Transformer Parameter Calculation

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1 Introduction

AUX supports three different modules for the calculation of transformer parameters at power frequency:

(A) Section 2: Module TRELEG for the calculation of [R], [L] or [R], $[L]^{-1}$ parameters of single and three-phase transformers;

(B) Section 3: Module BCTRAN for the calculation of [R], $[L]^{-1}$ parameters of single and three-phase transformers.

(C) Section 4: Module TOPMAG for the calculation of [R], [L] or [R], $[L]^{-1}$ parameters of three-phase core-type transformers, taking into account the topology of the magnetic circuit formed by the core and the windings.

All these models are designed to match the standard open and short circuit tests of a transformer at power frequency. They represent transformers as a coupled impedance matrix (represented either as [R], [L] or as [R], $[L]^{-1}$). This class of models is valid as long as the capacitances between windings, from windings to the tank and core, and between layers or windings can be ignored. The range of validity of these models is usually between power frequency and 6 kHz to 10 kHz, depending on the type of transformer. Adding capacitances to the terminals of the model can approximate the asymptotic behaviour of the frequency response of the windings at very high frequencies, but cannot model the dynamics of the transformer in the mid-frequencies range. For a more accurate transformer model with a wide frequency response, the HFT (High Frequency Transformer) model should be used. The HFT model is generated using the support program FDBFIT described in Section 6.

All three models described in this Section reproduce the behaviour of a transformer at power frequency. BCTRAN allows an 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 impedance matrix at dc (which may or may not be stable), whereas BCTRAN becomes an uncoupled resistance matrix at dc which represents winding resistances. In general, BCTRAN is better behaved that TRELEG. Although conceptually different, from a numerical point of view, TOPMAG is an extension of BCTRAN that allows the reproduction of specific zero sequence power frequency tests that BCTRAN cannot reproduce. However, TOPMAG requires additional test data that may not be available for standard factory data sheets.

2 Module "TRELEG"

The effects of a three-leg core in a transformer are apparent in the different values determined for short-circuit impedances in positive and zero sequence. These values are used by the program to calculate a 3N X 3N impedance matrix model, where N = number of windings on any leg ($N \leq 5$). It is also possible to use this program to calculate an N X N matrix to represent a single-leg core, a shell type, or a 5-leg core transformer. In the latter cases, the values of the impedances (short-circuit and magnetizing) will be equal in both zero and positive sequence.

The program accepts data for short-circuit tests performed with up to two of the windings connected in delta. This is the standard form in which a manufacturer will provide test data.

TRELEG requires that winding data be entered so that *delta-connected windings appear last*. Also the windings are assumed to be concentrically-located on the core, and entered (into the data file) in the order from outer to inner winding. When windings are not concentric, or when the delta-connected windings are not innermost on the core, the program provides an option for the user to retain delta-connected windings as the last windings, and to provide the magnetizing impedance of each winding. In the absence of any test data, the positive sequence magnetizing impedance of windings in per unit can be assumed to increase with increasing diameter, while the zero sequence magnetizing impedance decreases. The variation from one winding to another will be approximately equal to the positive sequence short-circuit reactance between them. It does not appear that this approximation of magnetizing impedances has any significant effect on the resulting model.

2.1 Data-Deck Structure for "TRELEG"

The structure of the data deck for a TRELEG transformer model is as follows:

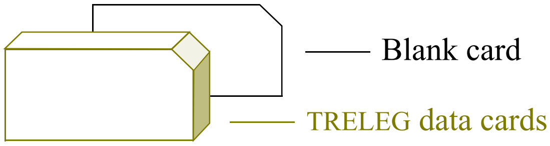
1. First comes a "BEGIN NEW DATA CASE" card.

1 1234567890123456789	2 3 4 5 6 7 8 0123456789012345678901234567890123456789012345678901234567890
BEGIN NEW DATA CASE	
A19	

2. Next comes an "XFORMER" special-request card, with a value of "33." in columns 38–40 .

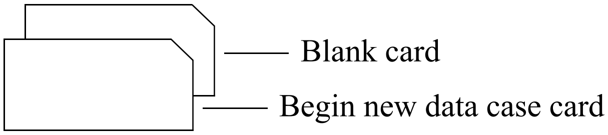
1234567	1 2 3 890123456789012345678901234567	4 890	5 6 7 8 1234567890123456789012345678901234567890
XFORMER		33.	
A7		F3.0	

3. Next come data cards which give the electrical parameters of the transformer.



4. Parameters for more than one transformer can be provided by repeating the data of Point 3 as many times as desired. Each such grouping is a separate data case within "TRELEG", corresponding to a different transformer. A *blank card* terminates these.

5. To indicate the end of all AUX data cases add a "BEGIN NEW DATA CASE" card at this point, followed by a *blank card*.



"TRELEG" Data cards:

Class I Card 1

```
                 1              2              3         4         5         6         7         8
1 23 45 678901234567 890123456789 01 12345678901234567890123456789012345678901234567890
```

	N	ND	f	SBVA	IS	
	I2	I2	E12.0	E12.0	I2	

N (2-3)	number of windings
ND (4-5)	number of delta windings *(≤2)*
F (6-17)	frequency in Hz (60 in North America)
SBVA (18-29)	base MVA (3-phase rating)

IS (30-31)	flag indicating the presence of a 3-leg core transformer = 0 3-leg core transformer = 1 single-phase transformer

Class II: *(present only if NDELTA = 2 for transformers with N=3 windings.*

Card 2 & 3 (exactly 2 cards)

```
           1           2           3           4           5           6           7           8
1 234567890123 456789012345 67890123456789012345678901234567890123456789012345678901234567890
```

	TPKMR	TPKMX	
	E12.0	E12.0	

TPKMR (2-13) TPKMX (14-25)	real and imaginary parts of the positive sequence test between the wye and two delta-connected windings. This data can be left blank, if unknown. In such case, the program will internally simulate the test and generate the requested data.

```
           1           2           3           4           5           6           7           8
1 234567890123 456789012345 67890123456789012345678901234567890123456789012345678901234567890
```

	TZKMR	TZKMX	
	E12.0	E12.0	

TZKMR (2-13) TZKMX (14-25)	real and imaginary parts of the zero sequence test between wye and two delta windings.

Class III

Exactly (N-1) N/2 cards containing the short-circuit test data between different windings. If NDELTA=2, the zero sequence data can be left blank since the program will generate appropriate numbers based upon the data from cards 2 & 3.

			1	2	3 4	5	6 7 8
1	23	45	678901234567	890123456789	012345678901	234567890123	456789012345678901234567890
	I	J	TPR	TPX	TZR	TZX	
	I2	I2	E12.0	E12.0	E12.0	E12.0	

I, (2-3) J (4-5)	numbers of windings between which the test has been conducted
TPR (6-17) TPX (18-29)	real and imaginary parts of the positive sequence test in p.u.
TZR (30-41) TZX (42-53)	real and imaginary parts of the zero sequence test in p.u.

Terminate the Class III data cards with a blank card.

Class IV

One card specifying the flag (KZOUT) to determine whether the output impedance matrix is to be in p.u., ohms, mH, 1/ohms or 1/mH.

		1 2 3 4 5 6 7 8
1	23	45678901234567890123456789012345678901234567890123456789012345678901234567890
	KZOUT	
	I2	

KZOUT (2-3)	= 0	output of [R] and [X] in p.u.
	= 1	output of [R] and [X] in ohms
	= 2	output of [R] in ohms and [L] in mH
	= -1	output of [R] in ohms and $[X]^{-1}$ in mho (S)
	= -2	output of [R] in ohms and $[L]^{-1}$ in 1/mH

Class V

Exactly N cards containing winding number, rated voltage of the winding, indicator of delta windings and the node names to be used by the program in punching the branch impedance cards.

```
                 1            2           3            4            5            6            7               8
1  23 4 5  6 789012345678 901234567890 123456 789012 345678 901234 567890 123456 78901234567890
```

	I		IND		VR	R	NA(I)	NB(I)	NA(I1)	NB(I1)	NA(I2)	NB(I2)	
	I2		I1		E12.0	E12.0	A6	A6	A6	A6	A6	A6	

J (2-3)	winding number *(delta windings should always have the highest numbers!)*
IND (5)	winding connection flag = 0 for wye-connected windings = 1 for delta-connected windings
VR(J) (7-18)	rated voltage of winding J, in kV rms
R(J) (19-30)	dc resistance of winding J, in ohms
NA(I), NB(I)	node names for phase A of winding J
NA(I1), (31-36) NB(I1) (37-42)	node names for phase B of winding J
NA(I2), (55-60) NB(I2) (61-66)	node names for phase C of winding J

Class V data cards have to be terminated with a blank card.

Card VI

```
                 1            2           3            4            5            6            7               8
1  23  4567890123456789012345678901234567890123456789012345678901234567890123456789 0
```

	NT	
	I2	

NT (2-3)	Flag indicating how the magnetizing impedances (XPOZ, XZERO) are specified. = 1 magnetizing impedances are known for each winding, (N data cards follow). ≠ 1 it is assumed that XPOZ and XZERO is known only for the first winding.

Class VII

One or N cards containing values for magnetizing impedances in positive and zero sequence for the first (when NT=1) or all the windings (NT ≠ 1).

```
            1           2          3         4         5         6         7         8
1 234567890123 456789012345 67890123456789012345678901234567890123456789012345678901234567890
```

	XPOZ	XZERO	
	E12.0	E12.0	

XPOZ (2-13), XZERO (14-25)	Positive and zero sequence magnetizing impedance in p.u.

Note that when XPOZ and XZERO are known for each winding they should be entered in order corresponding to the assigned number starting from the lowest numbered (see Class V data cards). For single-phase transformers, set XPOZ = XZERO. Class VII data has to be terminated with a *blank card* in this case. For a more complete discussion of XZERO for a three leg-core transformers see Section 3.3.

2.2 Sample "TRELEG" Data Case

Consider a case of 3-phase, 3-leg, core-type transformer. A listing of this data file follows:

```
BEGIN NEW DATA CASE
C     BENCHMARK DC-36A
C     TEST OF  "TRELEG"  SUPPORTING PROGRAM
C     3-PHASE, THREE-LIMB CORE TRANSFORMER
C     YIELDS  (9 X 9)  MATRICES  [R]  AND  [WL]  AS OUTPUT.
XFORMER                              33.
C 345678901234567890123456789012345678901234567890123456789012
```

```
  3 1    60.         750.0
  1 2  .0017         .13       .0057       .115
  1 3  .0042         .35       .0096       .268
  2 3  .0044         .2        .0143       .136
BLANK CARD ENDING MEASUREMENTS.
  1
C  1
  1 0  288.6751346 .473       HIGHA       HIGHB       HIGHC
  2 0  138.5640646 .029875    LOWA        LOWB        LOWC
  3 1   28.        .01128     TERTA TERTB TERTB TERTC TERTC TERTA
BLANK CARD ENDING WINDINGS.
  1
  100.0        1.
  99.87        1.13
  99.67        1.33
BLANK CARD END MAGNETIZING IMPEDANCES.
BLANK CARD ENDING "TRELEG" DATA CASES.
BEGIN NEW DATA CASE
BLANK
```

An excerpt from the corresponding output file follows:

```
**********   80-COLUMN CARD-IMAGE LISTING OF UNIT-7 PUNCHED CARDS   *********
 --------------------------------------------------------------------------------
          1         2         3         4         5         6         7         8
          0         0         0         0         0         0         0         0
 --------------------------------------------------------------------------------
 51,HIGHA ,      ,,,              0.473000000000E+00,  0.223333333341E+05 ,,,,,
 52,LOWA  ,      ,,,             -0.646793103332E-01,  0.107059927425E+05 $
                                  0.298750000000E-01,  0.514227199959E+04 ,,,,,
 53,TERTA ,TERTB ,,,             -0.362556943699E-01,  0.215874652794E+04 $
                                 -0.357184214476E-01,  0.103714560936E+04 $
                                  0.112800000000E-01,  0.209767040000E+03 ,,,,,
 54,HIGHB ,      ,,,              0.000000000000E+00, -0.110000000004E+05 $

       .
       .
       .
 59,TERTC ,TERTA ,,,             -0.494356580077E-01, -0.106342221589E+04 $
                                 -0.325054568924E-01, -0.509650587464E+03 $
                                  0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                 -0.494356580077E-01, -0.106342221589E+04 $
                                 -0.325054568924E-01, -0.509650587464E+03 $
                                  0.000000000000E+00, -0.102798080000E+03 ,,,,,
                                 -0.362556943699E-01,  0.215874652794E+04 $
                                 -0.357184214476E-01,  0.103714560936E+04 $
                                  0.112800000000E-01,  0.209767040000E+03 ,,,,,
 --------------------------------------------------------------------------------
```

2.3 Interpretation of TRELEG's Output

The impedance matrix produced by the program is symmetrical and is represented by its lower triangular part only. As an example, the impedance matrix for a three-winding, three-phase transformer would have the following general form:

```
Z11
Z12  Z22                                         leg I
Z13  Z23  Z33


M11  M12  M13   Z11
M12  M22  M23   Z12  Z22                         leg II
M13  M23  M33   Z13  Z23  Z33


M11  M12  M13   M11  M12  M13   Z11
M12  M22  M23   M12  M22  M23   Z12  Z22         leg III
M13  M23  M33   M13  M23  M33   Z13  Z23  Z33


     leg I        leg II          leg III
```

Zik = coupling between windings on one leg (including self impedance Zii).

Mik = coupling between windings on different legs.

3 Module "BCTRAN"

BCTRAN accurately reproduces the behaviour 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 an 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 that TRELEG.

3.1 Linear Magnetizing Impedance and Excitation Test 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 $[L]^{-1}$-matrix generated by BCTRAN is singular and cannot be inverted to a [Z]-matrix. However, since the EMTP is based on a nodal admittance matrix formulation, the fact that [Z] is not invertible 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 (see reference [2]), which is added to the [R], $[L]^{-1}$-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 test. These two values are converted to a 3x3 submatrix with diagonal elements Y_s and off-diagonal elements Y_m,

$$Y_s = (Y_o + 2Y_1)/3 \tag{1}$$

$$Y_m = (Y_o - Y_1)/3 \tag{2}$$

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

If shunt admittances are connected across all windings, as shown in Figure 1, 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 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 p.u. (or $Z_m = 100$ p.u.) and a short-circuit input impedance of 0.10 p.u., these differences are approximately 0.1%. Note that the imaginary parts of (Y_s, Y_m) become part of the $[L]^{-1}$-matrix, as indicated by the large, dotted box in Figure 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".

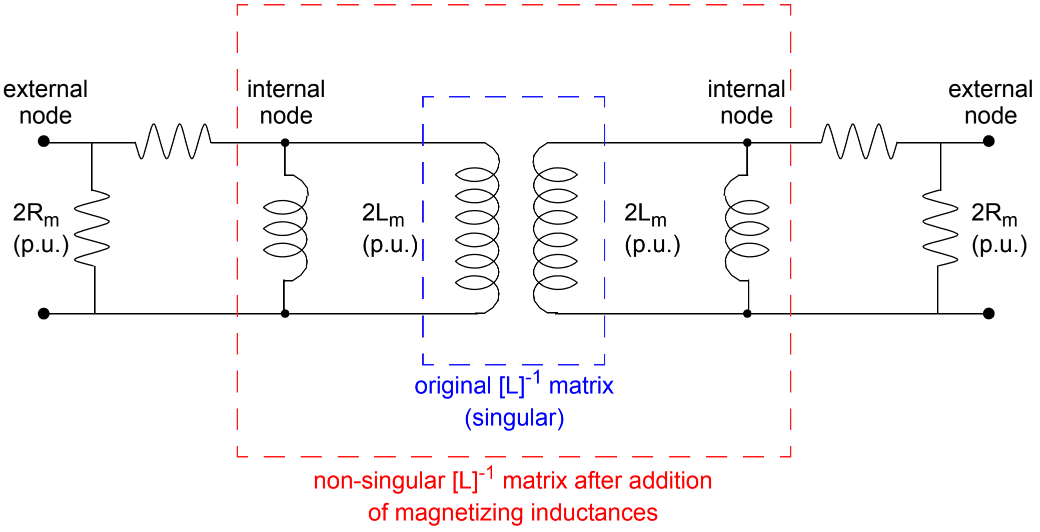


Figure 1: Addition of Magnetizing Branches Across all Windings (shown for single-phase transformer with N=2)

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". As explained in reference [2], it may be best to connect the shunt admittance across the winding closest to the core on transformers with cylindrical windings.

3.2 Description of the Data Deck

The structure of the data deck for a BCTRAN transformer model is as follows:

1. First comes a "BEGIN NEW DATA CASE" card.

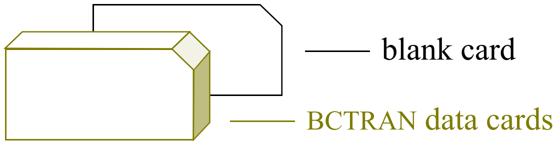
1 1234567890123456789	2 3 4 5 6 7 8 01234567890123456789012345678901234567890123456789012345678901234567890
BEGIN NEW DATA CASE	
A19	

2. Next comes an "XFORMER" special-request card, with a value of "44." in columns 38–40 .

 1234567	1 2 3 890123456789012345678901234567	4 890	5 6 7 8 1234567890123456789012345678901234567890
XFORMER		44.	
A7		F3.0	

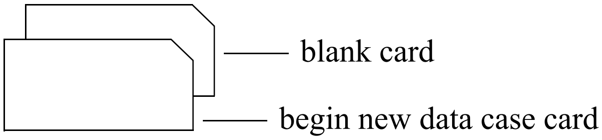
3. Next come data cards which give electrical parameters of the transformer. These data cards consist of:

   - One card for excitation data
   - Exactly N cards for winding data, one for each transformer winding.
   - Exactly (N(N-1))/2 cards for short-circuit test data, one for each short-circuit test between a pair of windings. Terminate the short-circuit test data with a *blank card*.



4. Parameters for more than one transformer can be provided by repeating the data of Point 3 as many times as desired. Each such grouping is a separate data case within "BCTRAN", corresponding to a different transformer. A *blank card* terminates these.

5. To indicate the end of all AUX data cases add a "BEGIN NEW DATA CASE" card at this point, followed by a *blank card*.



Note that there will be two blank cards at the end of the last transformer data deck: one to terminate the short-circuit test data and one to terminate "XFORMER" data cases.

Excitation Data

One card with the format shown below.

12	1 3456789012	2 3456789012	3 3456789012	4 3456789012	5 3456789012	6 3456789012	7 3456789012	34	56	78	8 90
N	f (Hz)	I_{excit}^{pos} (percent)	S_{rating}^{pos} (MVA)	$LOSS_{excit}^{pos}$ (kW)	I_{excit}^{zero} (percent)	S_{rating}^{zero} (MVA)	$LOSS_{excit}^{zero}$ (kW)	NPHASE	ITEST	IPUT	IPRINT
I2	E10.2	E10.2	E10.2	E10.2	E10.2	E10.2	E10.2	I2	I2	I2	I2

N (1–2)	Number of windings per core leg (link). *Present limit: N≤10*. Example: A 230/500 kV three-phase transformer without a tertiary winding has N=2; if a tertiary winding is added, then N=3.
f (3-12)	Rated frequency in Hz (needed to convert reactances into inductances).

I_{excit}^{pos} (13–22)	Exciting current in percent, based on three-phase power rating S_{rating}^{pos} and rated voltages, in the positive sequence excitation test.
S_{rating}^{pos} (23-32)	Three-phase power rating in MVA, on which exciting current I_{excit}^{pos} of the positive sequence test is based.
$LOSS_{excit}^{pos}$ (33–42)	Excitation loss in kW in the positive sequence excitation test. See Section 3.3 for possible modifications of this value by the program.
I_{excit}^{zero} (43–52)	Exciting current in percent, based on three-phase power rating S_{rating}^{pos} and rated voltages, in the zero sequence excitation test.
S_{rating}^{zero} (53–62)	Exciting current in percent, based on three-phase power rating S_{rating}^{pos} and rated voltages, in the zero sequence excitation test
$LOSS_{excit}^{zero}$ (63–72)	Excitation loss in kW in the zero sequence excitation test. See Section 3.3 for possible modifications of this value by the program

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 2) in the zero sequence excitation test

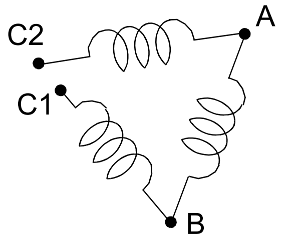


Figure 2: Open Delta Connection

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.

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.

NPHASE (73–74)	= 1	For three-phase transformer banks consisting of single-phase transformers.
	= 0 or blank	For three-phase transformers.

ITEST (75–76) Number of the winding from which the excitation tests were made.

IPUT (77–78) Number of the winding across which the magnetizing branch is to be placed. If ITEST and IPUT are both zero or blank, then the program connects magnetizing branches across all windings. If ITEST is specified (>0), then IPUT must also be specified (>0). IPUT = ITEST is permitted. For more details see Section 3.3.

IPRINT (79–80)	= 0 or blank	Matrices [R] and $[L]^{-1}$ will be printed and saved on file.
	> 0	Matrices [R] and [ωL] will be printed and saved on file.
	< 0	Matrices [R] and $[\omega L]^{-1}$ as well as matrices [R] and [ωL] will be printed and saved on file.

Winding Data

Exactly N cards, one for each transformer winding. The N cards can be read in arbitrary order. The format is shown below.

	1	2		3		4		5	6	7 8
123	4567890123	4567890123	4	567890	123456	789012	345678	901234	567890	12345678901234567890
k	$V_{rating-k}$ (kV)	R_k (Ω)		NAME 1	NAME 2	NAME 3	NAME 4	NAME 5	NAME 6	
				winding k phase 1		winding k phase 2		winding k phase 3		
I3	E10.2	E10.2		A6	A6	A6	A6	A6	A6	

k (1–3)	Winding number. Number windings consecutively 1, 2, 3, ..., N (where $N \leq 10$). A wye-wye-connected 230/500 kV three-phase transformer with a delta connected tertiary of 30 kV would have 3 windings (i.e., 1 = high voltage 500 kV, 2 = low voltage 230 kV, 3 = tertiary voltage 30 kV).

$V_{rating-k}$ (4–13)	Rated voltage in kV; line-to-ground for wye-connected windings, and line-to-line for delta connected windings. In the example above: V_1=500/ $\sqrt{3}$ kV, V_2 = 230/ $\sqrt{3}$ kV, V_3= 30 kV.
R_k (14–23)	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. 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 R_1 p.u. = R_2 p.u. for two winding transformers. For three-winding transformers, there are three equations in three unknowns R_1 p.u., R_2 p.u., R_3 p.u. 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.
NAME 1 . . . NAME 6	Columns 25–30; 31–36; 37–42; 43–48; 49–54; 55–60. Node names. The terminals of the winding in each one of three phases have to be assigned node names to produce output data in the form of branch cards which can be used directly as input by the EMTP. Exactly six node names are required per winding (one pair for each one of the three phases). If a terminal is connected to ground (e.g., the neutral in wye connection), then use a blank field as the name for 'ground'.

Short-Circuit Test Data

Exactly N(N-1)/2 cards, one card for each short-circuit test between a pair of windings, *terminated by a blank card*. The cards can be read in arbitrary order. The card format is shown below.

		1	2	3	4	5			6 7 8
12	34	5678901234	5678901234	5678901234	5678901234	5678901234	56	78	9012345678901234567890
i	k	P_{ik} (kW)	Z^{pos}_{ik} (%)	S^{pos}_{rating} (MVA)	Z^{zero}_{ik} (%)	S^{zero}_{rating} (MVA)	IDELTA	ILOSS	
I2	I2	E10.2	E10.2	E10.2	E10.2	E10.2	I2	I2	

i
(1–2)
k
(3–4)
Numbers of the pair of windings between which the short-circuit test is made.

P_{ik}
(5–14)
Load losses in kW in the positive sequence test. If $P_{ik}>0$, then this value is used in Equation 3 below to find the positive sequence reactance:

$$X_{ik}\text{ p.u.} = (Z_{ik}\text{ p.u.})^2 - (R_i\text{ p.u.} + R_k\text{ p.u.}) \qquad (3)$$

with
Z_{ik} p.u. = p.u. short-circuit impedance in test between i and k,

and
R_i p.u. + R_k p.u. = p.u. load losses on the same MVA basis as Z_{ik} p.u. if load losses are nonzero; if load losses are not given, these are the specified p.u. winding resistances on the same MVA basis.

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

Equation 3 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 3, the three test values supplied by the user are:

$$X_{12}^{\text{closed }\Delta} = X_1 + \frac{X_2 X_3}{X_2 + X_3} \qquad (4)$$

$$X_{13} = X_1 + X_3 \qquad (5)$$

$$X_{23} = X_2 + X_3 \tag{6}$$

which can be solved for X_1, X_2, X_3:

$$X_1 = X_{13} - \sqrt{X_{23}X_{13} - X_{23}X_{12}^{\text{closed}\,\Delta}} \tag{7}$$

$$X_2 = X_{23} - X_{13} + X_1 \tag{8}$$

$$X_3 = X_{13} - X_1 \tag{9}$$

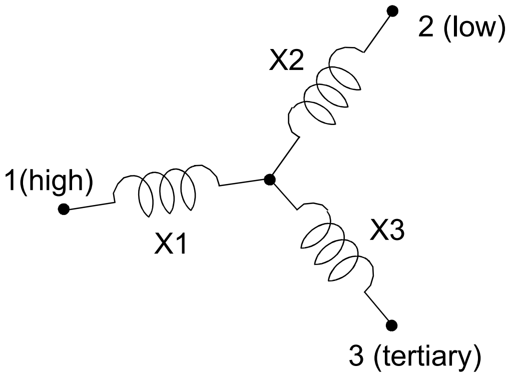


Figure 3: Equivalent star circuit for zero sequence short-circuit tests of a three-winding transformer (all reactances must be in p.u.)

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 4, which becomes:

$$\left|Z_{12}^{\text{closed}\,\Delta}\right| = \left|R_1 + jX_1 + \frac{(R_2 + jX_2)(R_3 + jx_3)}{(R_2 + R_3) + j(X_2 + X_3)}\right| \tag{10}$$

with $\left|Z_{12}^{\text{closed}\,\Delta}\right|$ 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 Card

Z_{ik}^{pos} (15–24)

Short-circuit input impedance in percent in the positive sequence test between windings 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_{rating}^{pos} (25–34)

Three-phase power rating in MVA, on which Z_{ik}^{pos} is based.

Z_{ik}^{zero} (35–44)
S_{rating}^{zero} (45–54)

Same as preceding two parameters, respectively, except for zero sequence test. If IDELTA = 0, then P_{ik} from the positive sequence test is also used to calculate the zero sequence reactance with Equation 3. If S_{rating}^{zero} = 0 or blank, it is assumed to be equal to S_{rating}^{pos}.

If IDELTA>0, then the winding resistances are used to obtain reactances from impedances. In Ydd connections, the zero sequence test cannot be performed between the closed delta connected windings. Set Z_{ik}^{zero} = 0 or blank in such a case.

The program will then automatically calculate a reasonable value from

$$X_{d-d}^{zero} = X_{d-d}^{pos}\left|\frac{Z_{y-2d}^{zero}}{Z_{y-2d}^{pos}}\right| \tag{11}$$

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

IDELTA (55–56)

= 0 or blank	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 if IDELTA=0.
> 0	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 connection, "d" would be the additional shorted winding in the zero sequence test between "Y" and "y". In the Ydd-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 the message

```
"Input value of zero sequence short-circuit impedance from 'i'
to 'idelta' is ignored and set equal to value from 'i' To 'k'
because both impedances must be equal if there are closed
deltas in 'k' and 'idelta'".
```

The program *cannot* handle Ddd-connections with IDELTA>0.

For three-phase transformer banks consisting of single-phase transformers, input the single-phase data as positive sequence parameters and leave the fields for the zero sequence input parameters blank, including IDELTA.

ILOSS (57–58) Specify ILOSS on the first short-circuit test data card.

= 0 or blank	Read-in winding resistances will be used.
> 0	Winding resistances will be calculated from load losses P_{ik}, provided $N \leq 3$ and $P_{ik} \geq 0$ for all short-circuit tests. Read-in winding resistances are then ignored.

3.3 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.

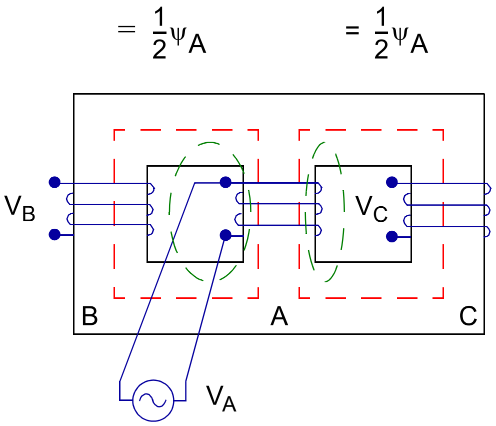


Figure 4: Three-Limb Core-Type Design

Often, the zero sequence exciting current is not given by the manufacturer. In such cases, a reasonable value can be found as follows: Excite one phase of a winding (A in Figure 4), and estimate how much voltage will be induced in the other two phases (B and C). For the three-limb core design of Figure 4, 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

$$\frac{I_{excit}^{zero}}{I_{excit}^{pos}} = \frac{1+k}{1-2k} \qquad (12)$$

Equation 12 is derived from:

$$\begin{aligned} V_A &= Z_s I_A \\ V_B &= Z_m I_A \\ V_C &= Z_m I_A \end{aligned} \qquad (13)$$

with Z_s = self impedance of phase A in excitation test, and Z_m = mutual impedance to phases B and C. Then

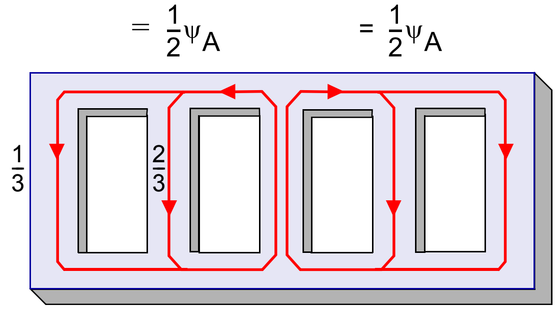
$$V_B = V_C = \left(\frac{Z_m}{Z_s}\right) V_A = -\left(\frac{Z_{pos} - Z_{zero}}{2Z_{pos} + Z_{zero}}\right) V_A = -k \cdot V_A \qquad (14)$$

Since the exciting current is proportional to $1/Z_{pos}$ in positive sequence, and to $1/Z_{zero}$ in zero sequence, the relationship for k in Equation 14 can be transformed into Equation 12.

Obviously, k cannot be exactly 0.5, because this would lead to an infinite zero sequence exciting current. A reasonable value for I^{zero}_{excit} of a three-limb core-type design might be 100%. If I^{pos}_{excit} = 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 5) and shell-type designs (Figure 6). In the five-limb core-type design, maybe two thirds of approximately (1/2) ψ_A returns through legs B and C. In that case, k would be one third, or

$$\frac{I^{zero}_{excit}}{I^{pos}_{excit}} = 4$$



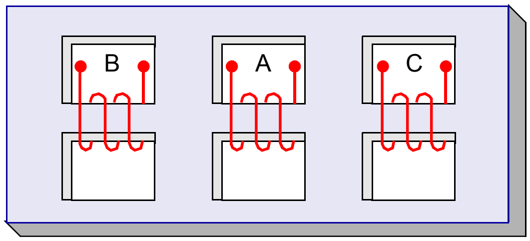


Figure 5: Five-Limb Core-Type Design

Figure 6: Shell-Type Design

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.

3.4 Error Messages

The following messages indicate fatal errors in the input data. In each case program execution will be terminated and no more input cards will be read from the data deck of this case or of any following cases.

1. "`NUMBER OF WINDINGS = 'n'`"

   Number of windings is either 1 or greater than 10.

2. "`EITHER ITEST = 'i' OR IPUT = 'k' NOT PERMITTED`"

   A winding has been specified from which the excitation test has been made but no winding has been specified across which the magnetizing branch should be connected, or vice versa.

3. "`'i'k' WRONG WINDING NUMBERS`"

   Message refers to pairs of windings between which the short-circuit test was made, in the following cases:

   (A) Both windings have the same number.

   (B) Either one or both of the winding numbers are larger than N, the specified number of transformer windings.

   (C) Data for this pair of windings has already been read in a preceding card.

4. "`LOAD LOSSES OR WINDING RESISTANCES TOO LARGE 'i'k`"

   If argument of square root in Equation 3, Section 2.2 is negative.

5. "`ONLY 'n' SHORT-CIRCUIT TESTS SPECIFIED, BUT 'm' ARE NEEDED`"

   Not enough short-circuit test data have been read in.

6. "`IDELTA='idelta' WRONG IN SHORT-CIRCUIT TEST BETWEEN 'i' AND 'k'`"

   (A) IDELTA is either i or k (see Section 3.2, Short-circuit Tests Data Card).

   (B) IDELTA > N, with N being the specified number of transformer windings.

7. "`MODIFICATION OF ZERO SEQUENCE SHORT-CIRCUIT TEST BETWEEN 'i' AND 'k' NOT POSSIBLE. ERROR CODE = 'm'`"

   This particular case cannot be handled by the present version of the program.

8. "`DIAGONAL ELEMENT IN ROW 'i' CLOSE TO ZERO`"

   Can happen during internal calculations to convert input data into $[L^{-1}]$ form (i.e., in the inversion process with Equation 11 of reference [2] -very unlikely-, or with the inversion of Equation 20b of reference [2] - possible if exciting current is very small).

9. "`P.U. EXCITATION LOSS LARGER THAN P.U. EXCITING CURRENT (EITHER IN POS. OR ZERO SEQUENCE)`"

3.5 Description of the Output

Section 3.6 shows a sample output. The results consist of two parts:

Shunt Resistances for Representation of Excitation Losses

Depending upon parameters IPUT and ITEST on the excitation data card (Section 3.2), the program will provide one of the following results with short explanations:

```
"SHUNT RESISTANCES FOR REPRESENTATION OF EXCITATION LOSSES:"

          (A)   "PLACE SHUNT RESISTANCE MATRIX ACROSS WINDING 'IPUT' WITH
                R(SELF/OHM)= '_____' AND R (MUTUAL/OHM) = '_____'"

          (B)   "PLACE SHUNT RESISTANCE MATRIX ACROSS ALL TERMINALS WITH THE
                FOLLOWING VALUES:"

                "WINDING NO.     R(SELF/OHM)      R(MUTUAL/OHM)"

                  '_____'          '_____'            '_____'

                     .                .                  .

                     .                .                  .

          (C)   "LEAVE OFF, BECAUSE SERIES RESISTANCES ALREADY PRODUCE LOSSES
                WHICH ARE GREATER THAN INPUT VALUES OF EXCITATION LOSSES."
```

Resistance and Reactance (or Inverse Inductances) Matrix

These matrices are printed, as well as written on file for direct input into the EMTP (see parameter IPRINT,in the Excitation Data card of Section 3.2). As an example, the impedance matrix for a three-winding, three-phase transformer would have the following general form (only lower triangular part of the symmetric matrix provided):

$$\begin{array}{ccc|ccc|ccc|c}
Z_{11} & & & & & & & & & \\
Z_{12} & Z_{22} & & & & & & & & \text{Leg I} \\
Z_{13} & Z_{23} & Z_{33} & & & & & & & \\
\hline
M_{11} & M_{12} & M_{13} & Z_{11} & & & & & & \\
M_{12} & M_{22} & M_{23} & Z_{12} & Z_{22} & & & & & \text{Leg II} \\
M_{13} & M_{12} & M_{33} & Z_{13} & Z_{23} & Z_{33} & & & & \\
\hline
M_{11} & M_{12} & M_{13} & M_{11} & M_{12} & M_{13} & Z_{11} & & & \\
M_{12} & M_{22} & M_{23} & M_{12} & M_{22} & M_{23} & Z_{12} & Z_{22} & & \text{Leg III} \\
M_{13} & M_{12} & M_{33} & M_{13} & M_{12} & M_{33} & Z_{13} & Z_{23} & Z_{33} & \\
\hline
 & \text{Leg I} & & & \text{Leg II} & & & \text{Leg III} & &
\end{array}$$

Zik = coupling between windings on one leg (including self impedance Zii).

Mik = coupling between windings on different legs.

3.6 Test Example

To illustrate the AUX-request for "BCTRAN", a partial listing of benchmark DCNEW-8 is shown below:

```
BEGIN NEW DATA CASE
C     BENCHMARK DCNEW-8A
C     TEST OF "BCTRAN" 3-PHASE TRANSFORMER ROUTINE OF EMTP.   THIS
C     PARTICULAR TEST CASE IS FROM HERMANN'S ORIGINAL UBC WRITEUP.
C  45678901234567890123456789012345678901234567890123456789012345678901234567890
XFORMER                              44.
 360.       .428      300.      135.73    .428      300.      135.73       1 3 0
  1132.79056 .2054666   H-1         H-2         H-3
  263.393059 .0742333   L-1         L-2         L-3
  350.       .0822      T-1   T-2   T-2               T-1
 1 20.        8.74      300.      7.3431941 300.       3 1
 1 30.        8.68      76.       26.258183 300.
 2 30.        5.31      76.       18.552824 300.
BLANK CARD TO TERMINATE THE SHORT-CIRCUIT TEST DATA
BLANK CARD TO TERMINATE "XFORMER" DATA CASES
BEGIN NEW DATA CASE
BLANK
```

The corresponding punch file of the AUX simulation contains the EMTP branch cards of a coupled RL branch with the high-precision format. Note that the "USE RB" option is enabled since BCTRAN generates a [R] and [L^{-1}] matrices. A partial listing for the above example is shown here:

```
$VINTAGE, 1
  USE RB
 1H-1                       0.2054666000E+000.2651269237E-01
 2L-1                       0.0000000000E+00-.5957848438E-01
                            0.7423330000E-010.1808547434E+00
 3T-1   T-2                 0.0000000000E+000.5124542161E-02
                            0.0000000000E+00-.7106950227E-01
                            0.8220000000E-010.7656071131E-01
 4H-2                       0.0000000000E+000.1317410104E-02
                            0.0000000000E+00-.1044760157E-02
                            0.0000000000E+00-.2174181664E-02
                            0.2054666000E+000.2651269237E-01
.
.
.
 9      T-1                 0.0000000000E+00-.2174181664E-02
                            0.0000000000E+000.2647586814E-02
                            0.0000000000E+000.2417436248E-02
                            0.0000000000E+00-.2174181664E-02
                            0.0000000000E+000.2647586814E-02
                            0.0000000000E+000.2417436248E-02
                            0.0000000000E+000.5124542161E-02
                            0.0000000000E+00-.7106950227E-01
                            0.8220000000E-010.7656071131E-01
```

4 Subroutine "TOPMAG"

4.1 Introduction

Conceptually, this model takes into account the topology of the magnetic circuit formed by the core and the windings to assemble an equivalent electric circuit representation for the transformer (Figure 7 below). For three-limbed and five-limbed units, each core-limb is modelled individually, and interfaced to an admittance matrix reproducing the correct magnetic coupling among windings. An additional 3-phase winding (termed *fictitious winding*) is needed to establish this interface, since core limbs are electrically isolated from the windings. Node names for fictitious windings are assigned by the user, and ought to be unique for each transformer.

(A) The output from the model consists of the following card images for direct insertion in an EMTP runstream: (1) a symmetric admittance matrix of order up to 3(N+1), depending on the core type and the specified modelling options, and

(B) a network of parallel RL branches modelling magnetizing currents due to the wound limbs (Z_b), the horizontal yokes (Z_k), and the zero-sequence return path through air for 3-limbed transformers, or through the outer limbs in 5-limbed transformers (Z_o).

The program requires that N(N-1)/2 positive-sequence short circuit test values be specified for an N-winding 5-limbed or single-phase transformers. For 3-limbed transformers, at least one additional parameter is needed to characterize the zero-sequence performance, as follows:

(A) (i) zero-sequence excitation current, or

(B) (ii) one zero-sequence short-circuit test impedance, performed with excitation on winding 1 and short-circuit on any other winding "m", provided that no other winding is connected in delta during the test.

For more accuracy, a full complement of N(N-1)/2 zero-sequence short-circuit test values may be specified, if they are available, provided that no more than one of the windings is connected in delta during tests.

Windings should be numbered from 1 to N, such that the winding positioned outermost on the wound limb is "1". This is normally the winding carrying the highest voltage rating. Winding "N" ought to be innermost on the core, and is normally the one with the lowest voltage rating. Windings are assumed to be concentric, fully covering the wound limb, (which may not always be the case in practice). For example a tapped HV winding may comprise two separate winding sections, one outermost on the core and a second (tapped) section innermost on the core. For higher accuracy, and perhaps for some studies, each such winding section ought to be modelled as a separate winding (requiring additional short-circuit test data, which is not normally available). However this is unlikely to be needed for most studies.

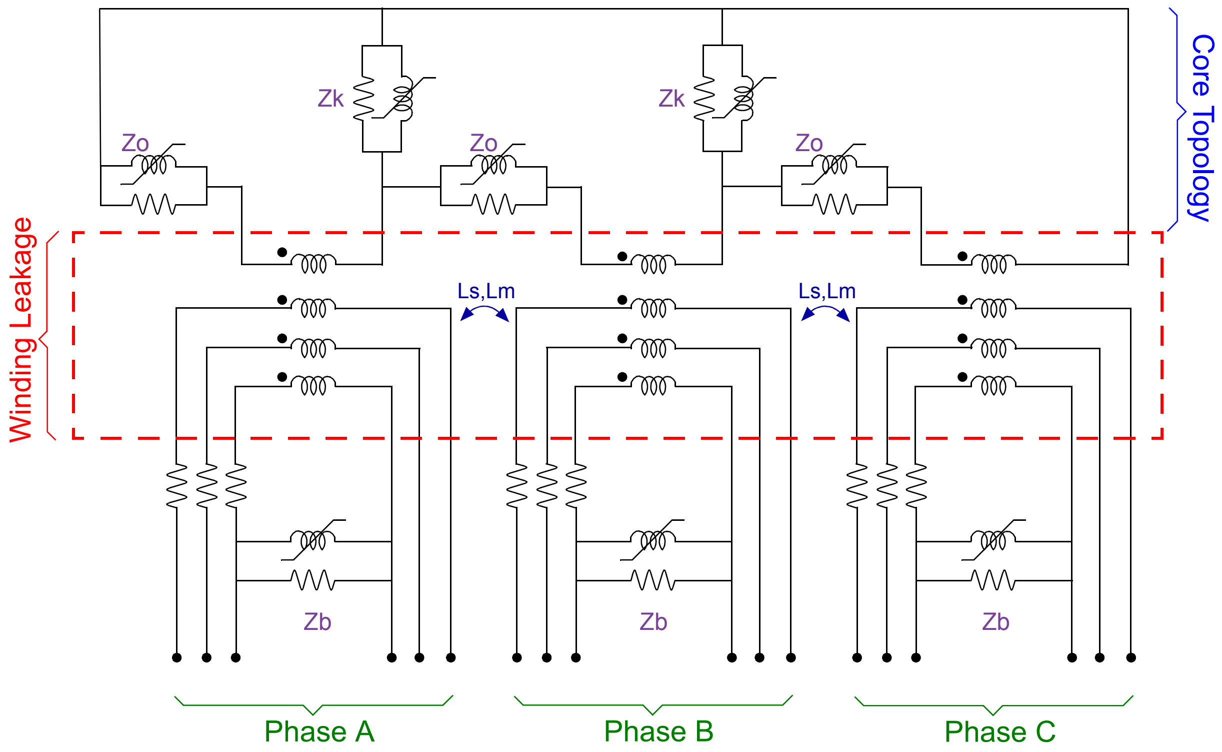


Figure 7: Schematic representation of model for 3-phase, 3-winding core type transformer

4.2 Description of the Data Deck

The structure of the data deck for a TOPMAG transformer model is as follows:

1. First comes a "BEGIN NEW DATA CASE" card .

1 1234567890123456789	2 3 4 5 6 7 8 0123456789012345678901234567890123456789012345678901234567890
BEGIN NEW DATA CASE	
A19	

2. Next comes an "XFORMER" special-request card, with a value of "55." in

3. Columns 38–40 .

```
        1         2         3         4         5         6         7         8
1234567 890123456789012345678901234567 890 12345678901234567890123456789012345678901234567890
```

XFORMER		55.	
A7		F3.0	

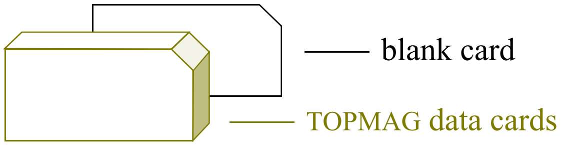
Next come the transformer data specification cards (similar to the input requirements for BCTRAN, with slight variations as described next.

Class 1: One card for excitation data.

Class 2: Exactly N cards for winding data, one for each transformer winding.

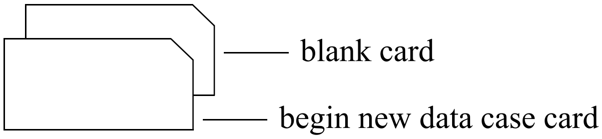
Class 3: One card for the fictitious winding which provides the interface to the circuit modelling core magnetics. Relative limb dimensions may be specified optionally.

Class 4: Exactly N(N-1)/2 cards for short-circuit test data, one for each short-circuit test between a pair of windings. Terminate the short-circuit data with a *blank card*.



4. Parameters for more than one transformer can be provided by repeating the data of Point 3 as many times as desired. Each such grouping is a separate data case within "TOPMAG", corresponding to a different transformer. A *blank card* terminates these.

5. To indicate the end of all AUX data cases add a "BEGIN NEW DATA CASE" card at this point, followed by a *blank card*.



Note that there will be two blank cards at the end of the last transformer data deck: one to terminate the short-circuit test data and one to terminate "XFORMER" data cases.

4.3 Class 1: Excitation Data

One card with the format shown below.

12	1 3456789012	2 3456789012	3 3456789012	4 3456789012	5 3456789012	6 3456789012	7 3456789012	34	56	78	8 90
N	f (Hz)	I^{pos}_{excit} (percent)	S^{pos}_{rating} (MVA)	$LOSS^{pos}_{excit}$ (kW)	I^{zero}_{excit} (percent)	S^{zero}_{rating} (MVA)	$LOSS^{zero}_{excit}$ (kW)	NTYPE	ITEST	ISOLKG	IPRINT
I2	E10.2	E10.2	E10.2	E10.2	E10.2	E10.2	E10.2	I2	I2	I2	I2

N (12)	Number of windings per core leg. Present limit: $N \leq 10$. Example: A 230/500 kV three-phase transformer without a tertiary winding has N=2; if a tertiary winding is added, then N=3.
f (3-12)	Rated frequency in Hz (needed to convert reactances into inductances).
I^{pos}_{excit} (13–22)	Exciting current in percent, based on three-phase power rating S^{pos}_{rating} and rated voltages, in the positive sequence excitation test.
S^{pos}_{rating} (23-32)	Three-phase power rating in MVA, on which exciting current I^{pos}_{excit} of the positive sequence test is based.
$LOSS^{pos}_{excit}$ (33–42)	Excitation loss in kW in the positive sequence excitation test. This value may be changed by the program based on specification for "ILOSS" under short-circuit test data.
I^{zero}_{excit} (43–52) S^{zero}_{rating} (53–62) $LOSS^{zero}_{excit}$ (63–72)	Same as preceding three parameters, respectively, except for zero-sequence excitation test. If the transformer has delta-connected windings, then the 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 in the zero sequence excitation test. For 3-phase transformer banks consisting of single-phase or 5-limbed units, input the data as positive-sequence parameters and leave the fields for the zero-sequence parameters blank.

For 3-limb units, I_{excit}^{zero} will be estimated by default if this entry is left blank. This is the *recommended* option, provided that at least one zero-sequence short-circuit test is specified with excitation on winding 1, and without any other winding connected in delta during the test (See Class 4 data). If a value for I_{excit}^{zero} is specified, it is used directly (also see ISOLKG under Class 1 cards).

NTYPE (73-74)	=1	For three-phase transformer banks consisting of single-phase units.
	= 5	For three-phase 5-limbed core.
	≠1 or 5	For three-phase 3-limbed core. If NTYPE is -ve, the debug facility will be activated and the magnitude of NTYPE will have the same meaning as indicated above.
ITEST (75-76)	Number of the winding from which the zero-sequence excitation test was made. (DEFAULT = 1)	
ISOLKG (77-78)	≥ 0	This is the recommended option for modelling 3-limbed transformers, provided a full complement of reliable N(N-1)/2 zero-sequence short-circuit impedances is available. The resulting coupling matrix is of order 3(N+1), matching the specified positive- and zero-sequence impedances. For single-phase or 5-limbed units, ISOLKG is irrelevant.
	< 0	In this event, even if zero-sequence short-circuit impedances are specified for 3-limbed units, they are ignored except for estimating I_{excit}^{zero} if it has not already been specified. This option is recommended if a full complement of zero-sequence test data is not available. Zero-sequence short-circuit impedances are therefore established by default on a physical basis.
IPRINT (79-80)	= 0 or blank	Matrices [R] and $[L]^{-1}$ will be printed and saved on file.
	≠ 0	Matrices [R] and $[\omega L]^{-1}$ will be printed and saved on file.

4.4 Class 2: Winding Data

Exactly N cards, one for each transformer winding. The cards can be read in arbitrary order, however the outermost winding on the core (usually the one with the highest voltage rating) should be designated as winding #1, and any winding remaining closed during short-circuit tests (if one exists) must be winding number "N". The card format is shown below.

	1	2		3		4		5	6	7 8
123	4567890123	4567890123	4	567890	123456	789012	345678	901234	567890	12345678901234567890
k	$V_{rating-k}$ (kV)	R_k (Ω)		NAME 1	NAME 2	NAME 3	NAME 4	NAME 5	NAME 6	
				winding k phase 1		winding k phase 2		winding k phase 3		
I 3	E10.2	E10.2		A6	A6	A6	A6	A6	A6	

k (1-3)	Winding number. Number windings consecutively 1, 2, 3..., N (N≤10). A wye-wye connected 230/500 kV three-phase transformer with a delta connected tertiary of 30 kV would have 3 windings (e.g., 1 = high voltage 500 kV, 2 = low voltage 230 kV, 3 = tertiary voltage 30kV).
$V_{rating-k}$ (4-13)	Rated voltage in kV; line-to-ground for wye-connected winding, line-to-line for delta connected winding. In the above example: $V_1 = 500/\sqrt{3}$ kV, $V_2 = 230/\sqrt{3}$ kV, $V_3 = 30$ kV.
R_k (14-23)	Winding resistance of one phase (in ohms). If the values differ among 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. 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 R_1 p.u. = R_2 p.u. for two winding transformers. For three-winding transformers, there are three equations in three unknowns R_1 p.u., R_2 p.u., R_3 p.u. 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.
NAME 1 . . . NAME 6	Columns 25-30; 31-36; 37-42; 43-48; 49-54; 55-60. Node names. The terminals of the winding in each one of three phases have to be assigned node names to produce output data in the form of branch cards which can be used directly as input by the EMTP. Exactly six node names are required per winding (one pair for each one of the three phases). If a terminal is connected to ground (e.g. the neutral in wye connection), then use a blank field as the name for 'ground'.

4.5 Class 3: Data for Duality Winding (and Optionally, Limb Dimensions)

Exactly one card, specifying the fictitious winding which implements the duality based magnetic model for the core. The card format is shown below.

The program produces a complete linear topological model for 3-limbed and 5-limbed core-type transformers. This includes generation of the coupling matrix, and linear magnetizing branches (including shunt conductance branches) for the wound limbs, the yokes and the zero-sequence magnetic path.

	1	2	3		4		5		6		7	8
123	4567890123	45678901234	567890	123456	789012	345678	901234	567890	12345	67890	12345	67890
	CUPCO		NAME 1	NAME 2	NAME 3	NAME 4	NAME 5	NAME 6	LENGTH		AREA	
			winding k phase 1		winding k phase 2		winding k phase 3		YkLm	OtLm	YkLm	OtLm
	E10.2		A6	A6	A6	A6	A6	A6	E5.0	E5.0	E5.0	E5.0

CUPCO (4-13)	This is normally left blank since a value is assigned by default. An option is provided here to override the default value in case numerical ill-conditioning problems are encountered with the model. This may be signalled by an error message during time domain solution warning about floating subnetworks. CUPCO defines the coupling between winding 1 and the fictitious winding. Its value essentially represents the reciprocal of the p.u. leakage impedance between windings 1 and 2, and should be large (eg. 10^3 to 10^4 range). If a value of less than 10 is specified, it is ignored.
NAME 1 . . . NAME 6	Columns 25-30; 31-36; 37-42; 43-48; 49-54; 55-60. Node names, as for Class 2 Cards *(unique for each transformer, otherwise an EMTP simulation could end up with two transformers with identical internal node names)*. The terminals of the winding in each one of three phases have to be assigned node names to produce output data in the form of branch cards which can be used directly as input by the EMTP. Exactly six node names are required (one pair for each one of the three phases). If a terminal is connected to ground (e.g. the neutral in wye connection), then use a blank field as the name for 'ground'.

LENGTHS: YkLm (61-65) OtLm (66-70)	Ratio of limb lengths may be specified if desired, otherwise a default value is assigned. This determines the unbalance in excitation current among phases for 3-limbed and 5-limbed units. The computed model reproduces the specified excitation current in the centre phase. For 3-limbed units, the established excitation current is a little higher in the outer phases (eg. about 39% higher for YkLm=0.5).
	YkLm: Ratio of yoke length to limb length;
	OtLm: Ratio of outer limb length (including horizontal section) to vertical (wound) limb length.
AREA: YkLm (71-75) OtLm (76-80)	Ratio of effective limb cross-sectional areas may be specified, if desired, for 5-limbed units. If no input is specified, a default value is assigned. For 3-limbed units, a value of 1 (unity) is always assumed.
	YkLm: Ratio of yoke area to limb area;
	OtLm: Ratio of outer limb area (including horizontal section) to vertical (wound) limb area.

4.6 Class 4: Short-Circuit Test Data

Exactly N(N-1)/2 cards, one card for each short-circuit test between a pair of windings, *terminated by a blank card*. The N cards can be read in arbitrary order. The format is shown below.

```
              1          2          3          4          5           6         7         8
12 34 5678901234 5678901234 5678901234 5678901234 5678901234 56 78 9012345678901234567890
```

i	k	P_{ik} (kW)	Z^{pos}_{ik} (percent)	S^{pos}_{rating} (MVA)	Z^{zero}_{ik} (percent)	S^{zero}_{rating} (MVA)	IDELTA	ILOSS	
I 2	I 2	E10.2	E10.2	E10.2	E10.2	E10.2	I 2	I 2	

i,k (1-2) (3-4)	Numbers of the pair of windings between which the short-circuit test is made. Excitation is applied to winding "i" with "k" short-circuited. The numbering order is crucial for zero-sequence tests since the tests are not necessarily reciprocal. For positive-sequence short-circuit tests, the order is immaterial.

P_{ik}
(5-14)

Load losses in kW in the positive-sequence test. If $P_{ik} > 0$, then this value is used in Equation 15 to find the positive-sequence reactance:

$$X_{ik}pu = \sqrt{(Z_{ik}pu)^2 - (R_i pu + R_k pu)^2} \tag{15}$$

with Z_{ik} pu = p.u. short-circuit impedance in test between i and k and

R_i pu + R_k pu = p.u. load losses on the same MVA base as $Z_{ik\ p.u.}$ if load losses are nonzero, or specified p.u. winding resistances on the same MVA base if load losses are not given.

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

Z_{ik}^{pos}
(15-24)

Short-circuit input impedance in percent in the positive-sequence test between windings 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_{rating}^{pos}
(25-30)

Three-phase power rating in MVA, on which Z_{ik}^{pos} is based.

Z_{ik}^{zero}
(35-44)
S_{rating}^{zero}
(45-54)

Same as the preceding two parameters, respectively, except that they correspond to zero-sequence test. For single-phase and 5-limbed units, these can be left blank.

For 3-limb units, a facility is provided for the model to be computed based on physical considerations, such that it is not necessary to specify all Z_{ik}^{zero} values. This option is recommended *only* if a full complement of measured test values is not available. In this event, ISOLKG must be set to a negative value (ie. <0). If ISOLKG < 0 *and* the specified $I_{excit}^{zero} = 0$ (or it is left blank), then I_{excit}^{zero} is estimated using one zero-sequence test value and all others are ignored. In these cases, the model is computed using positive-sequence short-circuit impedance, based on physical considerations. All zero-sequence impedances are established by default. (See I_{excit}^{zero} and ISOLKG under Class 1 cards).

If IDELTA = 0, then P_{ik} from the positive-sequence test is also used to calculate the zero-sequence reactance with Equation 15. If $S_{rating}^{zero} = 0$ or blank, it is assumed to equal S_{rating}^{pos}

If IDELTA > 0, then the specified winding resistances are used directly to determine reactances based on specified impedances.

IDELTA
(55-56)

= 0 or blank: 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 if IDELTA=0.

> 0: Number of the 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 (closed delta). For the most important case of three-winding transformers, the program can presently handle Yyd-connections only.

In the Yyd connection, "d" would be the additional shorted winding in the zero-sequence test between "Y" and "y".

The program *cannot* handle Ydd or Ddd-connections with IDELTA>0.

For three-phase transformer banks consisting of single-phase transformers, input the single-phase data as positive-sequence parameters and leave the fields for the zero-sequence input parameters blank, including IDELTA.

ILOSS
(57-58)

Specify ILOSS on the first short-circuit test data card.

= 0,
or blank

Specified winding resistances will be used directly.

> 0

Winding resistances will be calculated from load losses P_{ik}, provided $N \leq 3$ and $P_{ik} \geq 0$ for all short-circuit tests. Read-in winding resistances are then ignored.

4.7 Sample Data File

```
C TOPMAG DATAFILE
C BEGIN NEW DATA CASE
XFORMER                              55.
C --------------------------- XFMR DATA ----------------------------------------
C LONGWOOD TS AUTO NEI #44484 500/240/28-KV 750-MVA 3-PHASE
C  EXCITATION DATA:                                                     <N<I<I<I
C <---FRQ--><    pos ><  pos   ><   pos  ><    zer ><  zer   ><   zer  ><T<T<S<P
C           <  %I    >< S MVA  ><Loss(kW)><  %I    >< S MVA  ><Loss(kW)><Y<S<L<R
C           <--  exc ><  rating><   exc  ><    exc ><  rating><   exc  ><P<T<K<N
 3      60.0     0.030    750.0     200.0                                0 5 1
C
C W<-Vrating><- R ----> <----------- NODE NAMES ----------->
C G<(kV-LG Y><   dc   > <- PHASE A-><- PHASE B-><- PHASE C->
C #<(kV-LL D>< (ohms) > <FROM><-TO-><FROM><-TO-><FROM><-TO->
  1 288.67513 1.000000 RH1   HN    WH1   HN    BH1   HN
  2 138.56406  .000000 RX1         WX1         BX1
  3     28.00  .000000 RY1   RY2   WY1   WY2   BY1   BY2
C                                                           <-LENGTH-><--AREA-->
C  <- CUPCO->           <------------- NAMES -------------><YKLM<OTLM<YKLM<OTLM
                        RZ1   RZ2   WZ1   WZ2   BZ1   BZ2
C
C SHORT CCT TEST DATA:  FOR TAP 11 (NEUTRAL TAP)
C  W<--------><--------><---pos--><--------><---zer--><I<L
C  D<  pos   ><  pos   ><  S     ><   zer  ><  S     ><D<O
C  G< Loss   >< Z      ><   rat  ><  Z     ><   rat  ><E<S
C  #<  (kW)  ><  (%)   ><  (MVA) ><   (%)  >< (MVA)  ><L<S
 1 2   1032.20    13.780    750.00     12.82    750.00 3 0
 1 3    131.10    33.300    750.00     29.89    750.00 0
 2 3    130.10    18.000    750.00     17.21    750.00 0
C ---------------------------------- END OF XFMR DATA ---------------------------
BLANK CARD TERMINATING DATA CASE
BLANK CARD TERMINATING TOPMAG
BEGIN NEW DATA CASE
```

5 Modeling Hints for all Transformer Models

5.1 Saturation Effects

Since the air-core inductance (which is the slope of the ψ/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. Supporting evidence may be found in reference [6] and reference [8].

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_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 8, below).

For a more detailed discussion of the inclusion of saturation effects, please refer to reference [2].

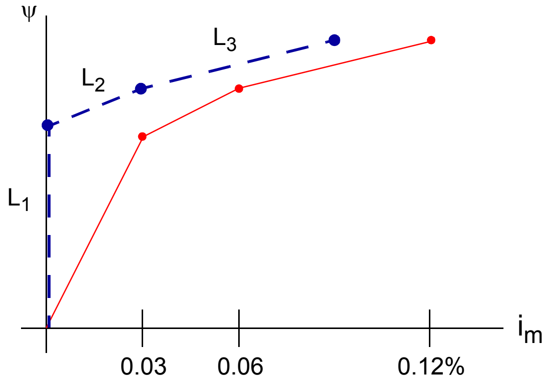


Figure 8: Definition of Nonlinear Inductance

5.2 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.

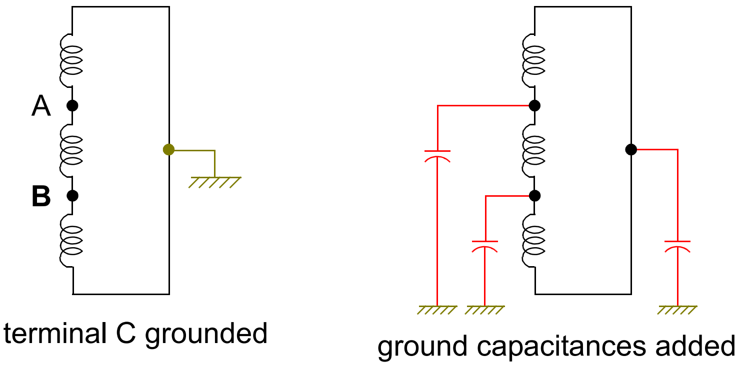


Figure 9: Means of avoiding floating delta connections

5.3 High-Frequency Effects

The above described models represent the linear behaviour 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 behaviour of the windings, e.g., as described in reference [1].

A more accurate representation can be obtained using the HFT model described in Section 6, RuleBook 1. The HFT model, however, requires measurements of the transformer impedances as a function of frequency, and these are genrally not available from in standard factory tests.

5.4 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 models produced by the described in this Section. It is possible, however, to develop more accurate models by modifying the short-circuit test data. In the case of Figure 10, 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.

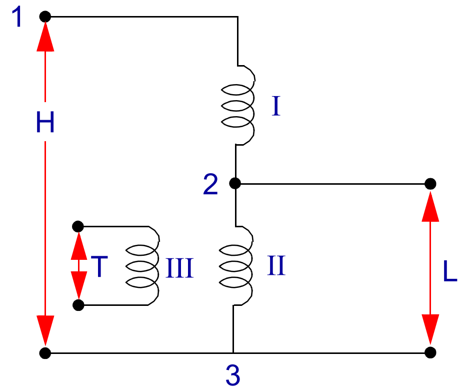


Figure 10: Autotransformer