BCTRAN Transformer Data Calculation function

1 Introduction

BCTRAN accurately reproduces the behavior of a three-phase, multi-winding transformer at power frequency. From a numerical point of view, it has a number of advantages over TRELEG. For instance, BCTRAN allows infinite magnetizing impedance, whereas TRELEG assumes that the magnetizing impedance is finite (for large values of the magnetizing impedance TRELEG may produce an ill-conditioned model). Also TRELEG degenerates to a coupled resistance matrix at dc (which may or may not be stable), whereas BCTRAN becomes an uncoupled positive resistance matrix at dc, which represents winding resistances. In general, BCTRAN is better behaved than TRELEG.

2 Linear magnetizing impedance and excitation data

The exciting current in 5-limb three-phase transformers and in single-phase transformers can often be ignored. If the current is ignored, the $\mathbf{L}^{-1}$ matrix generated by BCTRAN is singular and cannot be inverted to an impedance matrix. However, since the EMTP is based on a nodal admittance matrix formulation, this fact is not a problem.

For three-phase transformers with three-limb core construction, the exciting current in the zero sequence test is fairly high (e.g., 100%) and should not be ignored. The shunt admittance of the magnetizing branch, which is added to the $\mathbf{R}$, $\mathbf{L}^{-1}$ model to represent the exciting current and excitation losses, is calculated from the excitation test data. There are two sets of values: one for the positive and the other for the zero sequence tests. These two values are converted to a 3x3 submatrix with diagonal elements Y_s and off-diagonal elements Y_m,

$$Y_s = \frac{(Y_0 + 2Y_1)}{3} \tag{1}$$

$$Y_m = \frac{(Y_0 - Y_1)}{3} \tag{2}$$

This shunt admittance matrix is then either connected across one winding, or (1/N)-th of the pu values is connected across all N windings.

If shunt admittances are connected across all windings, as shown in Figure 2–1 for single phase transformer with 2 windings, then no correction is made by the program to account for the

influence of the short-circuit input impedances. As a consequence, the exciting current in the model of Figure 2–1 will be slightly larger than the specified value, and the short-circuit input impedance will be slightly smaller than the specified value. For an exciting current of 0.01 pu (or $Z_m = 100\,pu$) and a short-circuit input impedance of 0.10 pu, these differences are approximately 0.1%. Note that the imaginary parts of (Y_s, Y_m) become part of the $\mathbf{L}^{-1}$ matrix, as indicated by the large, dotted box in Figure 2–1. This modification makes the L^{-1} matrix nonsingular and invertible. The resistances R_m, which approximate hysteresis and eddy current losses, must be added as additional branches at the "external nodes".
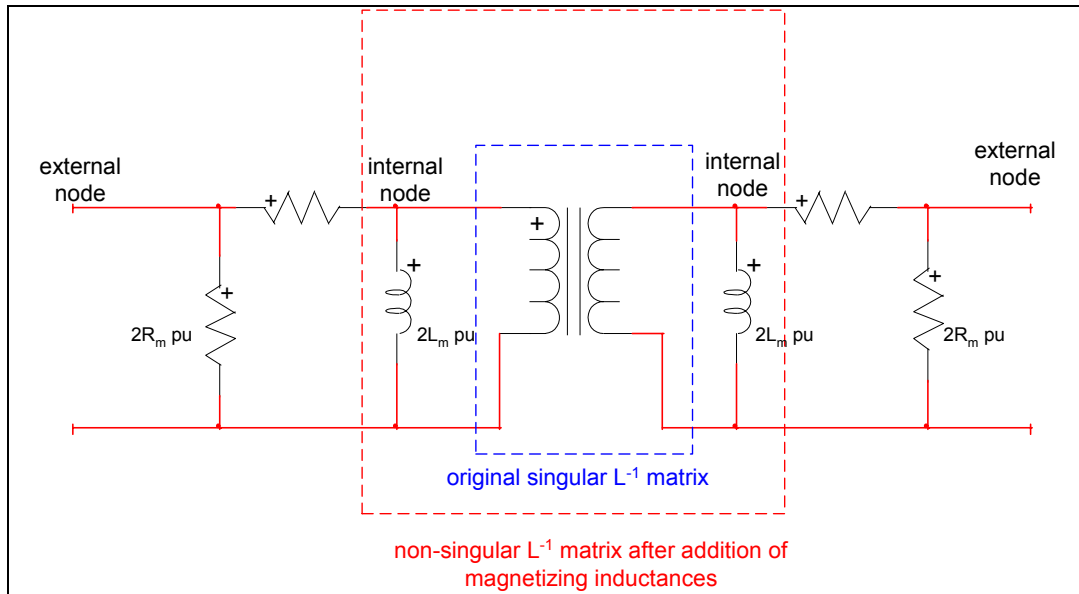

Figure 2–1 Addition of magnetizing branches across all windings

If the shunt admittance matrix is connected across one winding only, then the program makes a correction in the case where the excitation test is made across one winding "i" while the shunt admittance matrix is connected across another winding "k". In that case, the short-circuit input impedance between "i" and "k" is subtracted from the inverse of (Y_s, Y_m) and this modified shunt admittance is then connected across "k". This way, the specified excitation data and the excitation data obtainable from the model will be identical. If the user specifies zero excitation losses, they will be raised to the value $I^2_{exciting}R_i$ in this case, because in reality these losses must be at least as high as the I^2R losses in winding "i". It may be best to connect the shunt admittance across the winding closest to the core on transformers with cylindrical windings.

The electrical data required for calculating a BCTRAN model of a transformer are divided into three tabs:
- ❑ **Excitation data**
- ❑ **Windings**
- ❑ **Short-circuit test data**

The next sections detail the information entered on each tab. An example of BCTRAN usage can be found in the design file Examples\transformer_data\test1.ecf.

3 Excitation data

The excitation data section allows to define:

- **Number of windings per core leg.** This N limited to 10 in the present program. For example a 230/500 kV three-phase transformer without a tertiary winding has N=2; if a tertiary winding is added, then N=3.
- **Rated frequency** in Hz needed to convert reactances into inductances.
- **Positive sequence excitation test** to define:
  - **Exciting current** I_{excit}^{pos} in percent, based on three-phase power rating S_{rating}^{pos} and rated voltage.
  - **Three-phase power rating** S_{rating}^{pos} in MVA.
  - **Excitation loss** $Loss_{excit}^{pos}$ in kW as defined in section 3.1.
- **Zero sequence excitation test** section where is defined the related values:
  - **Exciting current** I_{excit}^{zero} in percent, based on three-phase power rating S_{rating}^{zero} and rated voltage.
  - **Three-phase power rating** S_{rating}^{zero} in MVA.
  - **Excitation loss** $Loss_{excit}^{zero}$ in kW as defined in section 3.1.

If the transformer has delta-connected windings, then the zero sequence excitation test really becomes a short-circuit test, since a closed delta acts as a short-circuit for zero-sequence currents. It is, therefore, assumed that delta connections are open (Figure 3–1) in the zero sequence excitation test On transformers with closed deltas, any reasonable value of I_{excit}^{zero}, S_{rating}^{zero} and $Loss_{excit}^{zero}$ can be used because the influence of these values will be overridden by the short-circuit test data to the closed deltas. On transformers with no delta-connected windings or open deltas, the zero sequence current determines how much voltage will be induced in the two other phases of a winding if one phase is energized.
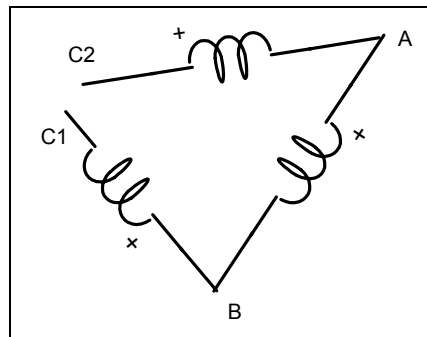

Figure 3–1 Open Delta connection

For three-phase transformer banks consisting of single-phase units, input the single-phase data as positive sequence parameters and leave the fields for the zero sequence parameters blank.
- Checkbox to indicate if the **3-phase transformer is made of single-phase transformers**.
- **Excitation test winding number** indicates the winding from which the excitation tests were made
- **Magnetizing branch winding** indicates the winding across which the magnetizing branch is to be placed. If the two numbers are not specified then the program will connect magnetizing branches across all windings. If the **Excitation test winding number** is specified then the **Magnetizing branch winding** must also be specified. The two numbers can be equal. For more details see section 3.1

❑ **Select the calculated matrices** to be saved in the model data file

3.1 Exciting current in zero sequence excitation test

If the transformer has delta-connected windings, it will be assumed that the delta connections are opened for the zero sequence excitation test. Otherwise, the test is not really an excitation test, but a short-circuit test between the excited winding and the delta-connected windings, since closed delta connections provide a short-circuit path for zero sequence currents.
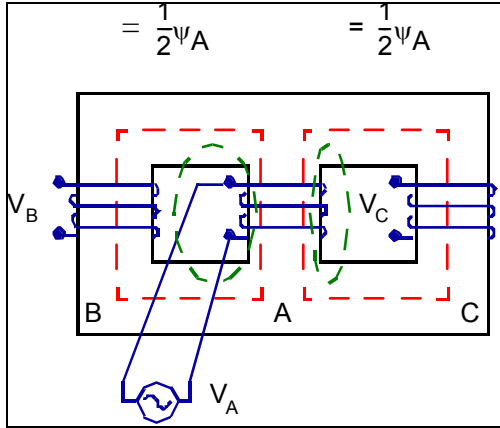

Figure 3–2 Three-limb core type designs

Often, the manufacturer does not give the zero sequence exciting current. In such cases, a reasonable value can be found as follows: excite one phase of a winding (A in Figure 3–2), and estimate how much voltage will be induced in the other two phases (B and C). For the three-limb core design of Figure 3–2, almost one half of flux A returns through phases B and C, which means that V_B and V_C will be close to 0.5 V_A (with reversed polarity). If we use k for this factor, then

$$\frac{I_{excit}^{zero}}{I_{excit}^{pos}} = \frac{1+k}{1-2k} \tag{3}$$

This equation is derived from

$$V_A = Z_s I_A$$
$$V_B = Z_m I_A \tag{4}$$
$$V_C = Z_m I_A$$

Where Z_s is the self-impedance of phase A in excitation test and Z_m is the mutual impedance to phases B and C. Then

$$V_B = V_C = \left(\frac{Z_m}{Z_s}\right) V_A = -\left(\frac{Z_{pos} - Z_{zero}}{2Z_{pos} + Z_{zero}}\right) V_A = -k V_A \tag{5}$$

Since the exciting current is proportional to $\dfrac{1}{Z_{pos}}$ in positive sequence, and to $\dfrac{1}{Z_{zero}}$ in zero sequence, the relationship for k in equation (5) can be transformed into equation (3).

Obviously, k cannot be exactly 0.5, because this would lead to an infinite zero sequence exciting current. A reasonable value for I_{excit}^{zero} of a three-limb core-type design might be 100%. If $I_{excit}^{pos} = 0.5\%$, this would produce k = 199/401 = 0.496, which comes close to the theoretical limit of 0.5 mentioned above.

Besides the three-limb core-type design, there are also five-limb core-type designs (Figure 3–3), and shell-type designs (Figure 3–4). In the five-limb core-type design, maybe two thirds of approximately $\frac{1}{2}\psi_A$ returns through legs B and C.
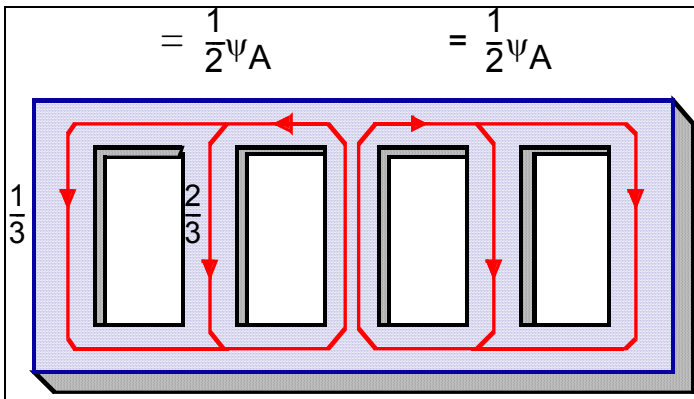

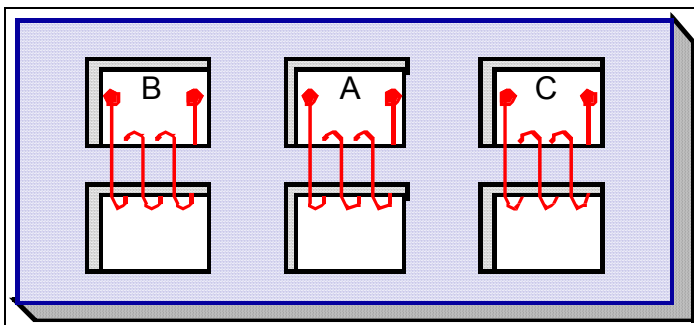**Figure 3–3 Five-limb core type design**

Figure 3–4 Shell type design

In that case, k would be one third, or

$$\frac{I_{excit}^{zero}}{I_{excit}^{pos}} = 4 \qquad (6)$$

The excitation loss in the zero sequence test is higher than in the positive sequence test, because the fluxes A, B, C in the three cores are now equal, and in the case of a three-limb core-type design, they must return through air and the tank, with additional eddy-current losses in the tank.

Neither the values for the zero sequence excitation current nor the value for the zero sequence excitation loss are critical if the transformer has delta-connected windings because excitation tests really become short-circuit tests in such cases.

4 Winding data

For each transformer winding the required data are:
- **V rating** is the rated voltage in kV; line-to-ground for wye-connected windings, and line-to-line for delta connected windings.
- **R (Ohms)** the Winding resistance in ohms of one phase (if the values differ in the three phases, use the average value). If the winding resistances are not known, they can be

calculated from the load losses supplied with the short-circuit data if N=2 or 3 where N is the number of winding.

Strictly speaking, the load losses are not only I^2R losses, but contain stray losses as well; however, this is ignored. In the calculation of winding resistances from load losses, it is assumed that in pu $R_1 = R_2$ for two winding transformers. For three-winding transformers, there are three equations in three unknowns in pu R_1, R_2 and R_3. For transformers with four or more windings (per phase), there is no easy way to find winding resistances from the load losses. Therefore, winding resistance must be specified as input data for N>4

❑ **k-node and m-node** are used for naming the left and right nodes for each phase on each winding. The names are mandatory, only trailing blanks are acceptable. The code name GND can be used to denote ground. The node names will appear on the 'RL coupled multiphase' device drawing after loading the data from this data calculation function. The names are used for reference; the actual connections must be made through the signals connected to the pins of the 'RL coupled multiphase' device into which the model data generated by BCTRAN can be loaded.

5 Short-circuit test data

The required data for each short-circuit test between a pair of windings i and k:

❑ **P** (P_{ik}) gives the load losses in kW in the positive sequence test. If $P_{ik} > 0$ then this value is used in the following (pu for all units) equation to find the positive sequence reactance:

$$X_{ik} = \sqrt{Z_{ik}^2 - (R_i + R_k)^2} \qquad (7)$$

with Z_{ik} being the pu short-circuit impedance in test between i and k and $R_i + R_k$ are the pu load losses on the same MVA basis as Z_{ik} if load losses are nonzero. If load losses are not given, these are the specified pu winding resistances on the same MVA basis.

P_{ik} can also be used to calculate winding resistances for N<3 (N is the number of windings), provided $P_{ik} \geq 0$ for all short-circuit test (see parameter LOSS below). Read-in winding resistances are then ignored.

Equation (7) is used for positive sequence values. It is also used for zero sequence values if the zero sequence test does not involve a third (delta-connected) winding. In the latter case, the following procedure is used. Let us assume that the high-voltage and low-voltage windings are wye-connected with their neutrals grounded. In this case, the zero-sequence short-circuit test between the high- and low-voltage windings will not only have the low-voltage winding shorted but the tertiary winding as well if the delta is closed (which is usually the case). This special situation is handled by modifying the data for an open delta so that the earlier approach can again be used. With the well-known equivalent star circuit of Figure 5–1, the three test values supplied by the user are:

$$X_{12}^{closed\,\Delta} = X_1 + \frac{X_2 X_3}{X_2 + X_3} \qquad (8)$$

$$X_{13} = X_1 + X_3 \qquad (9)$$

$$X_{23} = X_2 + X_3 \qquad (10)$$

which can be solved for X_1, X_2, X_3:

$$X_1 = X_{13} - \sqrt{X_{23}X_{13} - X_{23}X_{12}^{closed\,\Delta}} \qquad (11)$$

$$X_2 = X_{23} - X_{13} + X_1 \qquad (12)$$
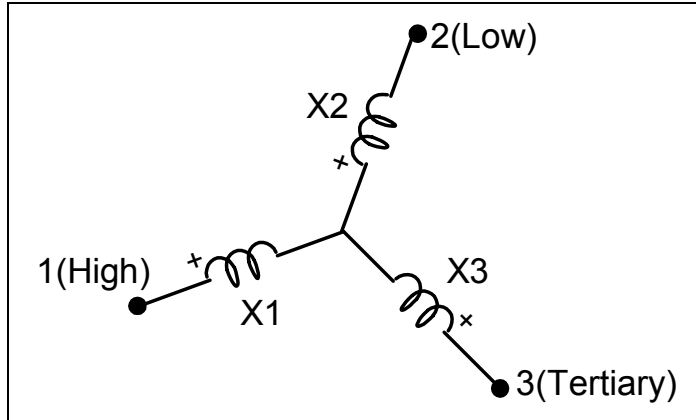
$$X_3 = X_{13} - X_1 \qquad (13)$$

Figure 5–1 Equivalent star circuit for zero sequence short-circuit tests of a three-winding transformer (all reactances must be in pu)

After this modification the program works with short-circuit reactances X_1+X_2, X_1+X_3 and X_2+X_3, which implies that winding 3 is no longer shorted in the test between 1 and 2. The modification scheme used in the program is more complicated because the resistances are also included in equation (8), which becomes:

$$\left| Z_{12}^{close\Delta} \right| = \left| R_1 + jX_1 + \frac{(R_2 + jX_2)(R_3 + jX_3)}{(R_2 + R_3) + j(X_2 + X_3)} \right| \qquad (14)$$

With $\left| Z_{12}^{close\Delta} \right|$ being the values supplied by the user, the R_1, R_2, R_3 being the winding resistances which were either directly supplied by the user or which were calculated from the load losses, as explained in the description of the winding data.

- ❑ **Z pos** is the short-circuit input impedance Z_{ik}^{pos} in percent in the positive sequence test between the specified winding pair i and k, based on S_{rating}^{pos} (three phase) and on the rated voltages of both windings. In North-American standards, the short-circuit input impedance is called "impedance voltage"; in some European standards it is called "short-circuit voltage."

- ❑ **S pos rating** (MVA) is the three-phase power rating S_{rating}^{pos} on which Z_{ik}^{pos} is based.

- ❑ **Z zero** is the short-circuit input impedance Z_{ik}^{zero} in percent in the zero sequence test between the specified winding pair i and k, based on S_{rating}^{zero} (three phase) and on the rated voltages of both windings.

- ❑ **S zero rating** (MVA) is the three-phase power rating S_{rating}^{zero} on which Z_{ik}^{zero} is based. If the parameter DELTA=0, then P_{ik} from the positive sequence test is also used to calculate the zero sequence reactance with equation (7). If $S_{rating}^{zero} = 0$ it is assumed to be equal to S_{rating}^{pos}.

If DELTA>0 then the winding resistances are used to obtain reactances from impedances. In wye-delta-delta connections, the zero sequence test cannot be performed between the closed delta connected windings. Set $Z_{ik}^{zero} = 0$ in such a case. The program will then automatically calculate a reasonable value from

$$X_{d-d}^{zero} = X_{d-d}^{pos} \left| \frac{Z_{y-2d}^{zero}}{Z_{y-2d}^{pos}} \right| \qquad (15)$$

Here "2d" in the subscript indicates that both deltas are shorted in parallel.

❑ **DELTA**
- DELTA=0 means that the zero sequence short-circuit test involves only windings i and k, as in transformers where all windings are wye-connected with grounded neutrals. If a transformer has a delta-connected winding and if the winding is not k, then the delta must be open in the test between i and k.
- DELTA>0 gives the number of additional winding which is short-circuited in addition to winding k in zero sequence test between i and k, as described earlier. This additional winding will normally be delta-connected (in the case of a closed delta). For the most important case of three-winding transformers, the program can presently handle Yyd-connections and Ydd-connections.

In the Yyd (wye-wye-delta) connection, "d" would be the additional shorted winding in the zero sequence test between "Y" and "y". In the Ydd (wye-delta-delta) connection (1=Y, 2=d, 3=d), 3 would be the additional winding in test between 1 and 2, and 2 would be the additional winding in test between 1 and 3, but both tests would produce identical impedances. This is recognized by the program, which prints an explicit message.
The program cannot handle Ddd (delta-delta-delta) connections with DELTA>0.

For three-phase transformer banks consisting of single-phase transformers, input the single-phase data as positive sequence parameters and set the fields for the zero sequence input parameters to 0, including DELTA.

❑ **LOSS**
- Set LOSS to 0 to use provided winding resistances.
- Set LOSS to 1 to calculate the winding resistance from load losses P (P_{ik}), provided the number of winding is ≤ 3 and P ≥ 0 for all short circuit tests.

6 BCTRAN model data file format

After entering all the required data, The BCTRAN Data Calculation Function can be invoked from the "Run this case" data tab to generate the model data file. The model can be used with the "RL coupled multiphase" device by loading the generated data through the "Load data from file" option of this device.

The BCTRAN model data file format for a sample transformer with 3 windings per core leg is shown in Figure 6–1. It is documented here for reference purposes only, since users are not required to manipulate these data files.
The shown example is available in the design file Examples\transformer_data\test1.ecf. This format used in the old EMTP-V3 files has been kept in this release of EMTP-EMTPWorks. The following sequence is enforced.
- ❑ Comment lines starting with "C" (in the first column) are allowed only up to the first actual transformer data line.
- ❑ The first comment line indicates that the model was generated with a BCTRAN run in EMTPWorks. It also indicates the type of the generated matrices.
- ❑ The next optional line indicates the frequency at which the reactance matrix is calculated. If the line is present it means that ohms are used for the reactance. It is noticed that this frequency must match the default power frequency of the design as selected in Simulation Options.
- ❑ The $VINTAGE has been also kept from the EMTP-V3, but it is simply skipped in EMTPWorks.
- ❑ Next lines are used to present the lower triangular part of the RL couple symmetric matrix. The first line for each row of the matrix has:
  - the winding number

- k-node and m-node names. The node names will appear on the "RL coupled multiphase" device drawing after loading the data from this data calculation function. The names are used for reference, the actual connections must be made through the signals connected to the pins of the "RL coupled multiphase" device.
- The R (columns 27 to 42) and L (columns 43 to 58) values in pair (continued on the next lines).

```
C BCTRAN BRANCH DATA - RESISTANCE MATRIX (OHMS) AND REACTANCE MATRIX (OHMS) AT
C F= 60.00
$VINTAGE, 1
 1H-1   GND               0.2054666000E+000.4143209749E+05
 2L-1   GND               0.0000000000E+000.1977102763E+05
                          0.7423330000E-010.9437879471E+04
 3T-1   T-2               0.0000000000E+000.1557956789E+05
                          0.0000000000E+000.7437550277E+04
                          0.8220000000E-010.5866218159E+04
 4H-2   GND               0.0000000000E+00-.5331063870E-01
                          0.0000000000E+000.9559994346E+00
                          0.0000000000E+000.1751763916E+01
                          0.2054666000E+000.4143209749E+05
 5L-2   GND               0.0000000000E+000.9559994346E+00
                          0.0000000000E+000.7376473969E+00
                          0.0000000000E+000.8362768655E+00
                          0.0000000000E+000.1977102763E+05
                          0.7423330000E-010.9437879471E+04
 6T-2   GND               0.0000000000E+000.1751763916E+01
                          0.0000000000E+000.8362768655E+00
                          0.0000000000E+000.6595965542E+00
                          0.0000000000E+000.1557956789E+05
                          0.0000000000E+000.7437550277E+04
                          0.8220000000E-010.5866218159E+04
 7H-3   GND               0.0000000000E+00-.5331063870E-01
                          0.0000000000E+000.9559994346E+00
                          0.0000000000E+000.1751763916E+01
                          0.0000000000E+00-.5331063870E-01
                          0.0000000000E+000.9559994346E+00
                          0.0000000000E+000.1751763916E+01
                          0.2054666000E+000.4143209749E+05
 8L-3   GND               0.0000000000E+000.9559994346E+00
                          0.0000000000E+000.7376473969E+00
                          0.0000000000E+000.8362768655E+00
                          0.0000000000E+000.9559994346E+00
                          0.0000000000E+000.7376473969E+00
                          0.0000000000E+000.8362768655E+00
                          0.0000000000E+000.1977102763E+05
                          0.7423330000E-010.9437879471E+04
 9GND   T-1               0.0000000000E+000.1751763916E+01
                          0.0000000000E+000.8362768655E+00
                          0.0000000000E+000.6595965542E+00
                          0.0000000000E+000.1751763916E+01
                          0.0000000000E+000.8362768655E+00
                          0.0000000000E+000.6595965542E+00
                          0.0000000000E+000.1557956789E+05
                          0.0000000000E+000.7437550277E+04
                          0.8220000000E-010.5866218159E+04
$VINTAGE, 0
```

Figure 6–1 BCTRAN model data file format with R and X () data

The model data file format is slightly different for the output of the inverse inductance matrix. The only differences are: absence of the frequency line and presence of the "USE RB" line indicating that inverse inductance matrix is given. It is shown in the figure below.

```
C BCTRAN BRANCH DATA - [R] IN(OHMS) AND INVERSE INDUCTANCE MATRIX (1/MILLIHENRIES)
$VINTAGE, 1
  USE RB
 1H-1    GND               0.2054666000E+000.2651269237E-01
 2L-1    GND               0.0000000000E+00-.5957848438E-01
                           0.7423330000E-010.1808547434E+00
Ö.
```

Figure 6–2 BCTRAN model data file with R and L^{-1} data

7 Generic transformer modeling hints

7.1 Saturation effects

Since the air-core inductance (which is the slope of the $\psi - i$ curve in the fully saturated region) is fairly low (typically twice the value of the short-circuit inductance), it may make a difference where the nonlinear inductance is added. It is best to put the nonlinear inductance across the terminals of the winding closest to the core, which is usually the tertiary winding in three-winding transformers.

This nonlinear inductance will be in parallel with the unsaturated value of the magnetizing inductance. Example: if the saturation curve is defined by three points at $i = i_m = 0.03\%$, 0.06% and 0.12%, and if 0.03% was used as magnetizing current for finding the impedance matrix, then the value of 0.03% must be subtracted in defining this nonlinear inductance (dashed line in Figure 7–1, below).
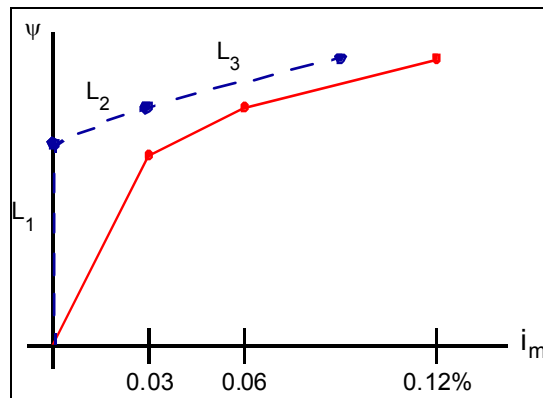

Figure 7–1 Definition of nonlinear inductance

7.2 Floating Delta connection

If transformer windings are connected in delta and nothing else is connected to it, then the delta is "floating". In a floating delta connection, the voltages to ground are not defined but only the voltages across the windings. This leads to a singular matrix with a respective error message termination. Therefore, either ground one terminal or add ground capacitance.
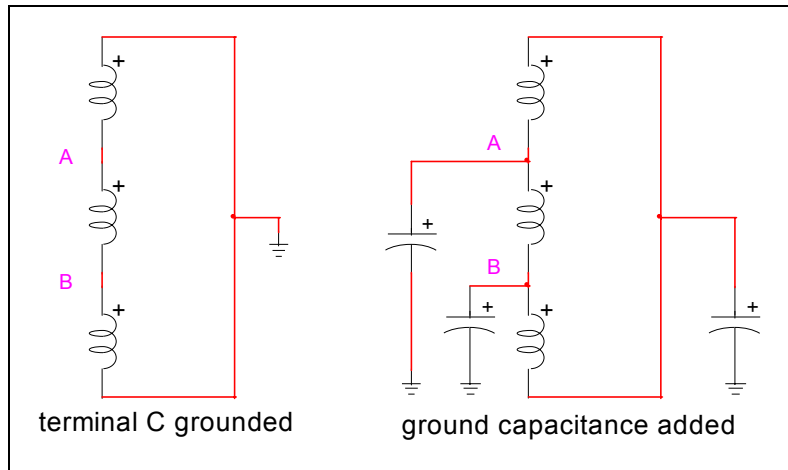
Figure 7–2 Means of avoiding floating delta connections

7.3 High-Frequency effects

The BCTRAN model represents the linear behavior of the transformer with reasonable accuracy from very low frequencies up to 6 kHz to 10 kHz or so. At higher frequencies, capacitances would have to be added to model the asymptotic behavior of the windings.

A more accurate representation can be obtained using the Frequency Dependent Branch (FDB) model. The FDB model, however, requires measurements of the transformer impedances as a function of frequency, and these are generally not available from in standard factory tests.

7.4 Autotransformers

If the user treats an autotransformer the same way as a regular transformer (that is, if one only looks at the outside terminals and ignores the fact that two windings have a common section inside), reasonably accurate results will be obtained with the BCTRAN model. It is possible, however, to develop more accurate models by modifying the short-circuit test data. In the case of Figure 7–3, the short-circuit test data between H-L, H-T, L-T would have to be changed into short-circuit test data between I-II, I-III, II-III. The transformer would then simply be represented as three coupled windings I, II, III with winding I going from node 1 to 2 and winding II going from 2 to 3.
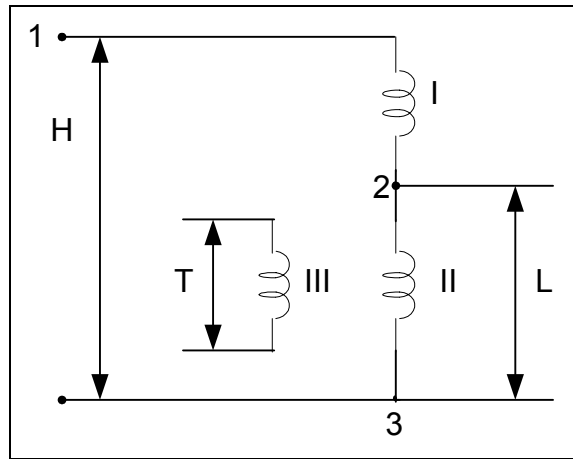
Figure 7–3 Autotransformer