A Transformer Model for Transformer Transfer Voltage Simulations

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Abstract - **This paper starts by describing a transformer model for transfer voltage studies. Measurements of the frequency characteristics of the transfer voltage of a generator step-up transformer at a hydroelectric power plant are then presented. In the measured results, some resonance frequencies are observed and the influence of the magnetizing resistance seems to be dominant. In order to study the relationship between the transfer voltage peak and the magnetizing resistance at the resonance frequency, simulations of transfer voltages are performed by changing the values of the magnetizing resistance in the transformer model. From the simulated results, it is understood that the magnitude of the transfer voltage is strongly affected by the magnetizing resistance and the overvoltage due to the resonance between the transformer winding inductance and the transformer low-voltage side capacitances could be generated by the surge transfer.**

Keywords: Transformer model, Transfer voltage, Frequency characteristics, EMTP

I . INTRODUCTION

In the insulation design for power stations and substations, it is necessary to study the transfer voltage which is transferred from the high-voltage side to the low-voltage side of a power transformer. Especially for the protection of equipment at the low-voltage side of the generator step-up transformer in a power plant, the transfer voltage is an important factor. There are a number of papers concerned with various aspects of the transfer voltage. At the beginning, efforts were mainly placed on the basic study of surge transfer phenomena [1],[2]. In the 1980's, efforts were continuously made for creating a transformer model, and many papers dealt with its frequency dependence or its high-frequency characteristics [3]-[12].

The idea of taking into account the frequency dependence of transformers has been presented before. To represent the frequency response of transformers, simple linear equivalent circuits [3],[10], transfer functions [4],[12], and state equations [9] have been used. As another kind of modeling method, using modal theory is a unique approach [6]-[8]. The methods mentioned above seem rather complex and may not be convenient for power systems surge analysis, because they are focusing on internal winding representation. In recent years, CIGRE has proposed the simple terminal type transformer model that consists of the EMTP TRANSFORMER model[13] and capacitance elements. This type of model is comparatively simple and clear in its physical meaning of electrostatic and electromagnetic transfer components [14]. On the basis of the CIGRE model, the authors have proposed a new transfer voltage model for three-phase two-winding transformers and derived parameter values using simple test data [15]. The analysis results were found to be comparable to the measured results. But the authors found that the discrepancy between measurements and analysis might be due to disregarding the frequency dependence of the transformer. Simulation results agree well with measurements when the frequency characteristics of the transfer voltage are taken into account [16].

In this paper, for the generalization of the transformer model, the procedure for making EMTP input data is summarized, and an example of the automatic data generating program using the MODELS language is shown. Then the frequency characteristics of the transfer voltage is studied by measurements and simulations. In order to study the relationship of the transfer voltage and the magnetizing resistance at the resonant frequency, simulations of transfer voltages are performed by changing values of the magnetizing resistance in the model. From the simulated results, it is understood that the magnitude of the transfer voltage is strongly affected by the magnetizing resistance and the overvoltage due to the resonance between the transformer winding inductance and the transformer low-voltage side capacitances could be generated by the surge transfer.

II . TRANSFORMER MODEL

A. Improved CIGRE model (for Y/D transformer)

As shown in Fig.1, the authors have proposed a model based on CIGRE model. The model can simulate the electromagnetic and electrostatic transfer components. The parameter values of the proposed model are derived using the values in Table 1. L_1 and L_2 can be obtained by sharing %IZ of the transformer. Rmag can be easily calculated from capacity and voltage [15], giving 12k Ω as the resistance value when the frequency of the transfer voltage is about 10kHz. R_1 and R_2 can be obtained from the measured result. But those values can be neglected as they are very small.

B. Considering frequency characteristics

The approximated equations, representing the frequency-dependent parameters L_1, L_2 and Rmag, were derived from the measured transfer voltages with various capacitance Ca being added. By using the low-voltage leakage inductance L_2'(=2/3L_2) seen from the high-voltage side and the total capacitance C'(=C_{HL}+C_{LG}+C_a) of the transformer, the oscillation period T_t (the period before correction) of the transfer voltage can be theoretically estimated.

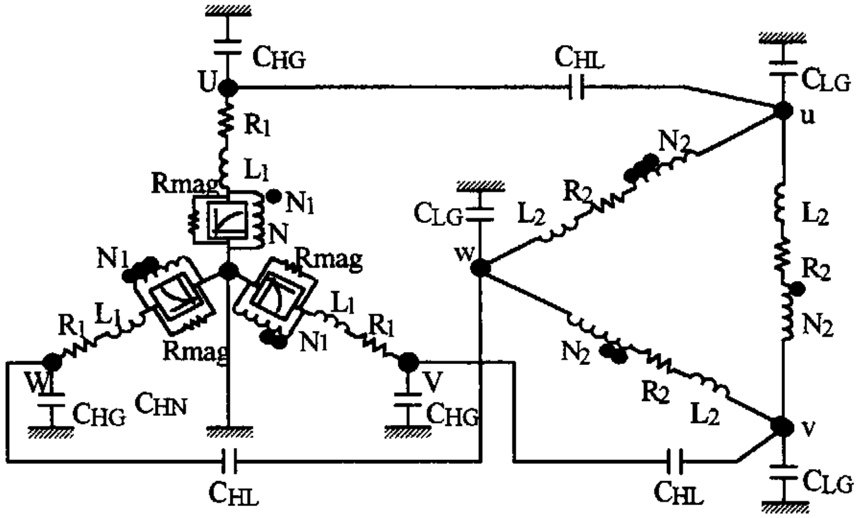
The correction factor K for L_1 and L_2 can be expressed by the square of the ratio of the measured period T_m and the estimated period T_t. In Fig.2, correction factor Ks for various transformers are shown. Rmag can be derived from calculated results which agree well with measured results and is converted in reference to the base capacity (45MVA) and the base voltage (154kV) to correct the difference in each transformer's core volume. In Fig.3, converted values of Rmag are shown. As shown in Fig.2 and Fig.3, these relationships are approximated as follows.

$$\begin{cases} K[pu] = -0.109\,Ln(ft[kHz]) + 1.0625 \\ Rmag\ [\Omega] = 7622.0\exp^{0.0844 ft[kHz]} \end{cases} \qquad (1)$$

C. Modeling procedure

Frequency-dependent parameters L_1 and L_2 used in EMTP can be corrected by multiplying K. Frequency-dependent parameter Rmag used in EMTP can be derived by inversely converting the value of Rmag at the frequency of the transfer voltage. Thus, a more accurate transformer transfer voltage model is obtained. Parameters can be automatically derived by using the MODELS simulation language[17] as shown in Appendix. In this case, the frequency-dependent parameters L_1, L_2 and Rmag controlled by MODELS cannot be represented directly in the TRANSFORMER model, thus these elements must be outside the TRANSFORMER model. Otherwise, parameters L_1, L_2 and Rmag in the TRANSFORMER model (Fig.1) are directly changed.

To verify the validity of the proposed model, a comparison was made between the measurements and the results obtained using the proposed model, where the value of the added capacitance Ca is varied. The simulation results agree with measured results relatively well. However, when the accuracy of the approximated equations decreases, namely, measured K or Rmag separate from the approximate curves, the error becomes larger. If the added capacitance is 50 ~ 500nF, the oscillation frequency of the transfer voltage is from 1 kHz to 100 kHz and the modeling error is smaller than 10% in this frequency range [16]. This application limit represents the situation where the surge suppression capacitor is connected to the low-voltage side of the transformer.



L_1, L_2:	high- and low-voltage leakage inductances	C_{HL}:	capacitance between high- and low-voltage winding
Rmag:	iron-loss resistance	C_{HG}:	capacitance between high-voltage winding and ground
R_1, R_2:	high- and low-voltage winding resistances	C_{LG}:	capacitance between low-voltage winding and ground
N_1, N_2:	high- and low-voltage turns		

Fig.1. The proposed transformer model (Y/D).

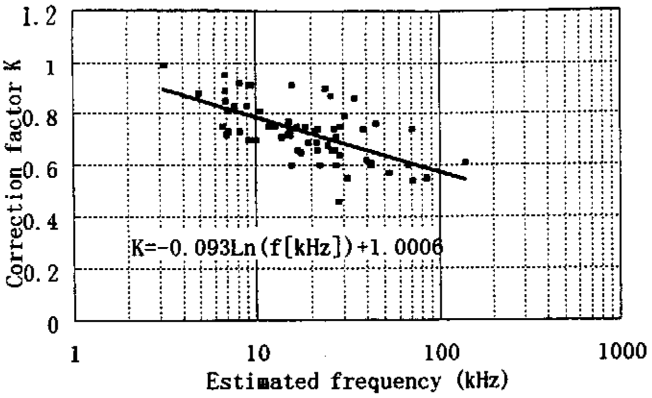


Fig.2. Correction factor K v.s. the estimated frequency.

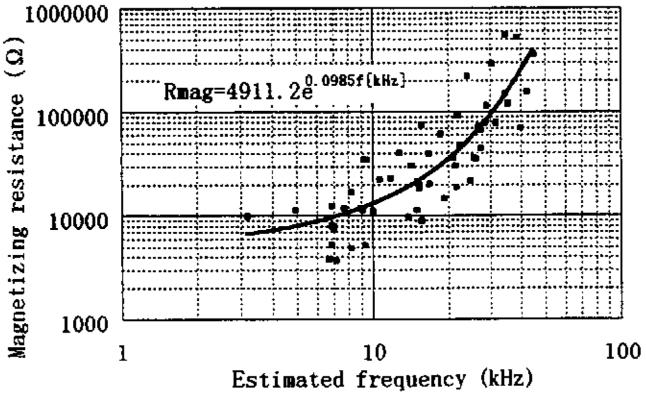


Fig.3. Magnetizing resistance v.s. the estimated frequency.

III. FREQUENCY CHARACTERISTICS MEASUREMENT

The frequency characteristic of the transfer voltage was measured for a transformer at the power plant. A measurement circuit to measure the voltage transferring into the low-voltage side is shown in Fig.4. Table 1 shows the specifications for the tested transformers. AC voltage of 1-450 kHz is applied. The various capacitances are added at the low-voltage side of the transformer to study the frequency dependence of the transfer voltage. The measured frequency characteristics of a 50 MVA shell type transformer are shown in Fig.5. From the figure, some aspects of the transfer voltage's frequency characteristics are observed. Resonance frequencies are present and the frequency varies with the added capacitance value. The observed resonance is basically the series resonance of the leakage inductance L₂' seen from the high-voltage side of the transformer and the added capacitance Ca. So, the resonance frequency fo is calculated as follows.

$$f_0 = \frac{1}{2\pi\sqrt{L_2{}' \cdot C_a}} \tag{2}$$

For the case of the 50MVA transformer, with Ca=55nF and Ca=300nF:

$$\begin{cases} f_{0(Ca=55nF)} = \dfrac{1}{2\pi\sqrt{0.99mH \times 55nF}} = 21.5kHz \\ f_{0(Ca=300nF)} = \dfrac{1}{2\pi\sqrt{0.99mH \times 300nF}} = 9.2kHz \end{cases} \tag{3}$$

The measured resonance frequencies are fo=20.4kHz for Ca=55nF (Fig.5(a)) and fo=9.6kHz for Ca=300nF (Fig.5(c)). The differences come from the fact that the values of L_2 used here are for the rated frequency 60Hz, and that the L_2 value at the resonance frequency is lower than that at the rated frequency. In the measured cases, the maximum transfer ratio at the resonance frequency is about 137.5% for Ca=55nF. The transfer ratio for Y/D transformers is calculated as follows.

$$RT = \frac{V_T}{V_S} \times \frac{V_H / \sqrt{3}}{V_L / 2} \tag{4}$$

where

V_T: transfer voltage magnitude at the resonance frequency (V)

V_S: magnitude of input voltage (100V)

V_H: high-voltage side voltage at the tap used (kV)

V_L: low-voltage side voltage (kV)

When the neutral point is opened (Fig.5(b)), the transfer voltage due to the neutral point's resonance occurs in addition to the directly transferred voltage from the terminal. The magnitude of the transfer voltage due to the neutral resonance is about half the magnitude of that from the terminal and occurs at a lower frequency (about 8kHz). In the real operation of this power station, a surge suppression capacitor (Ca=300nF) is connected to the low-voltage side of the transformer and the transfer ratio at the resonance frequency is about 80%.

The authors have conducted measurements on other transformers in the shop test, for which the transfer voltage ratio is lower than that for the real power plant, as shown in Fig.6. The origin of the higher transfer ratio seems to be the fact that the transformers in the power plant were manufactured several years ago. The iron-core characteristics of the transformer are different from those nowadays and the iron-losses of these transformers are higher than those of the transformers nowadays.

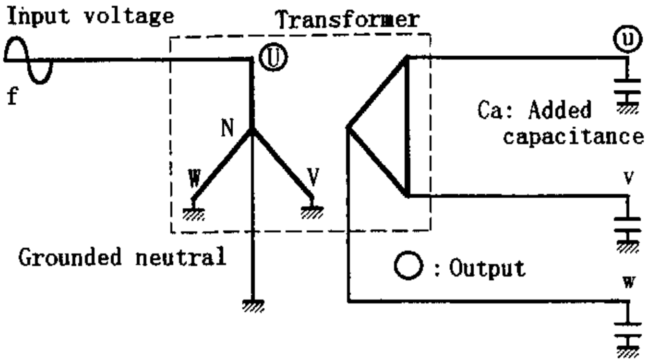


Fig.4. A measurement circuit to measure transfer voltage.

Table 1. Specifications for the transformers

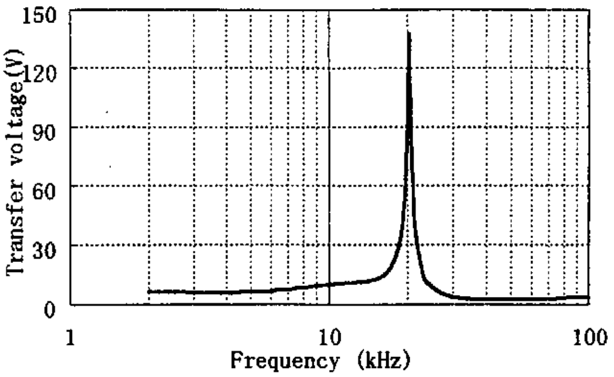
Item	Values
Rated capacity: P_{Tr}	50MVA
Rated voltages(high/low): V_H/V_L Winding connection (high/low)	161/12.6kV (Y/D)
Frequency: f	60Hz
Short circuit impedance: %Z	11.82%
Capacitance between high-voltage winding and ground(measured): C_{HG}	2083pF/phase
Capacitance between low-voltage winding and ground(measured): C_{LG}	7750pF/phase
Capacitance between high-voltage winding and low voltage winding (measured): C_{HL}	4083pF/phase

Note: %IZ is measurement value when the minimum tap is used. C_{HG}, C_{LG}, C_{HL} are measured values.

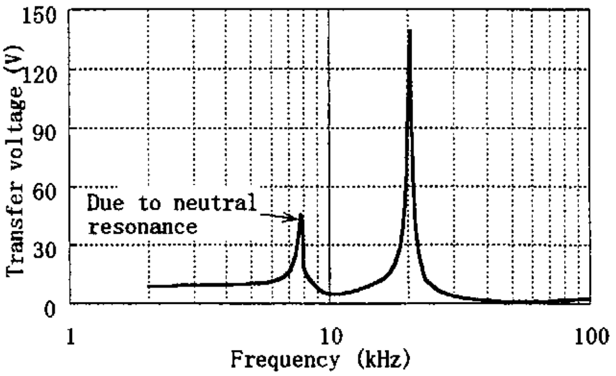
IV. INFLUENCE OF MAGNETIZING RESISTANCE

From the measured frequency characteristic, it is considered that the iron-loss affects greatly the magnitude of the transfer voltage at the resonance frequency. Thus, a simulation was performed to study the influence of the magnetizing resistance Rmag on the magnitude of the transfer voltage at the resonance frequency. The simulated circuit is the same as that shown in Fig.4. The input voltage is AC100V, the frequency of which is the resonance frequency derived from the measured results shown in Fig.5. The transformer model shown in Fig.1, is used.

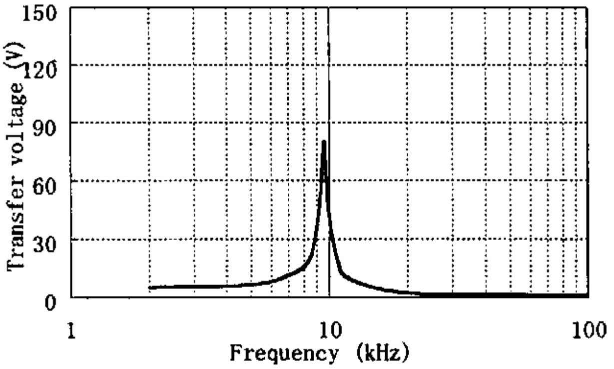
By changing the value of the magnetizing resistance Rmag, the u-phase voltage at the low-voltage side of the transformer is calculated. Calculated results are shown in Fig.7. From the figure, it is observed that the magnitude of the transfer voltage strongly depends on and linearly increases with the value of magnetizing resistance. If the iron-loss of the transformer increases for any reason, the possibility seems to be higher that the transferred overvoltage will increase on the low-voltage side of the transformer.



(a) neutral grounded, Ca=55nF



(b) neutral opened, Ca=55nF



(c) neutral grounded, Ca=300nF

Fig.5. Frequency characteristics of transfer voltage.

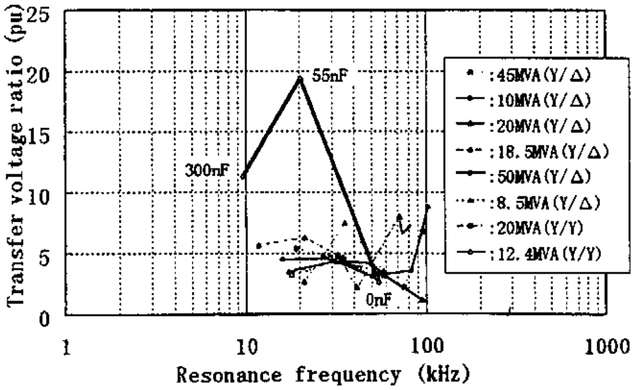


Fig.6 Transfer voltage ratio at the resonance frequency

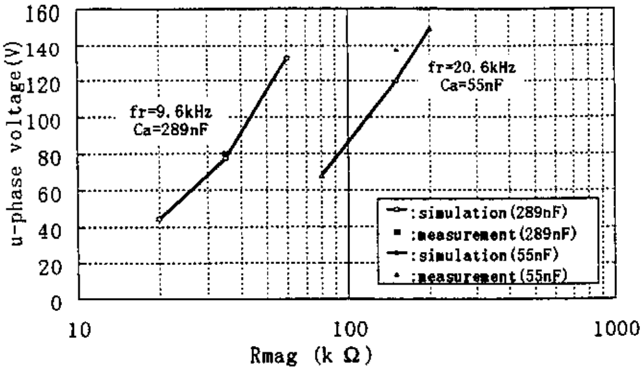


Fig.7 Transfer voltage v.s. magnetizing resistance.

V. CONCLUSIONS

The construction of a transformer model for transfer voltage studies taking into account the frequency characteristics of the transfer voltage was described in detail.

The measured frequency characteristics of the transfer voltage for a three-phase two-winding power transformer at the hydroelectric power plant were presented. In the measured frequency characteristics, some resonance frequencies are observed. Compared to other test results, it seems that the iron-loss of the transformer affects the transfer voltage.

To study the relationship between the transfer voltage and the magnetizing resistance at the resonant frequency, simulations were performed for the transfer voltages by changing the values of the magnetizing resistance. From the simulated results it is understood that the magnitude of the transfer voltage is strongly affected by the values of the magnetizing resistance and overvoltages due to the resonance between the transformer and the power system could be generated.

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VII. APPENDIX

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MODEL LEAKL
DATA  n              -- number of node pairs
      n2 {dflt: n*n}  -- number of matrix elements
INPUT v[1..n]
-- guessed voltages across terminals 1-3, 2-4
      v0[1..n]
-- steady-state voltages across terminals 1-3, 2-4
      i0[1..n]
-- steady-state currents into terminals 1, 2
VAR   i[1..n]
-- calculated currents into terminals 1, 2
      didv[1..n2]
-- calculated left-side nodal conductance matrix
OUTPUT i[1..n], didv[1..n]
DATA  P      -- [MVA] TRANSFORMER RATED CAPACITY
      VH     -- [kV ] HIGH VOLTAGE RATED VOLTAGE
      VL     -- [kV ] LOW  VOLTAGE RATED VOLTAGE
      fre    -- [Hz ] RATED FREQUENCY
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      IZ     -- [%Z]  leakage inductance
      CA     -- [uF]  C =CLH+CLG+CA
      FLA    -- High=1.0 or Low=2.0
      SET    -- Y/D=1.0, Y/Y=2.0, D/D=3.0
CONST PBASE {val:45.00}  -- [MVA] BASE POWER
      VBASE {val:154.0}  -- [kV ] BASE VOLTAGE
VAR   LH
-- [H] HIGT VOLTAGE SIDE LEAKAGE INDUCTANCE
      LL
-- [H] LOW  VOLTAGE.SIDE LEAKAGE INDUCTANCE
      LDUM  -- [H] CORRECTION LEAKAGE INDUCTANCE
      TT    -- CORRECTION CYCLE
      k     -- CORRECTION COEFFICIENT
      LU
-- [H] U-PASE variable value of inductance L
      LV
-- [H] V-PASE variable value of inductance L
      LW
-- [H] W-PASE variable value of inductance L
      st
-- used for converting Laplace s to time domain
      L[1..3]
-- [H] variable value of inductances L[1], L[2]
      gL[1..3]
-- [mho] conductance of L[1], L[2]
INIT
IF SET = 1 THEN
-- Y/D
    LH   := (VH*VH/P)*(IZ/100)*(1/2/pi/fre)*0.5
-- High side L
    LL   := (3*VL*VL/P)*(IZ/100)*(1/2/pi/fre)*0.5
-- Low  side L
  ELSIF SET = 2 THEN
-- Y/Y
    LH   := (VH*VH/P)*(IZ/100)*(1/2/pi/fre)*0.5
-- High side L
    LL   := (VL*VL/P)*(IZ/100)*(1/2/pi/fre)*0.5
-- Low  side L
  ELSIF SET = 3 THEN
-- D/D
    LH   := (3*VH*VH/P)*(IZ/100)*(1/2/pi/fre)*0.5
-- High side L
    LL   := (3*VL*VL/P)*(IZ/100)*(1/2/pi/fre)*0.5
-- Low  side L
  ELSE   write("**ERROR Tr.winding select number is
Nothing ERROR**")
  ENDIF
  IF SET = 1 THEN     LDUM := 2*LL/3
-- Y/D L'
  ELSIF SET = 2 THEN  LDUM := 2*LL
-- Y/Y L'
  ELSIF SET = 3 THEN  LDUM := 3*LL/5
-- D/D L'
  ENDIF
  TT   := 2*pi*sqrt(LDUM*(CA/1000000))
-- Estimated oscillation period
  k    := -0.093*ln(1/1000/TT)+1.0006
-- Estimated coefficient K
    IF k>1 THEN K:=1.0
    ENDIF
  -- Correction leakage inductance
  IF FLA = 1    THEN LU := LH*k
-- High side L'
  ELSIF FLA = 2 THEN LU := LL*k
-- Low  side L'
  ELSE  write("*** ERROR  FLA select number '1,2' is
Nothing ERROR ***")
        LU := 0.00
  ENDIF
        LV := LU
        LW := LU
  st               := 2/timestep
-- trapezoidal rule conversion from Laplace
  L[1..3]          := [LU, LV, LW]
-- initialize variable inductance values
  gL[1..3]         := 1/(st*L[1..3])
-- conductances converted from Laplace 1/sL
  didv[1..9]        := [gL[1], 0, 0, 0, gL[2], 0, 0, 0,
gL[3]]
-- conductance matrix
-- the next 2 initializations are needed for the
Laplace functions
  histdef(v[1..3]) := v0[1..3]
  histdef(i[1..3]) := i0[1..3]
 ENDINIT
EXEC
-- L[1] and L[2] are constant in this example
  CLAPLACE(i[1]/v[1]) := (1|s0)/(L[1]|s1)  -- i/v=1/sL
  CLAPLACE(i[2]/v[2]) := (1|s0)/(L[2]|s1)
  CLAPLACE(i[3]/v[3]) := (1|s0)/(L[3]|s1)
 ENDEXEC
ENDMODEL
```