INTERFACING WITH EMTP

A GENERAL-PURPOSE TRANSMISSION LINE MODEL

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Abstract - The transmission line models implemented in general purpose programs used for the analysis of electromagnetic transients in power systems are not adequate for directly taking into account (a) distributed nonuniform parameters (b) distributed non-linear parameters (c) distributed sources. However, these features are important in the analysis of many electromagnetic transient problems in power systems.

A multiphase transmission line model adequate for taking into account the above-mentioned parameters (a-c) has been developed. In this paper, application examples of this multi-purpose line model are presented, illustrating the solution of various electromagnetic transient problems in power systems.

The line model has been implemented as a separate set of Fortran routines that were then connected to EMTP using the standard interface provided by MODELS. This interface allows an external routine to be linked, and to be used in a data case as any regular model. Using a type-94 Thevenin circuit element, this Fortran model is connected directly to nodes of the data-case, and is included in the simulation without any time-step delay.

I. INTRODUCTION

The solution of electromagnetic transients in power systems often requires that, further to the transmission lines themselves, different elements of the network be modelled as distributed parameters, in particular the transmission towers, when fast surge transients are considered. Moreover, direct lightning causes very high stresses, for which the transmission line behaviour becomes non-linear, and strikes in the vicinity of the line originate important induced fields at the line location.

The transmission line models normally available in Electro-Magnetic Transient Programs - EMTP consider that (a) the parameters are uniform along the line, (b) the line behaviour is linear, (c) no external fields illuminate the line. However, considering the applications where these assumptions are not met, an increasing interest has been paid to the analysis of such problems as:

- modelling of nonuniform transmission lines, e.g. [1-3];
- inclusion of corona on transmission line modelling, e.g. [4-8];
- calculation of lightning induced voltages, e.g. [9-12].

The different transmission line models adopted follow ad-hoc approaches, conform to the particular purpose of concern.

Differently, the objective pursued by the authors is the development of a general-purpose transmission line model, allowing to consider the different conditions mentioned above.

II. TRANSMISSION LINE MODELLING

A multi-purpose single-phase transmission line model has been developed in the 1980's at the Technical University of Lisbon. It was capable of correctly including the non-linear effect of corona on the wave propagation [13,14] as well as taking into account the voltages induced by lightning along a transmission line [15]. This transmission line model has been interfaced with the ATP version of the EMTP [16].

Following a similar methodology, a multiphase transmission line has been developed and also interfaced with the ATP version of the EMTP. Validation of its correctness for including corona in the computation of surge propagation was presented in [17]. More recently, the algorithm for non-uniform transmission line modelling was implemented [18].

The method used to model the multiphase transmission line is based on a finite-differences approximation to the partial derivatives in the wave propagation equations. Considering a transmission line with n conductors, divided into N segments, the partial differential equations describing propagation are represented by the following set of 2n(N+1) equations in the time variable:

$$
\begin{aligned}
&h_{10}(u_{10},i_{10},\ldots,u_{n0},i_{n0},u'_{10},i'_{10},\ldots,u'_{n0},i'_{n0}) = 0\\
&h_{20}(u_{10},i_{10},\ldots,u_{n0},i_{n0},u'_{10},i'_{10},\ldots,u'_{n0},i'_{n0}) = 0\\
&\ldots\\
&h_{n0}(u_{10},i_{10},\ldots,u_{n0},i_{n0},u'_{10},i'_{10},\ldots,u'_{n0},i'_{n0}) = 0
\end{aligned}
\qquad (1.a)
$$

$$
\begin{aligned}
&a_{1s} = u_{1s+1} - u_{1s} + \Delta u_1(i_{1s},i'_{1s},\ldots,i_{ns},i'_{ns}) = 0 \qquad s=0,\ldots,N-1\\
&a_{2s} = u_{2s+1} - u_{2s} + \Delta u_2(i_{1s},i'_{1s},\ldots,i_{ns},i'_{ns}) = 0 \qquad s=0,\ldots,N-1\\
&\ldots\\
&a_{ns} = u_{ns+1} - u_{ns} + \Delta u_n(i_{1s},i'_{1s},\ldots,i_{ns},i'_{ns}) = 0 \qquad s=0,\ldots,N-1
\end{aligned}
\qquad (1.b)
$$

$$
\begin{aligned}
b_{1s} &= i_{1s} - i_{1s-1} + \Delta i_1 (u_{1s}, u'_{1s}, \dots, u_{ns}, u'_{ns}) = 0 \quad s=1,\dots,N \\
b_{2s} &= i_{2s} - i_{2s-1} + \Delta i_2 (u_{1s}, u'_{1s}, \dots, u_{ns}, u'_{ns}) = 0 \quad s=1,\dots,N \\
&\dots \\
b_{ns} &= i_{ns} - i_{ns-1} + \Delta i_n (u_{1s}, u'_{1s}, \dots, u_{ns}, u'_{ns}) = 0 \quad s=1,\dots,N
\end{aligned}
\tag{1.c}
$$

$$
\begin{aligned}
&h_{1N} (u_{1N}, i_{1N}, \dots, u_{nN}, i_{nN}, u'_{1N}, i'_{1N}, \dots, u'_{nN}, i'_{nN}) = 0 \\
&h_{2N} (u_{1N}, i_{1N}, \dots, u_{nN}, i_{nN}, u'_{1N}, i'_{1N}, \dots, u'_{nN}, i'_{nN}) = 0 \\
&\dots \\
&h_{nN} (u_{1N}, i_{1N}, \dots, u_{nN}, i_{nN}, u'_{1N}, i'_{1N}, \dots, u'_{nN}, i'_{nN}) = 0
\end{aligned}
\tag{1.d}
$$

where u' and i' denote the time derivatives of the voltage u and the current i, respectively. The functions Δu_k and Δi_k (with k=1,...,n) represent respectively the longitudinal voltage drop and the transverse current per segment of each conductor, and the boundary conditions are any given functions h_{k0} and h_{kN}.

The segment equations are written in their general implicit form to keep the algorithm independent from the particular line parameter modelling techniques to be used in applications, as well as to allow the inclusion of distributed voltage and/or current sources along the line.

Details on solution methods adopted for the time equations solution , can be found in [17].

III. INTERFACE BETWEEN THE LINE MODEL AND EMTP

For this study, we directly interfaced the line propagation Fortran program to the ATP version of EMTP by combining two features of ATP:

- in the circuit, we used a type-94 non-linear element for building our own representation of a transmission line as a component described in MODELS;
- and we used MODELS to access the Fortran program doing the actual simulation of the transmission line.

A short description of each method follows.

A. *Using ATP's Type-94 User-Defined Non-Linear Element*

Without the type-94 element, the modelling of electrical components by TACS or MODELS is limited to applications in which the one-time-step delay of the interface with EMTP is tolerable, often at the cost of having to select a smaller time step. The one-step delay has the effect of imposing prediction, with correction delayed by one time step, because the state of the component calculated in TACS or MODELS at time "t" does not affect the electric circuit until time "t+timestep". The behaviour of the component is usually represented in the circuit by letting values calculated in TACS or MODELS control the operation of voltage or current sources, time-varying resistances, and switches.

When using the type-94 non-linear element, one can instead represent a circuit component inside MODELS, and then connect that component directly to the circuit like a regular non-linear element of EMTP. The MODELS component is simulated simultaneously with the rest of the electric circuit, without a time-step delay.

The type-94 component is seen by EMTP as an electrical black box connected to the circuit as one or more branches. It is specified in the data case along with the other branches of the circuit. The associated model is defined in the MODELS section of the data case. The same model can be used by many type-94 components in the same data case.

The type-94 component performs a function similar to the USE statement of MODELS when using a model. In each type-94 use, arbitrary values can be assigned to the DATA parameters defined in the model simulating the component. The inputs to the model from a type-94 are fixed. Two sub-types of the type of the type-94 component can be used: one receives a Thevenin equivalent of the circuit and uses the compensation interface of EMTP, the other solves *i(v)* of the component and is driven by the iteration interface of EMTP. The Thevenin type is used in the application described by this paper. At each time step of the simulation, the model receives from EMTP a Thevenin equivalent of the circuit as seen from its terminals (consisting of open-circuit branch voltages, Thevenin resistance matrix, and its inverse). Also available to the model as inputs are the branch voltages and currents at the component's terminals at the previous time step of the simulation. EMTP expects the model to calculate as outputs the new values of voltages and currents at the type-94's terminals. These values are then included by EMTP in the solution of the electrical circuit using superposition. When using the Thevenin interface, no iteration is performed by EMTP for this operation. The electrical circuit as seen from the type-94 Thevenin component must appear locally linear, that is, any other non-linear elements in the circuit must be separated from the local subnetwork with transmission lines. Using the type-94 MODELS component, it is therefore possible for a user to write a model in the MODELS language to represent the behaviour of an electrical component. One important consideration is that the interface with the circuit is defined in terms of the voltages and currents of the user's data case, not in programming terms of EMTP common blocks and subroutines.

Listing 1 in the Appendix shows the use of a type-94 component in an ATP data case. The example shows a two-branch component (T1 to ground and T2 to ground) using the model named "line" with a Thevenin interface to EMTP. Data parameters are used to specify the operation of the line model.

B. *Adding external programs to EMTP using MODELS*

MODELS allows EMTP users to connect private subroutines and functions to EMTP. The procedures supplied by the user are declared in a model as "foreign" models or functions, and then used in an EMTP data case like regular models and functions of MODELS.

Listing 2 shows sections of the model "line" that is used in the data case by the type-94 component for representing the transmission line. It illustrates the declaration and use of the external subroutine interfaced with EMTP by MODELS for modelling the line.
Using the standard interface provided by MODELS, a user can in effect add code to EMTP without knowing the program's inner workings, and without requiring the assistance of EMTP developers. It is only necessary to re-link EMTP to include the user-supplied code, which then becomes directly available to MODELS.

IV. RESULTS

Three examples are presented as applications of the general-purpose transmission line model with EMTP.

A. *Transmission tower modelling*

The conditions of the experimental tests performed by Ishii et al. [19], for a typical 500 kV double-circuit tower, have been used for this example (fig. 1).
In this application, the tower is modelled as a lossless nonuniform transmission line with the surge impedance varying by discrete steps, and following a geometric progression. The tower surge impedance decreases from 220 Ω to 150 Ω, from top to bottom.
For representing the adjacent transmission line spans, a JMARTI line model is used. The lightning current is a ramp wave with 20 ns rise time. The 400 Ω lightning channel impedance is considered.
The simulation results, shown in fig. 2, are in good agreement with experimental results [19], showing the validity of the proposed nonuniform line model for representing the transmission tower.

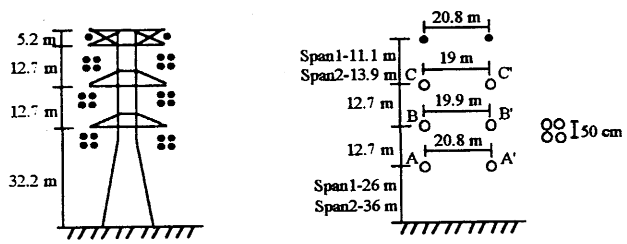

Fig. 1 - Geometry of the transmission tower and of the transmission line, at average height.

B. *Inclusion of corona on line modelling*

The conditions of the experimental tests performed by Gary et al on a three-phase transmission line are reproduced [20]. The surge with reference peak value of 850 kV is considered. Computed results are shown in fig. 3. Corona is taken into account by modifying the capacitance coefficients of the transmission line [21], according to:

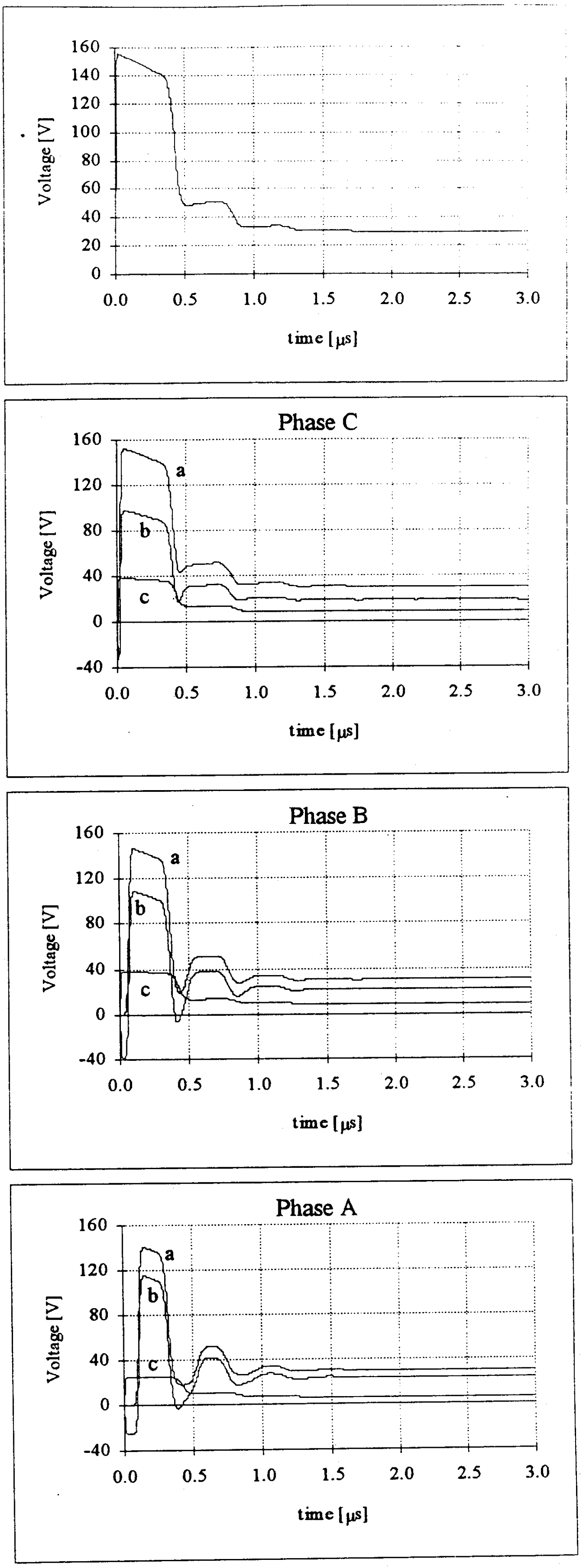

Fig. 2 - Computed overvoltages at the tower top, and at the different phases: (a) Voltage at the tower crossarm position; (b) voltage across the insulator string; (c) voltage induced on the phase conductor.

$$C_{ij} = C_{0_{ij}} + \sum_{k} \frac{C_{0_{ik}} C_{0_{kj}}}{C_{0_{kk}}} (\gamma_k - 1) \qquad (2)$$

where the value of γ_k, at each line segment, is controlled by the electric field, this being evaluated at each time step, taking into account the current values of the voltages and space-charges at each line segment. In the example presented here, γ_k is considered equal to 1.65 above the threshold field (E_{TH}= 33.44 kV/cm). $\gamma_k = 1$, if corona is not active.

The longitudinal parameters of the transmission line are considered frequency-independent, computed by the LINE CONSTANTS routine, at 50 kHz.

The computed results show that the overvoltage propagating along the stressed conductor (phase A) is significantly reduced by corona. Simultaneously, the wavefront rise time is increased. The distortion of the induced voltages caused by corona is significant (phases B and C).

C. *Lightning induced overvoltages*

The conditions of the experimental tests performed by Yokoyama et al are used [22]. In the three-phase arrangement used in the test site, no phase wire was grounded, thus allowing a single-phase equivalent to be used. Computed results are plotted in fig. 4, showing a good agreement with the measured values.

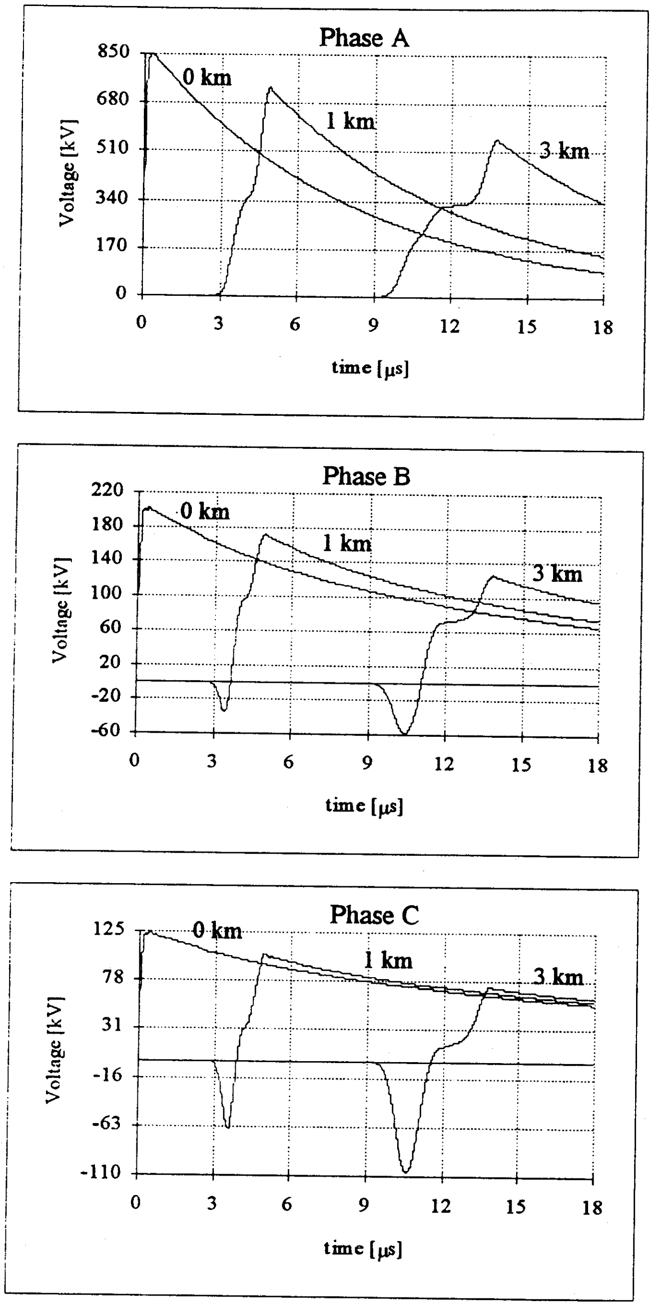

Fig. 3 - Surge propagation on a three-phase line, above corona threshold. Reference peak value at 0 km- 850 kV.

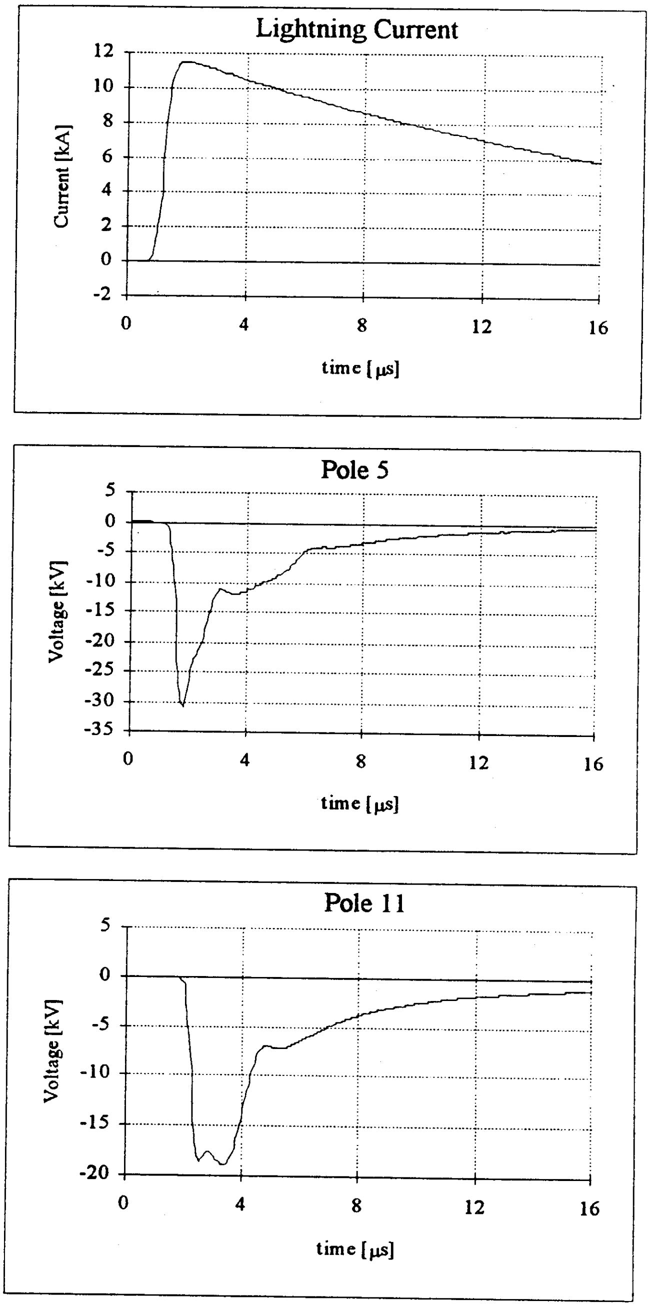

Fig. 4 - Computed lightning current, and induced voltages at poles 5 and 11 (as in [22]).

V. CONCLUSIONS

The implementation of a multiphase transmission line model in ATP-EMTP has been presented. The model can take into account (a) distributed nonuniform parameters (b) distributed non-linear parameters (c) distributed sources. Three application examples of this multi-purpose line model are presented, illustrating (a) the modelling of a transmission tower, (b) the inclusion of corona in the modelling of a transmission line, and (c) the computation of lightning-induced overvoltages. In each case, computation results were compared to published experimental results, and a good agreement was found.

VI. APPENDIX

Listing 1. Using a type-94 component in a data case.

```
94T1        LINE   THEV
94T2
 >DATA LINEID 301. { line id in file rlcg.dat
 >DATA LEN    4000. { line length
 >DATA NCOND     1. { line conductors
 >DATA NSEG    100. { segments in line model
 >END
```

Listing 2. Model connecting the type-94 component to the Fortran line model.

```
MODEL line

COMMENT
|
| This model is a numerical interface between:
| - the Thevenin interface of type-94 in EMTP
| - the representation of a multi-conductor
|   line in the external subroutine MOD003.
|
| It provides to MOD003 the Thevenin voltage
| and resistance matrix of the network at
| each time step of the simulation.
|
| From the calculated i and v at both ends
| of the line in MOD003, it provides to EMTP
| the branch current and voltage at each
| conductor at the line terminals.
|
| It is built for use in EMTP as an n-branch
| type-94 MODELS component in the Thevenin
| mode.
|
ENDCOMMENT
-----------------------------------------
-- Declarations required for any Thevenin model
-----------------------------------------
DATA   n              -- number of branches
       n2 {dflt:n*n}  -- size of impedance matrix
INPUT  vth[1..n]      -- V-th for each branch
       rth[1..n2]     -- R-th matrix, symmetrical
       gth[1..n2]     -- inverse of rth
       vpr[1..n]      -- V-branch at previous t
       ipr[1..n]      -- I-branch at previous t
VAR    vb[1..n]       -- V-branch at this t
  .    ib[1..n]       -- I-branch at this t
OUTPUT vb[1..n], ib[1..n]
------------------------------
-- Declarations of external data
------------------------------
DATA lineid -- line identifier [-99999..999999]
     len    -- line length                   [m]
     ncond  -- number of conductors        [1..]
     nseg   -- number of line segments     [1..]
-----------------------------------------
-- Declaration of foreign subroutine "mod003"
--  to be used as local model "linemodel"
-----------------------------------------
MODEL linemodel FOREIGN mod003
{ ixdata: 30,
  ixin:   2*nc2 +2*ncond +1,
  ixout:  24*ncond +4,
  ixvar:  97 +10*ncond +2*ncond*(ncond-1)
          +2*nc2 +17*nseg1*ncond +8*nseg1*nc2
}
INIT
  ...
ENDINIT
EXEC
  ...
  USE linemodel AS linemodel
    DATA
      xdata[1]  := lineid
      xdata[2]  := len
      xdata[3]  := nseg
      xdata[4]  := ncond
    ...
    INPUT
      xin[1]  := t
      xin[i21..i22]  := vth[1..ncond]
      xin[i31..i32]  := vth[ncond+1..n]
      xin[i41..i42]  := rtho[1..nc2]
      xin[i51..i52]  := rthn[1..nc2]
    OUTPUT
      vb[1..ncond]    := xout[o11..o12]
      vb[ncond+1..n]  := xout[o21..o22]
      ib[1..ncond]    := xout[o31..o32]
      ib[ncond+1..n]  := xout[o41..o42]
      ...
  ENDUSE
ENDEXEC
ENDMODEL
```

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