switch

A measuring switch is always closed, in the transient simulation as well as in the ac steady-state solution. It is used to obtain current, or power and energy, in places where these quantities are not otherwise available.

The need for the measuring switch arose because the EMTP does not calculate currents for certain types of branches in the updating procedure inside the time step loop. These branches are essentially the polyphase coupled branches with lumped or distributed parameters. The updating procedures could be changed fairly easily to obtain the currents, as an alternative to the measuring switch.

10.2 Statistical Distribution of Switching Overvoltages

Since circuit breakers can never close into a transmission line exactly simultaneously from both ends, there is always a short period during which the line is only closed, or reclosed, from one end, with the other end still open. Travelling waves are then reflected at the open end with the well-known doubling effect, and transient overvoltages of 1 p.u. at the receiving end are therefore to be expected. In reality, the overvoltages can be higher for the following reasons:

(a) the line is three-phase with three different mode propagation velocities,

(b) the network on the source side of the circuit breaker may be fairly complicated, and can therefore create rather complicated reflections,

(c) the line capacitance may still be charged up from a preceding opening operation ("trapped charge" in reclosing operations),

(d) the magnitude of the overvoltage depends on the instant of closing (point on waveshape),

(e) the three poles do not close simultaneously (pole spread).

In the design of transmission line insulation, it would make little sense to base the design on the highest possible switching surge overvoltage, because that particular event has a low probability of ever occurring, and because the line insulation could not be designed economically for that single high value. Furthermore, it is impossible or very difficult to know which combination of parameters would produce the highest possible overvoltage. Instead, 100 or more switching operations are usually simulated, with different closing times and possibly with variation of other parameters, to obtain a statistical distribution of switching surge overvoltages. This is usually shown in the form of a cumulative frequency distribution (Fig. 10.7).

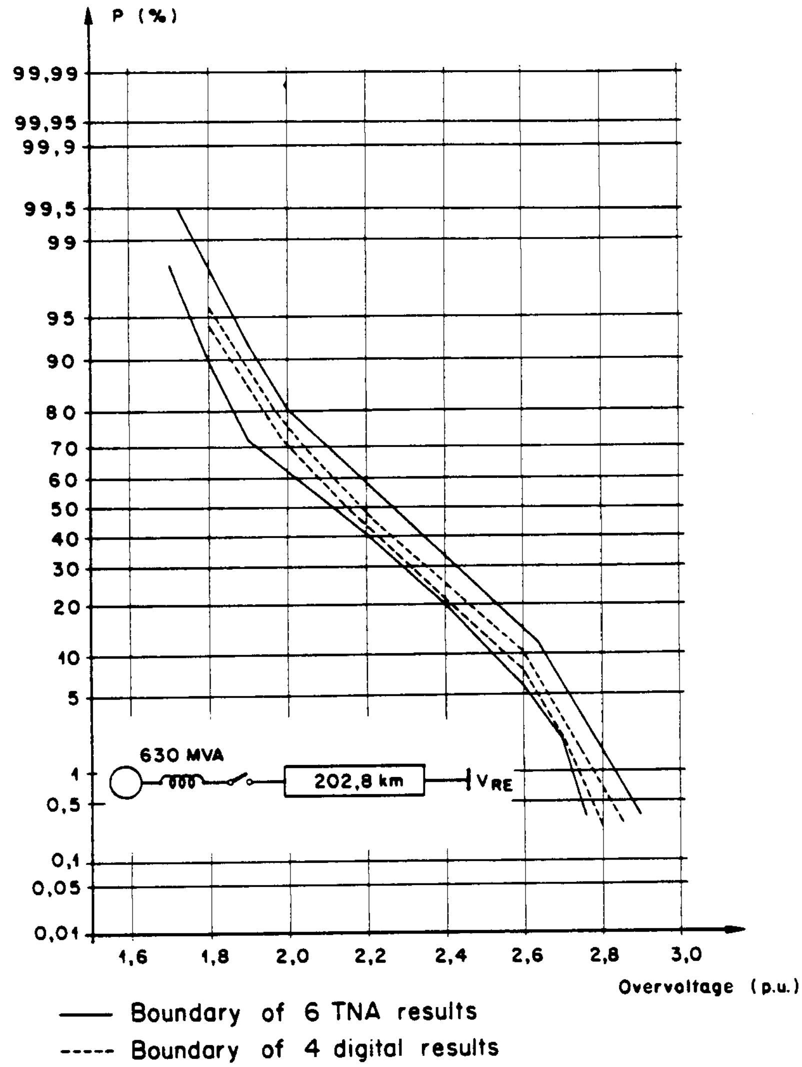


Fig. 10.7 - Cumulative frequency distribution of receiving end overvoltages from 100 digital computer and TNA simulations [18]. Reprinted by permission of CIGRE

For the left-most curve in Fig. 10.7, an overvoltage of 1.6 p.u. or higher would have to be expected in 5% of the switching operations. Insulation design for withstanding a certain overvoltage often refers to a 2% probability. The withstand voltage of insulators does not only depend on the peak value, but on the waveshape as well. For irregular waveshapes, as they occur in switching surges, it is very difficult to take the waveshape into account, and it is therefore usually ignored.

The BPA EMTP has special switch types for running a large number of cases in which the opening or closing times are automatically varied. The output includes statistical overvoltage distributions, e.g., in the form of Fig. 10.7. There are two types, one in which the closing times are varied statistically, and the other in which they are varied systematically. How well these variations represent the true behavior of the circuit breaker is difficult to say. Before the contacts have completely closed, a discharge may occur across the gap and create "electrical" closing slightly ahead of mechanical closing ("prestrike"). There is very little data available on prestrike values, however.

10.2.1 Statistics Switch

The closing time T_{CLOSE} of each statistics switch is randomly varied according to either a Gaussian (normal) distribution, or a uniform distribution, as shown in Fig. 10.8. After each variation, for all such switches, the case is rerun to obtain the peak overvoltages. The mean closing time T and the standard deviation σ are specified by the user. In addition to closing time variations of each individual switch, a random delay can be added, which is the same for all statistics switches, and which always follows a uniform distribution.

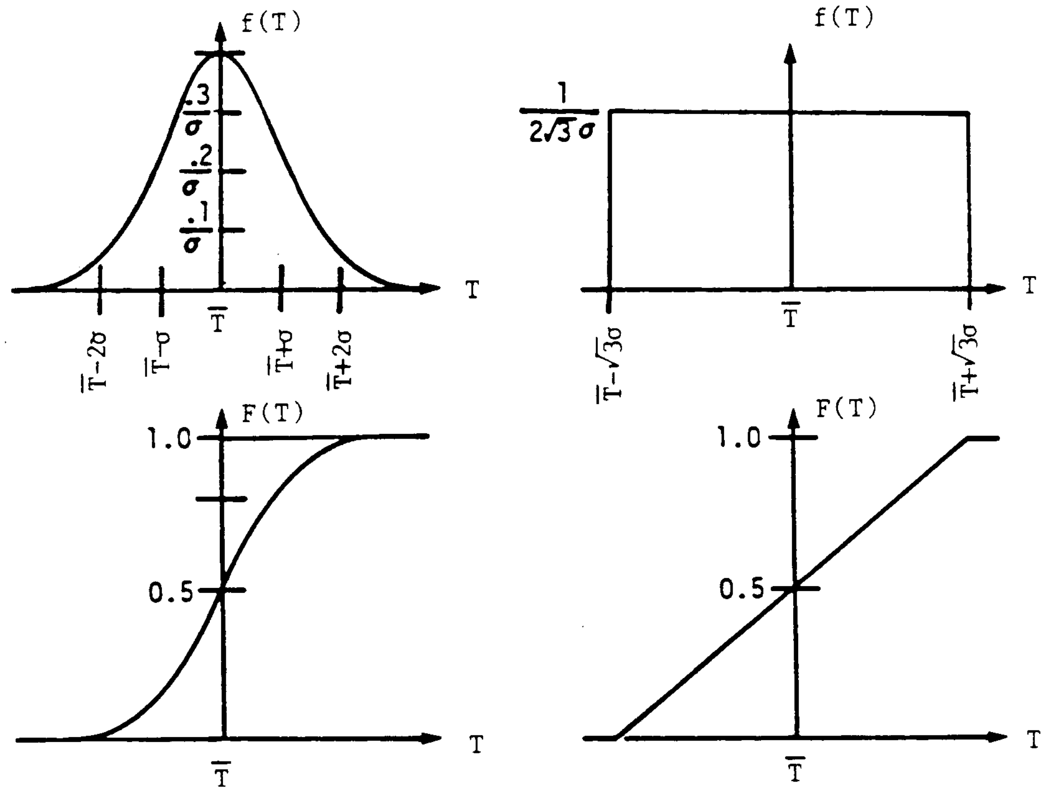


Fig. 10.8 - Probability distribution for the closing time T_{CLOSE} of the statistics switch. f(T) = density function, F(T) = cumulative distribution function

There is also an option for dependent "slave" switches, in which the closing time depends on that of a "master" switch,

$$T_{CLOSE-slave} = T_{CLOSE-master} + T_{random} \tag{10.2}$$

with

$T_{CLOSE-master}$	=	statistically determined closing time of a "master" statistics switch,
T_{random}	=	random time delay defined by a mean time and standard deviation.

This slave switch may in turn serve as a master switch for another slave switch. Slave switches are usually used to model circuit breakers with closing resistors. The first contact to close would be the master switch, with the next one or more contacts to close being slave switches.

Statistics switches can also be used for random openings, instead of closings, but this option is less important. In realistic simulations, the current interruption only occurs at the first current zero after T_{OPEN}, and there are only a few combinations of phase sequences in which the three poles of a three-phase circuit can interrupt. It may be just as easy to simulate these combinations directly, rather than statistically.

10.2.2 Systematic Switch

Each systematic switch has its closing time systematically varied, from T_{min} to T_{max} in equal increments of ΔT. If this is done for the three poles of a three-phase circuit breaker, it can result in a very large number of cases which have to be run automatically, as indicated in Fig. 10.9.

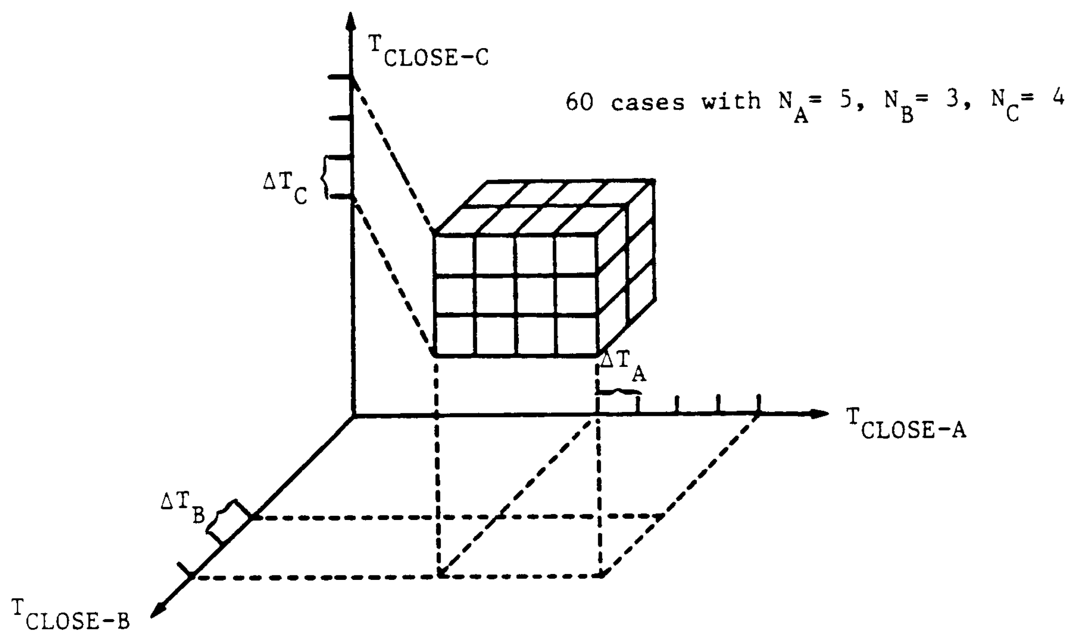


Fig. 10.9 - Three-dimensional space for three closing times $T_{CLOSE-A}$, $T_{CLOSE-B}$, $T_{CLOSE-C}$

Again, there is an option for dependent "slave" switches, in which the closing time is

$$T_{CLOSE-slave} = T_{CLOSE-master} + T_{OFFSET} \tag{10.3}$$

where T_{OFFSET} is now a constant, rather than a random variable as in Eq. (10.2). As in the case of statistics switches, slave switches are used to model the second (or third,...) contact to close in circuit breakers with closing resistors. Slave switches do not increase the dimension of the vector space shown in Fig. 10.9 for three master switches.

10.3 Solution Methods for Networks with Switches

There is more than one way of handling changing switch positions in the transient solution part of the EMTP. For the ac steady-state solution part, the problem is simpler, because the equations are only solved once. In that case, it is best to use 2 nodes for open switches, and 1 node for closed switches, as shown in Fig. 10.1.

In some programs, the switch is represented as a resistance R, with a very large value if the switch is open and a very small value if the switch is closed. As explained in Section 2.1, very large values of R do not cause numerical problems in solution methods based on nodal equations, but very small values can cause numerical problems. This approach was therefore not chosen for the EMTP. The calculation of the switch current is trivial in this approach, with

$$i_{km} = (v_k - v_m)/R \tag{10.4}$$

The compensation method described in Section 12.1.2 provides another approach for handling switches. To represent M-switches, an M-phase Thevenin equivalent circuit would be precomputed with an equation of the form

$$[v_k] - [v_m] = [v_{k-0}] - [v_{m-o}] - [R_{Thev}][i_{km}] \tag{10.5}$$

The switch currents, which are needed for the superposition calculation (Eq. (12.8) in Section 12.1.2), are simply $[i_{km}] = 0$ if all switches are open or

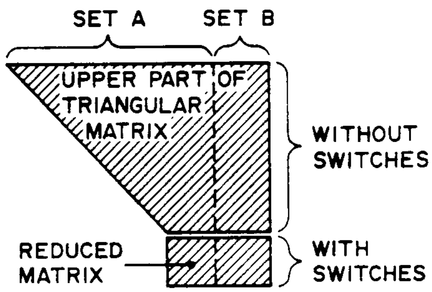
$$[i_{km}] = [R_{Thev}]^{-1}\{[v_{k-0}] - [v_{m-0}]\} \tag{10.6}$$

if all switches are closed. If only some switches are closed, then $[R_{Thev}]$ in Eq. (10.6) is a submatrix obtained from the full matrix after throwing out the rows and columns for the open switches. The switch currents are automatically obtained in this approach, and there should not be any numerical problems. The compensation-based method is not used in the EMTP now, though it may be chosen in future versions for the inclusion of arc characteristics. It was used in a predecessor version of the EMTP developed by the author in Munich. The treatment of switches in the UBC EMTP, as discussed next in Section 10.3.1, is essentially the same as the compensation-based method, even though the programming details are different.

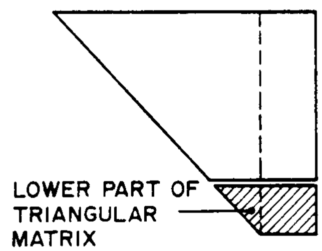
A third approach is to change the network connections whenever a switch position changes. As indicated in Fig. 10.1, there are two nodes whenever the switch is open, and only a single node whenever the switch is closed. This approach has been implemented in the EMTP, in two different ways.

10.3.1 Network Reduction to Switch Nodes

In the UBC EMTP, and in an older version of the BPA EMTP, nodes which have switches connected are eliminated last, as indicated in Fig. 10.10. Before entering the time step



(a) initial reduction



(b) completion of triangularization whenever switches change position

Fig. 10.10 - Matrix reduction for nodes with switches

loop, normal Gauss elimination is used on those nodes with unknown voltages (subset A) which do not have switches connected to them. For the rest of the nodes of subset A with switches, the Gauss elimination is stopped at the vertical line which separates the non-switch nodes from the switch nodes. This creates the reduced matrix illustrated in Fig. 10.10(a). All switches are assumed to be open in this calculation.

Whenever a switch position changes in the time step loop, this reduced matrix is first modified to reflect the actual switch positions. If the switch between nodes k and m is closed, then the two respective rows and columns are added to form one new row and column using the higher node number between k and m, and the other row and column for the lower node number is discarded. If the switch is open, no changes are made in the reduced matrix. After these modifications, the triangularization is completed for the entire matrix of subset A, as indicated in Fig. 10.10(b). In repeat solutions, the addition of rows for closed switches must be applied to the right-hand sides as well. In the backsubstitution, the voltage of the discarded lower node number is set equal to the voltage of the retained higher node number.

Using this reduced matrix scheme has the advantage that the triangularization does not have to be done again for the entire matrix whenever switch positions change. Instead, re-triangularization is confined to the lower part. This scheme works well if the network contains only a few switches. If there are many switches, as in HVDC converter station simulations, then this method becomes less and less efficient, and straightforward re-triangularization may then be the best approach, as described in Section 10.3.2. When the method was first programmed, only two rows and columns could be added. This has led to the restriction that a node with unknown voltage can only have one switch connected to it in this scheme, because two closed switches connected to one node would require the addition of three rows and columns (to collapse three nodes into one). This restriction no longer applies to newer BPA versions which use the method of Section 10.3.2.

The current calculation for closed switches in the time step loop uses the row of either node k or m in the reduced matrix (where the switch was assumed to be open) after the right-hand sides have been modified by the downward operations with the upper part of the triangular matrix. In effect, this sums up the currents through the branches connected to k or m, which must be equal to the switch current. In the ac steady-state solution, the switch currents are no calculated at all, but simply set to zero at $t = 0$. This is obviously incorrect, but the values will be correct at Δt, $2\Delta t, \ldots t_{max}$.

10.3.2 Complete Re-Triangularization

In newer versions of the BPA EMTP, the reduction scheme discussed in the preceding section is no longer used. Instead, the matrix is built and triangularized completely again whenever switch positions change, or when the slope of piecewise linear elements changes. The current is calculated from the original row or either node k or m, with all switches open, with the proper right-hand side.

With this newer scheme, any number of switches can be connected to any node, as long as the current in each switch is uniquely defined. A delta-configuration of closed switches, or two closed switches in parallel, would therefore not be allowed. Also, a switch cannot connect two voltage sources together, which is unrealistic anyhow because it would create an infinite current. The switch currents are now calculated in the ac steady-state solution as well, and switch currents are therefore correct at all times, including at $t = 0$.

10.3.3 Switch-Closing

When the EMTP prints a message that a switch is closed after T seconds, T will always be an integer multiple of Δt, because the EMTP cannot handle variable step sizes so far. The actual closing time T will therefore differ somewhat from the user-specified time T_{CLOSE}, as explained in Fig. 10.3.

The network will already have been solved, with the switch still open, when the decision is made to close the switch at time T. As shown in Fig. 10.11, all voltages and currents at $t = T$ are therefore the "preclosing" values. After the network solution at $t = T$, the matrix is rebuilt and re-triangularized for the closed switch position, and in the transition from T to $T + \Delta t$, it is assumed that all variables change linearly with finite slope, rather than abruptly.

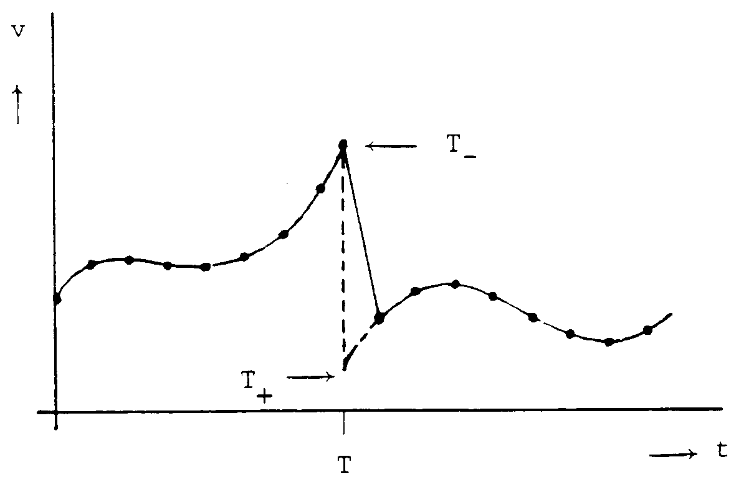


Fig. 10.11 - Switch closing or opening at time T

In many cases, the linear transition with a finite slope indicated in Fig. 10.11 is a reasonable assumption. For example, if the voltage v were the voltage across a capacitor, then v could not change abruptly anyhow. On the other hand, if it were the voltage across an inductance it could indeed jump, as indicated by the dotted line in Fig. 10.11. Such voltage jumps are very common in HVDC converter stations. The exact method for handling such jumps would be the addition of a second "post-change" solution at T_+ after the "pre-change" solution at T_-, without advancing in time. As explained in Appendix II, methods are now known to re-initialize at T_+, but they have not yet been implemented in the EMTP.

10.3.4 Switch Opening

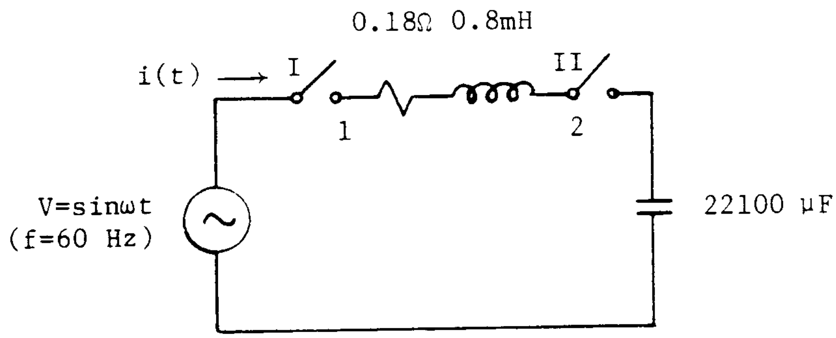
The treatment of switch opening in the solution is similar to that of switch closing. Again, the network will already have been solved, with the switch still closed, when the decision is made to open the switch at time T. To explain the transition from T to T + Δt, Fig. 10.11 can again be used: all voltage and currents at t = T will be the "pre-change" values, and after these values have been obtained, the matrix will be rebuilt and re-triangularized for the "post-change" configuration. All variables are then assumed to vary linearly rather than abruptly in the transition from T to T + Δt.

As already explained in Section 2.2.2,, not re-initializing the variables at T_- with a second "post-change" solution creates numerical oscillations in the voltages across inductances. They can be prevented with the re-initialization method of Appendix II, which has not yet been implemented in the EMTP, or with the damping resistances discussed in Section 2.2.2. For many years it was thought that the numerical oscillations occur only because the current is never exactly zero when the switch opens, with a residual energy $L(\Delta i)^2/2$ left in the inductance. It is now known that they also occur if Δi = 0. Decreasing Δt will not cure the oscillations either.

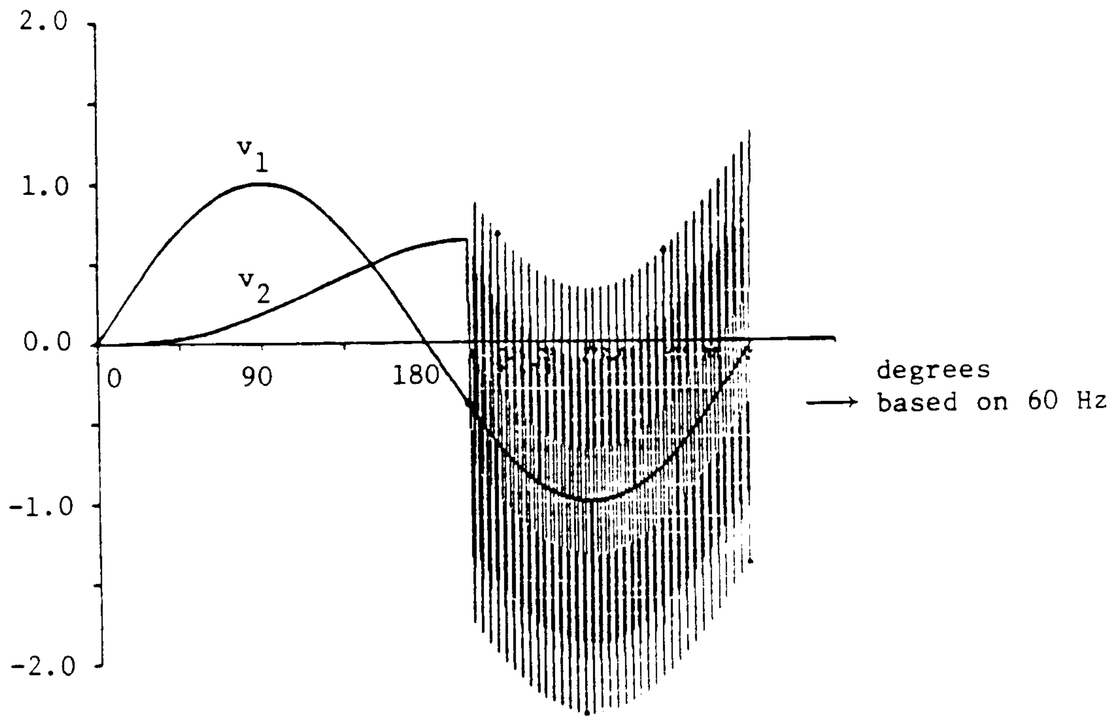
There are cases where the numerical oscillation, in place of the correct sudden jump, can serve as an indicator of improper modelling. An example is transient recovery voltage studies, where a sudden jump in voltage would indicate that the proper stray capacitances are missing from the model. Fig. 10.12 shows a simple example: both switches I and II in the network of Fig. 10.12(a) are closed at t = 0 to charge the capacitor. Switch II opens when the capacitor is charged up and when the current is more or less zero. Fig. 10.12(b) shows the numerical oscillations in the voltage v_2 on the feeding network side. By adding a stray capacitance to the left side of the switch, as illustrated in Fig. 10.12(c), the transient recovery voltage on the feeding side would no longer have the unrealistic jump, as shown in Fig. 10.12(d).

10.4 Arc Phenomena in Circuit Breakers

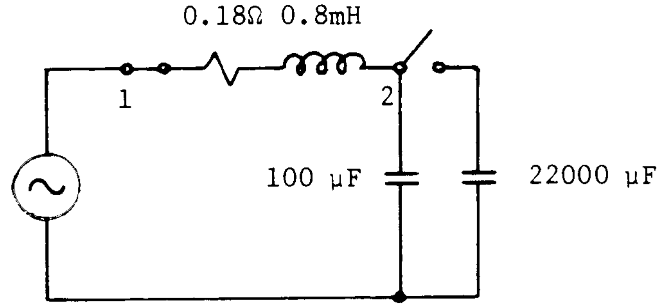
When the contacts of a circuit breaker open, they draw an electric arc which maintains the current flow until interruption takes place at current zero. In high voltage circuit breakers, the arc resistance is negligibly small if normal load currents or high short-circuit currents are



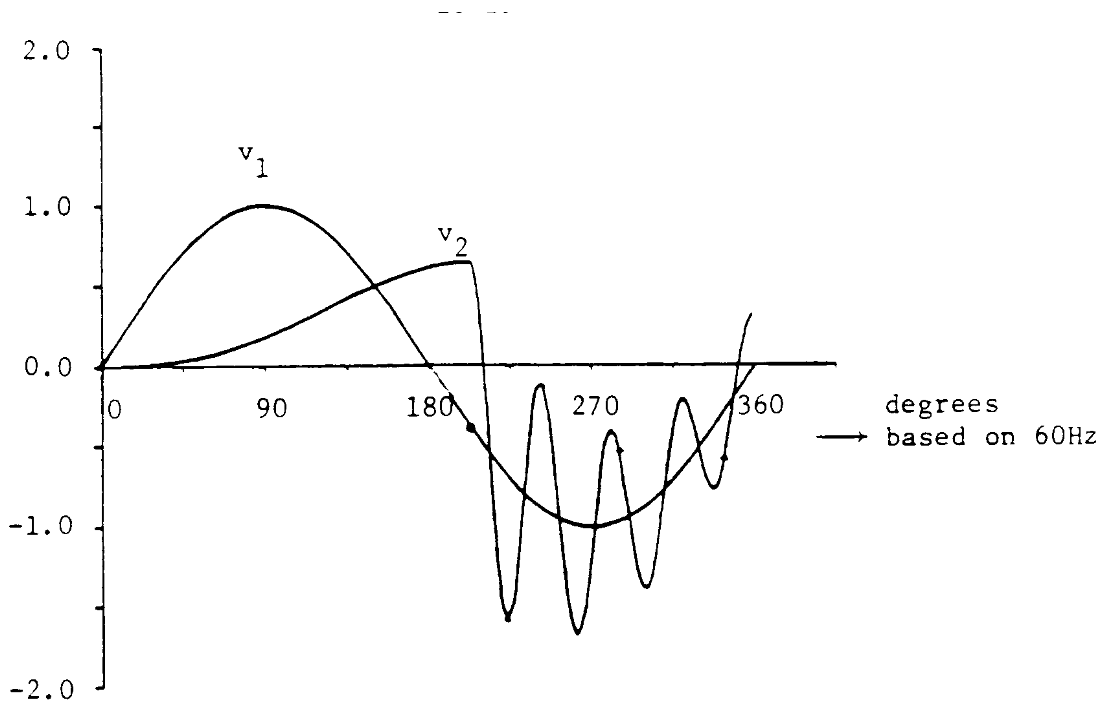
(a) network



(b) voltage across inductance



(c) modified network



(d) voltage across inductance

Fig. 10.12 - Capacitor charging and discharging

interrupted. In the interruption of small inductive currents (e.g., in switching off an unloaded transformer), the arc resistance is higher because of the falling arc characteristic, and may be important in deciding whether current interruption is successful or not. Immediately after current interruption, a transient recovery voltage builds up across the contacts, which can lead to reignition if it exceeds the dielectric strength which re-appears as the gap between the contacts is being de-ionized.

There is no circuit breaker arc model in the EMTP now, but work is in progress to add one. Static arc models are not good enough, and differential equations describing the arc must be used instead. Most experts working on current interruption problems use a modification of an equation first proposed by Mayr, of the form

$$\frac{dg}{dt} = \frac{1}{\tau(g)}\left(\frac{i^2}{P(g)} - g\right) \tag{10.7}$$

where

g = arc conductance,

i = arc current,

$\tau(t)$ = conductance-dependent time constant,

P(g) = conductance-dependent heat dissipation.

The parameters $\tau(t)$ and P(g) are dependent on the characteristics of the particular circuit breaker. A detailed investigation into the usefulness of various arc equations is presently being done by CIGRE Working Group 13.01

("Practical Application of Arc Physics in Circuit Breakers").

If high-frequency oscillations develop in the arc current prior to interruption, as they sometimes do in switching off small inductive currents or in other current-chopping situations, then reignition may occur within 1/4 cycle after current interruption (the term "restrike" is used to describe resumption of current conduction if it occurs 1/4 cycle or longer after current interruption, which most likely occurs in the interruption of capacitive currents). For deciding whether reignition occurs, the arc equation of Eq. (10.7) cannot be used. Instead, the transient recovery voltage is compared again the dielectric strength, which increases as a voltage is compared against the dielectric strength, which increases as a function of time, and if it exceeds it, then reignition occurs. For the breakdown itself, Toepler's equation can be used, which is of the form [173]

$$g = \frac{1}{ks} \int_0^t i(u)\, du \qquad (10.8)$$

where

k = constant,

s = gap spacing

i = current in gap (starting from an extremely small value).

v = voltage across gap.