ELECTRIC POWER RESEARCH INSTITUTE

Literature Survey on Transformer Models for the Simulation of Electromagnetic Transients with Emphasis on Geomagnetic-Induced Current (GIC) Applications

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ABSTRACT

Previous studies have demonstrated that geomagnetically induced currents (GICs) caused by geomagnetic disturbances (GMDs) can cause half-cycle saturation in power transformers. To better understand transformer vulnerability to GMDs, transformer models need to be developed that can accurately model the impact of very low frequency GICs on the transformers. This report presents the results of a literature survey of transformer models for the simulation and analysis of electromagnetic transients for the purpose of analyzing the impact of GMDs on transformers. The report is intended for use by engineers and researchers who are involved in power system studies that address GMDs. The Electric Power Research Institute (EPRI) plans to use the results of the report to identify research gaps in the areas of transformer electrical models. Thermal models will be addressed later after gaining an understanding of electrical models.

Keywords

Electromagnetic transients
Geomagnetic disturbance
Geomagnetic-induced current
GIC
GMD
Half-cycle saturation
Transformer models

EXECUTIVE SUMMARY

Previous studies have demonstrated that geomagnetically induced currents (GICs) caused by geomagnetic disturbances (GMDs) can cause half-cycle saturation in power and generator step-up (GSU) transformers. Half-cycle saturation produces harmonics, consumes VARs, and results in transformer heating. The harmonics can cause misoperation of protective relays, overloading of capacitor banks, and heating in generators. The reactive loading increase can lead to voltage depression, transmission line disconnection, and even system voltage collapse. The heating can result in localized hot spots that cause damage to transformer insulation, windings, leads, bracing, and tank walls; gassing of transformer oil; accelerated aging; and possible transformer failure.[1]

To better understand transformer vulnerability to GMDs, transformer models need to be developed that can accurately model the impact of very low frequency GICs on the transformers. This report presents the results of a literature survey of transformer models for the simulation and analysis of electromagnetic transients for the purpose of analyzing the impact of GMDs on transformers. The targeted frequency range includes low- and mid-frequency transients because GIC frequencies are very low. The report is intended for use by engineers and researchers who are involved in power system studies that address GMDs. The Electric Power Research Institute (EPRI) plans to use the results of the report to identify research gaps in the areas of transformer electrical models. Thermal models will be addressed later after gaining an understanding of electrical models.

The three basic types of models—leakage flux models, matrix representation models, and topological models—are described in this report. The latter type of model is the most accurate in theory. Most topological models are based on the duality principle that enables derivation of an equivalent electrical circuit from magnetic equations. However, there are several limitations with duality-based models:

- There is an abundance of research and advanced modeling methods in the literature, and some of the duality-based models are considered accurate. However, there is no clear consensus supported by validation and transformer manufacturers on the most accurate modeling approaches and assumptions made in such models.
- The representation of leakage flux remains problematic in topological models, and topological circuits may provide inaccurate results in saturation—the condition that occurs when transformers are exposed to severe GMDs. Yet, a key aspect for GIC is the accurate modeling of transformer magnetization.
- Sophisticated duality-based models require the input of extensive data, and these data are not available in most cases. Although some modeling approaches offer alternatives to accommodate the lack of data, the level of accuracy remains related to the availability of measurements and transformer design details.

Research must be pursued to eliminate the above limitations and simplify data requirements as much as possible.

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[1] EPRI white paper, *How the EPRI Geomagnetic Disturbance (GMD) Research Fits Together* (1026425).

As future work, EPRI proposes to deliver templates with simplified models for the most common transformer design types using basic nameplate data. It must be assumed that detailed design data and measurements are not available in most practical cases. In addition to topological models, EPRI also proposes to conduct research on simplified models using available magnetization characteristic and short-circuit tests. The developed models should provide transformer performance analysis with sensitivity to parameters for GIC applications.

The validation of models remains a key issue. EPRI recommends working with transformer manufacturers to gather significant amounts of test data and developing models that the industry can confidently use for typical transformer types.

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1

INTRODUCTION

The impact of Geomagnetic Disturbances (GMDs) on the grid is of rising concern to the electric utility industry. GMDs have the potential to cause system wide disturbances, and in extreme cases cause widespread disruption of electric service and equipment damage [1]. Although severe events are rare, the potential effects of geomagnetically induced current (GIC) on the grid cannot be ignored, and action is needed to maintain the reliability of the grid during an extreme GMD event.

GMDs result from a distinct process that begins with the sun. Coronal mass ejections (CMEs) are the primary solar activity that drives solar magnetic disturbances on the Earth. CMEs involve the ejection of a large mass of solar energetic particles that escape from the sun's halo (corona), traveling to the Earth in a time span of 15 hours to 4 days. The charged particles from the CME interact in a complex manner with the Earth's magnetosphere, resulting in significantly enhanced fluctuations in the near-space electric current systems (see Figure 1-1).

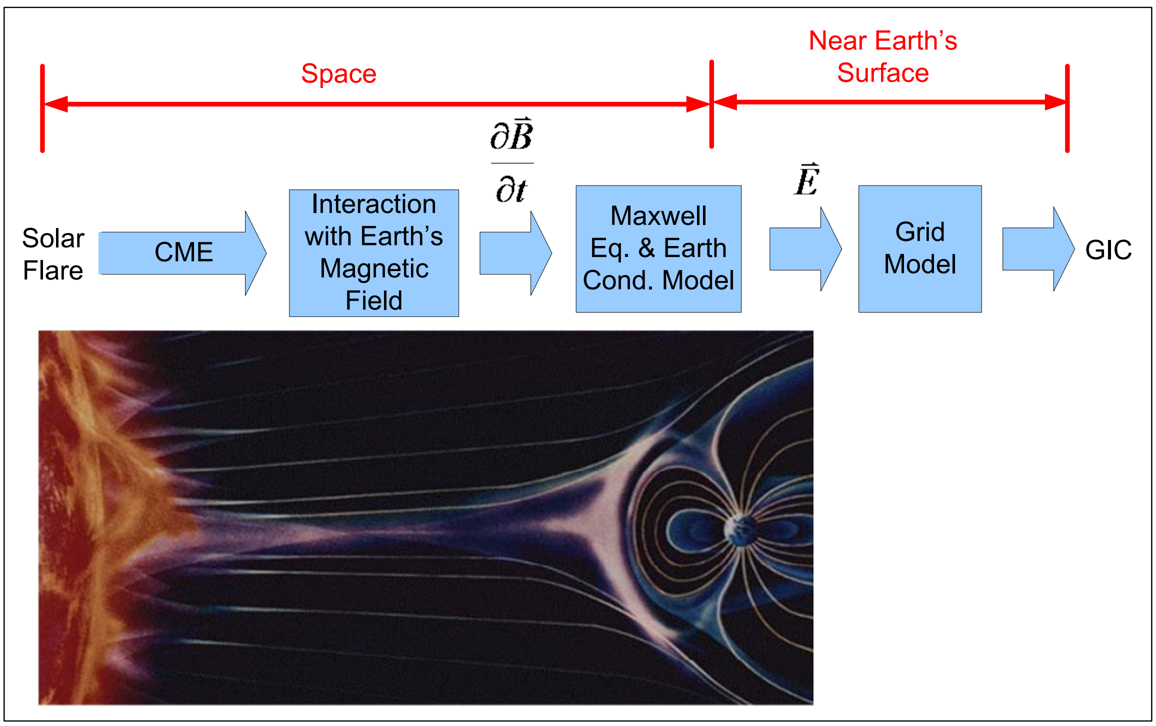

Figure 1-1
Storm Interaction with the Earth and the Grid

Fluctuations in the near space current system are characterized by a slowly varying magnetic field that induces a geoelectric field at the earth's surface. The resulting geoelectric field induces a voltage in transmission lines that drives geomagnetic-induced currents (GICs) wherever there is a path for them to flow [2] (see Figure 1-2). The GIC frequencies are very low, typically from 0.01 Hz to 1 mHz.

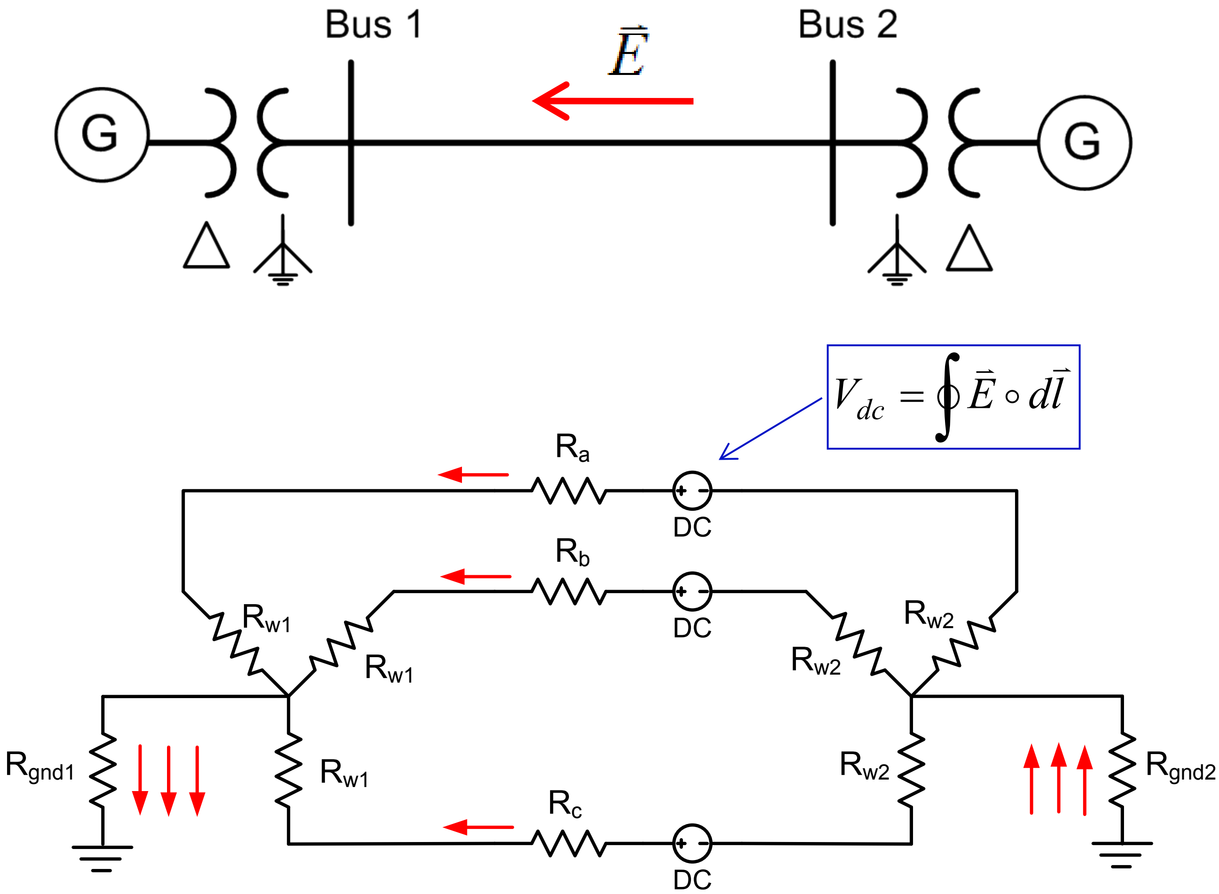

Figure 1-2
Geomagnetically Induced Current (GIC) Example [1]

The impacts of GICs on the transmission system are caused by half-cycle saturation of power and generator step-up (GSU) transformers. When GICs flow through the transformer windings, they create a flux offset that can drive the core into deep saturation for one-half of the power cycle as shown in Figure 1-3 [1]. The resulting exciting current has a distinct "pulse" shape during one-half of the power cycle, whereas the exciting current in the other half-cycle is almost negligible. In the normal operation case, the mean flux is zero, and the current has a full-cycle sinusoidal shape.

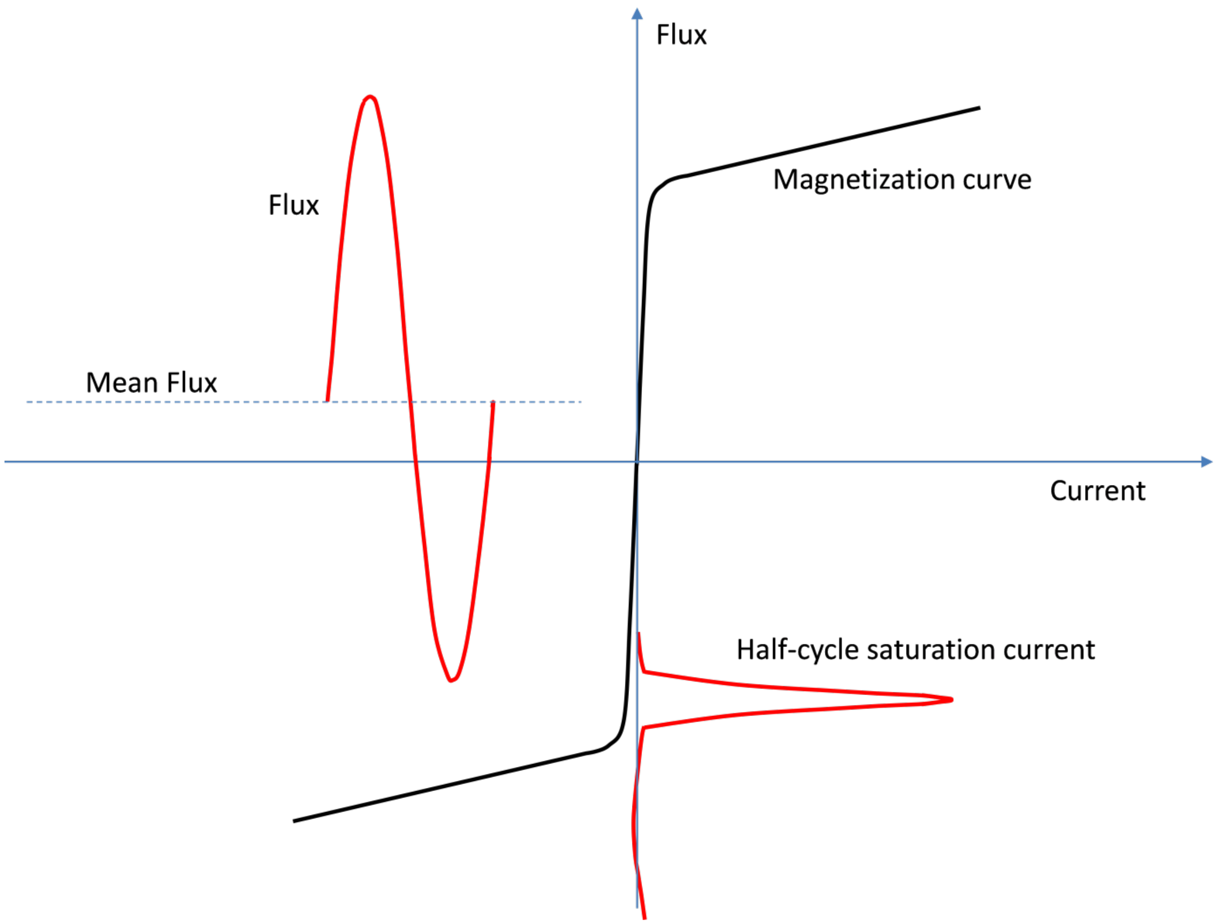

Figure 1-3
Half-Cycle Saturation Caused by the Flow of GIC [1]

The primary effects of half-cycle saturation of power transformers on the grid are increased harmonic current injection and var losses. The exciting current of a power transformer experiencing half-cycle saturation contains considerable fundamental and harmonic components. Half-cycle saturation generates both even and odd order harmonics. These harmonics can cause misoperation of protective relays (capacitor bank and harmonic filter bank protection schemes are particularly vulnerable), capacitor bank and harmonic filter overloading, and heating in generators. The increases in reactive loading are due to the dramatic increase in the fundamental component of the exciting current, which can lead to voltage depression, transmission line disconnection, and even system voltage collapse.

During the saturated interval, the magnetizing current rises to a large value and causes flux to escape from the confines of the core and to penetrate other structural members that are either shielded by the core steel or separated by air. This generally does not happen in normal operation, and the transformer designer may not have anticipated the magnetizing flux flow into specific regions. See other details in [3].

On March 13, 1989, Hydro-Quebec experienced a complete blackout of its system due to a severe geomagnetic storm [4]. Service interruption costs, together with equipment damage costs, are estimated to be approximately $6 billion. The blackout resulted from the saturation of transformers by GICs and the ensuing operation of protection equipment because of the injected harmonics. In the Hydro-Quebec network, one of the consequences of GICs was the tripping of static compensators due to overcurrent (excess harmonic currents in the capacitor branch) or overvoltage.

Clearly the transformers are key components in the studies of power systems subjected to GICs. The purpose of this report is to perform a literature survey on transformer modeling in EMT-type (Electromagnetic Transients) simulation tools. The considered models are those for low to mid-frequency transients and transmission system applications. Additionally, the steady-state aspect is included in the low frequency range.

An example of an EMT-type tool is EMTP-RV (www.emtp.com).

2 TRANSFORMER MODELS

Transformer Types

Because the AC and DC flux paths in transformers may vary with core designs, the following transformer types need to be modeled:

- Single-phase (shell-form and core-form)
- Three-phase, shell-form
- Three-phase, three-legged core-form
- Three-phase, five-legged core-form

The three-phase, shell-form construction includes five- and seven-legged cores. Seven limb transformers are becoming more prevalent in the industry to reduce transformer height. While models will be needed for system and component vulnerability assessment, the literature search uncovered no past work on the subject.

Instead of using a bank of single-phase transformers, it can be economically advantageous to design a single three-phase transformer. The basic three-phase design is the core form. In the three-legged core-form, three sets of windings are placed over three vertical core legs. Each core leg carries windings corresponding to one phase. The top and bottom yokes are used to join the core legs to create a closed magnetic circuit (see drawing in [5], page 56 and Figure 2-1). The flux through each core leg is normally sinusoidal, with 120 degrees of phase shift between the phases. For the balanced case, there is no need for a flux return path. In the unbalanced case, the residual flux must travel along a high-reluctance path through air.

In three-legged, core-form transformers, third harmonic flux and residual flux from unbalanced voltages may leave the iron core and enter the free space inside the transformer. Additionally, the induced currents in the internal metal parts may cause severe heating. The five-legged, core-form design can be used to solve this problem up through about 2,500 kVA. It provides flux paths around the three core legs between the top and bottom yokes. A fourth and fifth core leg provide return paths for the residual flux from the top to the bottom yoke (see drawing in [5], page 58). The five-legged design can be a five-legged stacked core (see Figure 2-2) or a five-legged wound core (see Figure 2-3).

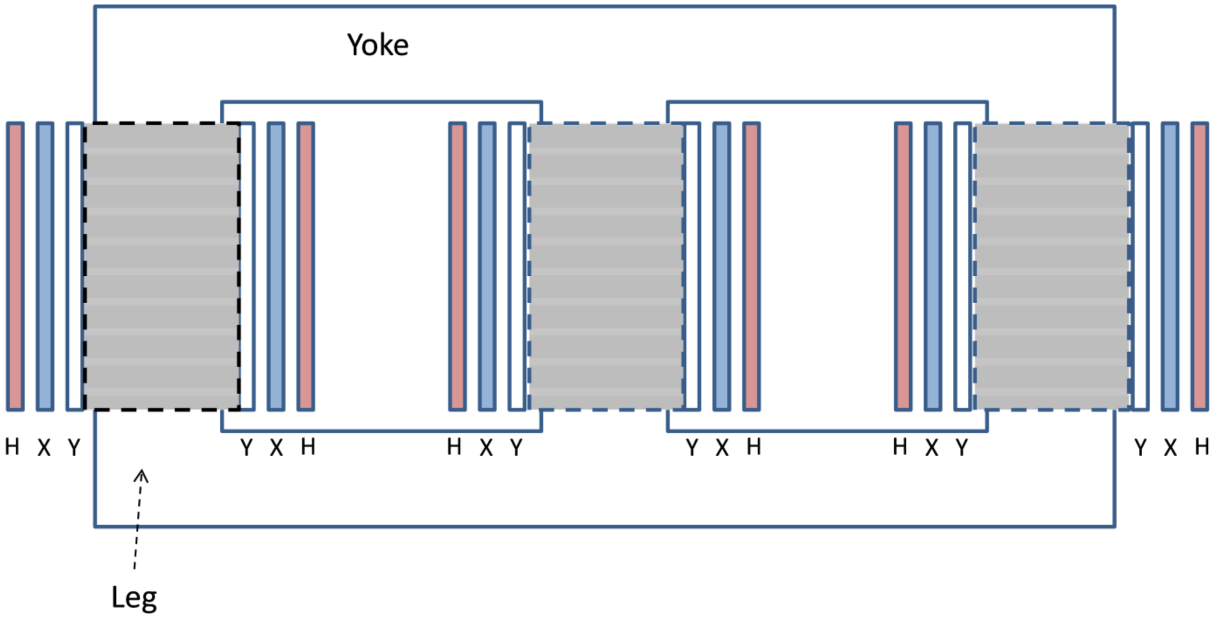

Figure 2-1
Three-Legged Core-Form Transformer with Three Windings per Leg (Y, X, and H)

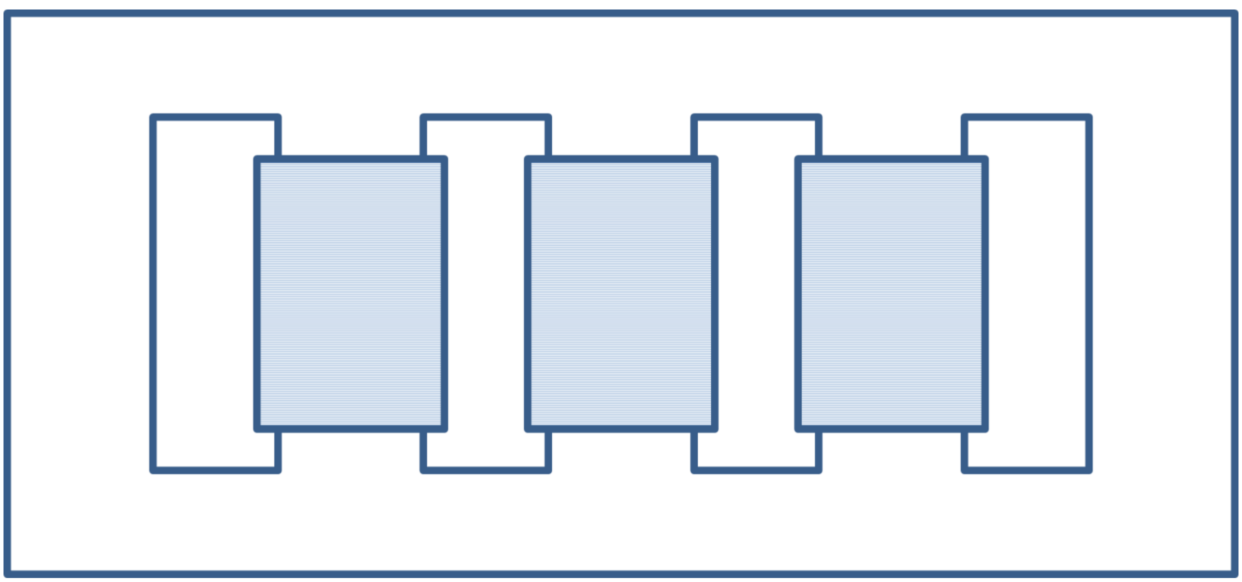

Figure 2-2
Five-Legged Stacked-Core Design

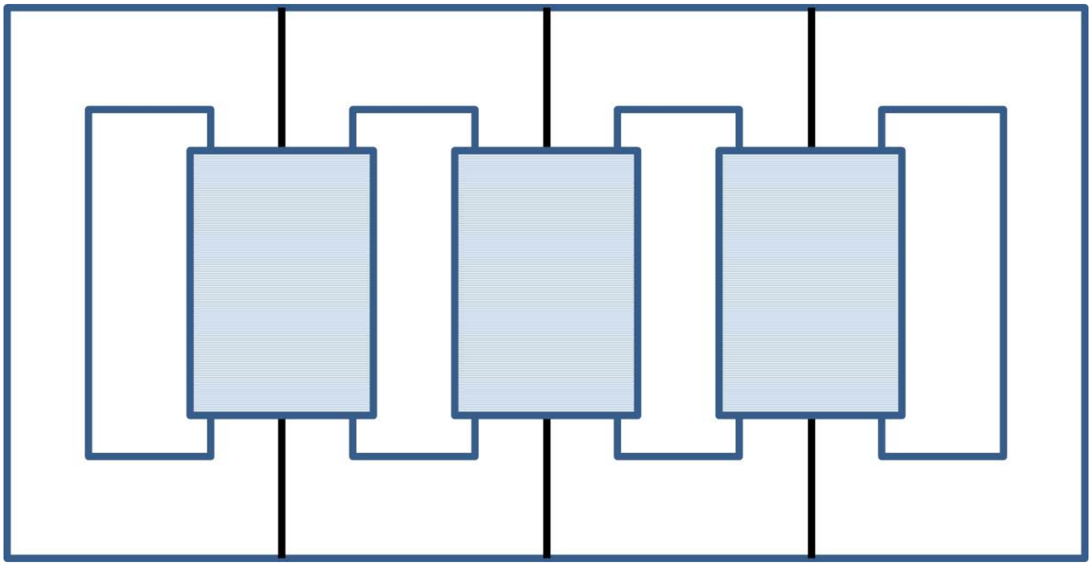

Figure 2-3
Five-Legged Wound Core Design

The shell-form design is completely different from the core-form design. In a shell-form transformer, the windings are constructed from flat, coiled spirals stacked together like pancakes. This is why the windings in a shell-form design are often referred to as pancake windings. The low voltage winding can be split into two windings, with the high-voltage winding sandwiched between the two halves of the low-voltage winding. In some shell-form designs, the low- and high-voltage windings can be split into more than two windings. The pancake coils have a square shape with rounded outer corners, the coils are stacked horizontally (see drawing in [5], page 59 and Figure 2-4), and the return paths for the core encircle the coils to form a shell (i.e., the shell-form design).

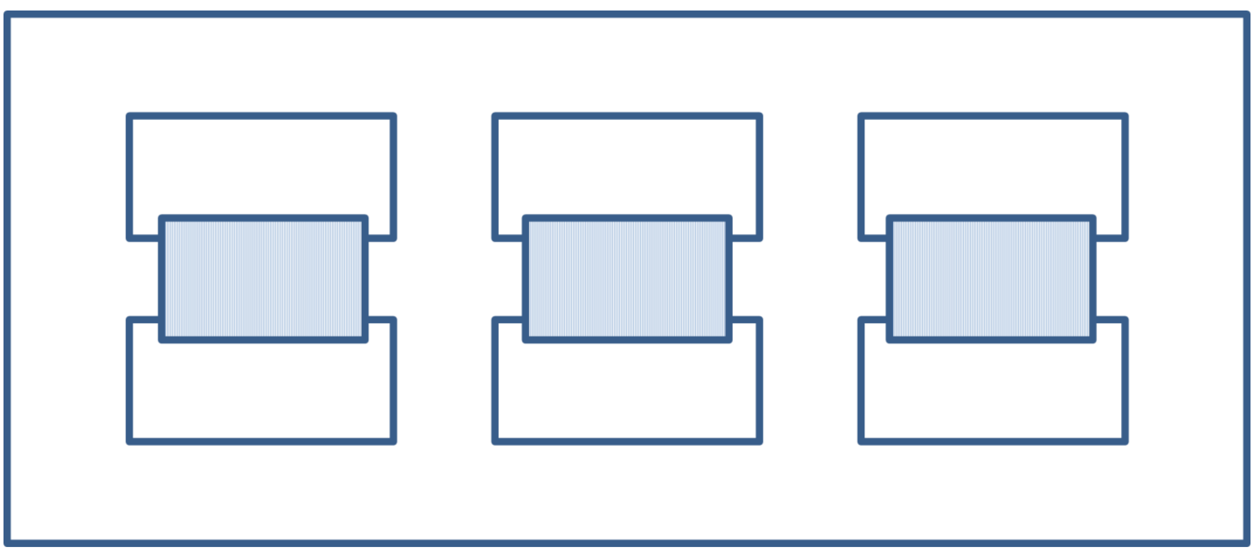

Figure 2-4
Shell-Core Design

The shell-form design does not feature a strong magnetic interaction among the different phases at normal excitation levels.

Of the two core configurations described above for power transformers, the core-form units are more common in North America. The shell-form units generally exhibit a superior short-circuit withstand strength. However, modern core-form units now incorporate innovations that provide comparable strength.

Winding configurations in power transformers can vary widely, including different dimensions, construction, insulation, spacing among turns, and spacing associated to the neighboring windings on the given limb. Cylindrical windings are usually positioned concentrically around a limb, so that windings that carry a higher voltage rating are outermost on the limb and larger in diameter. Some transformers may also need to use separate concentric sections. In other cases, two secondary windings can be displaced axially, while remaining concentric to the high-voltage winding. However, this configuration is difficult to brace for short circuits.

Transformer Models

Transformer models may vary depending on the frequency content of the transients. If low-frequency transients are considered, as for GIC studies, then the transformer model falls into the low- to slow-front frequency transients category. In this category, important transformer model components include:

- Short-circuit impedance
- Saturation and hysteresis
- Eddy current losses

Transient tools include models of different complexity levels to accurately duplicate the physical behavior of transformers. This section documents mainly models implemented in commercial grade software packages, as well as other developments presented in publications.

Saturable Transformer Component (STC)

The saturable transformer component (STC) model is based on a single-phase (decoupled phases) model. The single-phase divided leakage flux model is shown in Figure 2-5. This model is also referred to as the T-model [6]. The resistances R_1 and R_2 are series resistances that include Joule losses and eddy current losses in the windings (usually calculated at power frequency), in addition to L_1 and L_2 that represent leakage inductances divided among the two windings.

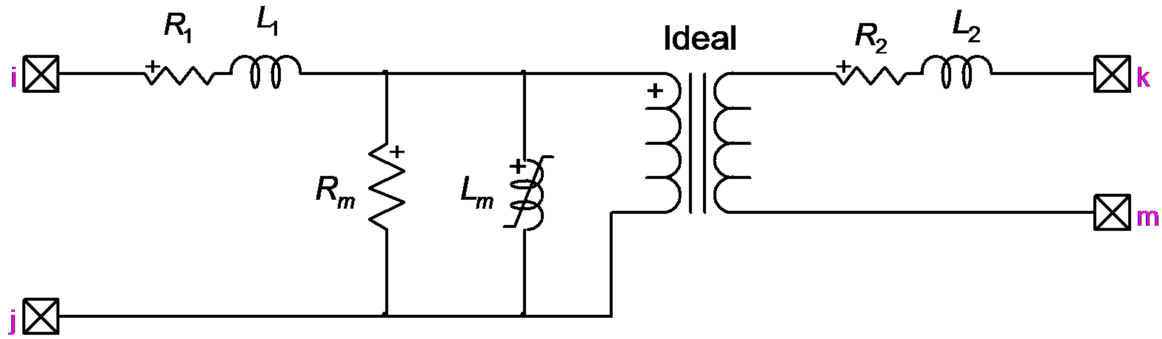

Figure 2-5
Single-Phase, Divided-Leakage Flux Model

Leakage flux exists in the spaces between windings and in the spaces occupied by the windings [7]. These flux tubes create impedance (leakage reactance) between the windings. When estimating the leakage reactance through short-circuit tests, the ampere-turns of LV and HV windings are assumed to be equal and opposite, which means that there is no mutual component of flux in the core.

A primary current is required to magnetize the core, which is represented by the inductor L_m in Figure 2-5. The model of Figure 2-5 is used as a building block for the STC version shown in Figure 2-6. For an N-winding transformer, there are $N(N-1)/2$ independent impedances. As explained in [8], the STC representation is only valid for transformers with less than four windings. However, it is still possible to use this approach and develop four-winding transformer models [9].

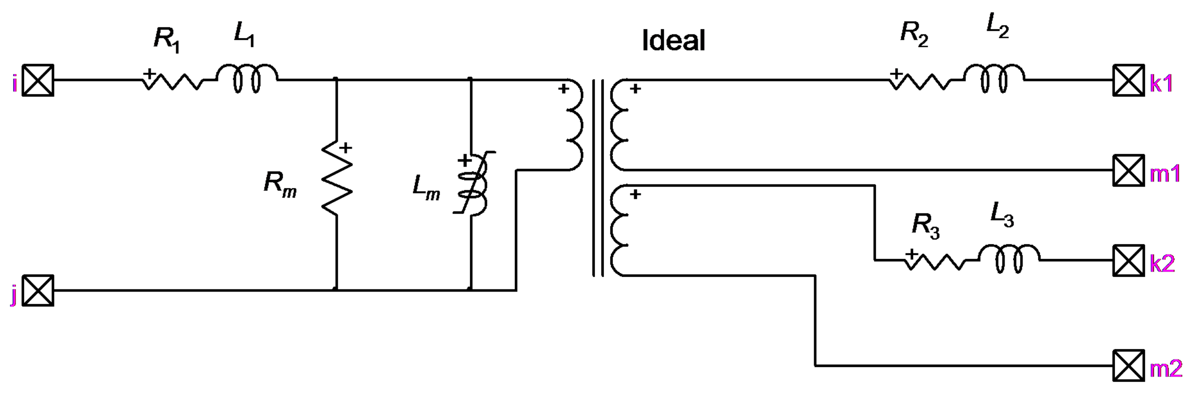

Figure 2-6
STC Model Composed of N Windings

In the STC model, the winding losses are not frequency dependent, and they are calculated at power frequency from available short-circuit tests. R_m and L_m (magnetization branch) are used to model the core behavior for nonlinearities (saturation and hysteresis) and eddy current losses. Users choose the location of the magnetization branch at the high-voltage winding (generic practice for single-phase units), but better results can be obtained by connecting externally to the lower voltage side. The constant R_m usage is valid for a narrow frequency range and is not valid under saturated conditions (e.g., half-cycle saturation). Alternative formulations can also be used to accommodate a wider frequency range [10].

Researchers explain in [11] that the separation of leakage flux between the primary and secondary is not physically correct because the leakage flux paths may change and modify the linked winding portions. Negative leakage inductances may appear in the case of three-winding transformers and potentially create numerical problems in EMT-type simulation tools. These negative values appear in the model and not in reality, and establish the fact that the STC model is not a physical model.

When the STC model represents coupled three-phase transformers, it does not account for magnetic coupling between the phases, and the zero-sequence impedance is the same as the positive sequence impedance when it is not modified by transformer connections. It is possible to include a zero-sequence impedance correction circuit [12], but additional tests are required for the calculation of its values.

Leakage impedances are calculated from short-circuit tests. However, the distribution of the total leakage impedance on the primary and secondary windings is not clearly defined. Some publications [13] suggest using 75% to 90% on the high-voltage side. The separation of leakage inductances is not related to a physical relation.

In circuit-based simulation tools for electromagnetic transients (EMT-type tools), the actual circuit of Figure 2-6 is assembled and solved using network equations. The data input mask of a three-phase transformer model is shown in Figure 2-7. The corresponding model circuit is presented in Figure 2-8. The non-ideal units contain the subcircuit of Figure 2-5.

It is possible to obtain nonlinear magnetizing branch data from manufacturer tests. These tests are usually given in the form of an RMS-voltage and RMS-current function. It is possible to convert RMS data into a time-domain nonlinear function of flux and current using the conversion technique described in [16] (see also [17]-[19]).

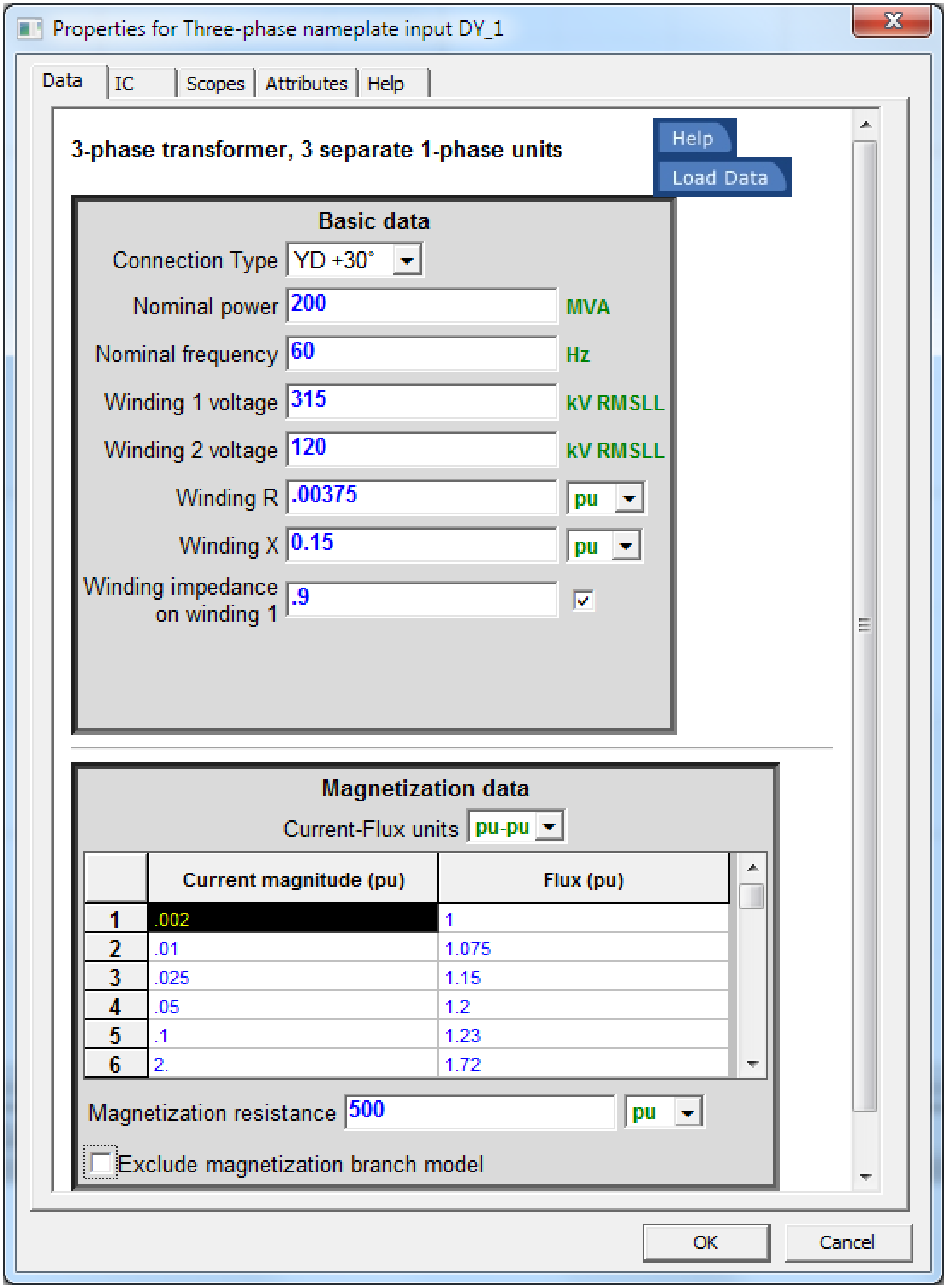

Figure 2-7
Data Input Mask for a Three-Phase Transformer Model in EMTP-RV, STC Approach

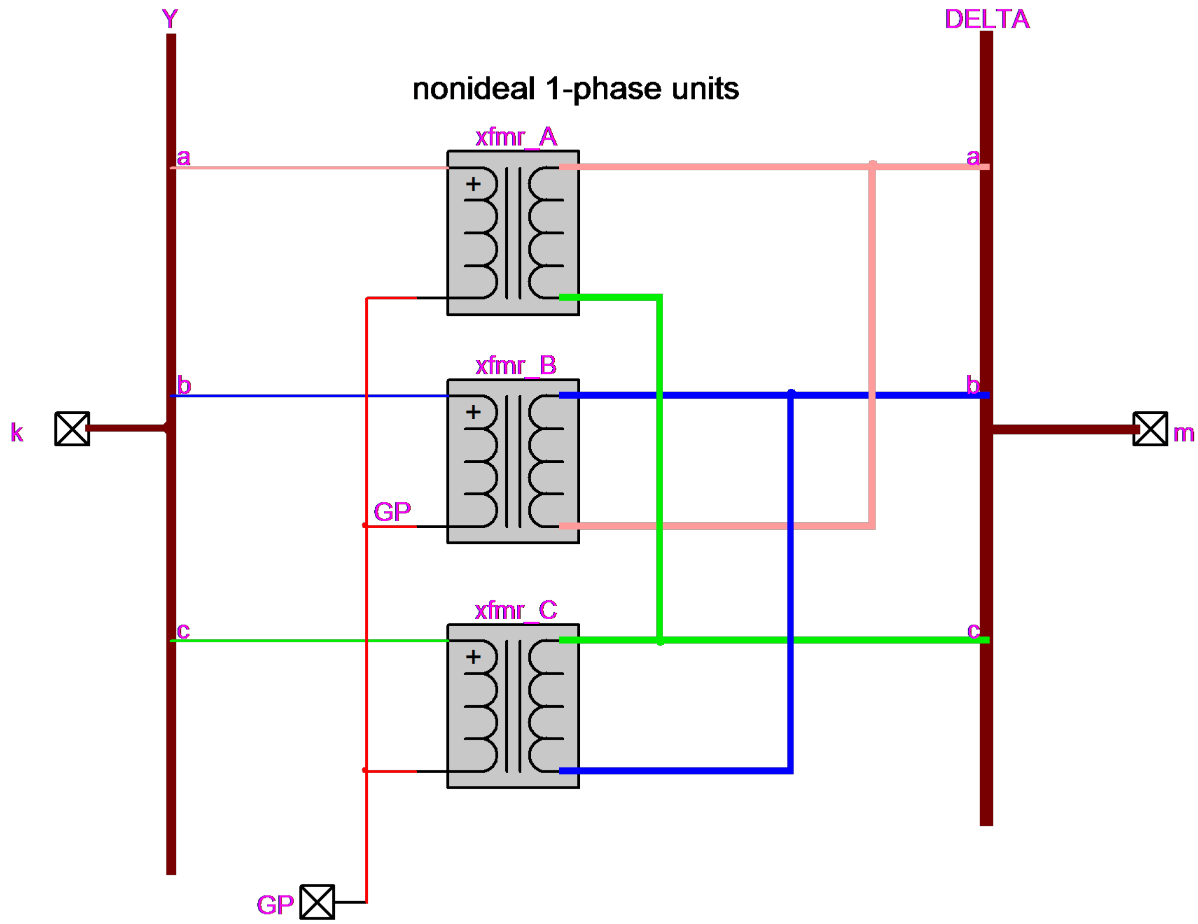

Figure 2-8
Three-Phase Transformer Model Circuit Equivalent in EMTP-RV, STC Approach, Yd11 Connection Type

Matrix Representation Models, BCTRAN

The matrix representation models are based on self and mutual inductance representation [14]. These models can be used for transformers with more than three windings. In this approach, the magnetic flux is not divided, and each winding is modeled as a combination of self and mutual inductances. The generic steady-state and time-domain equations are given by

$$\mathbf{V} = \mathbf{Z}\,\mathbf{I} \qquad \text{Eq. 2-1}$$

$$\mathbf{v} = \mathbf{R}\,\mathbf{i} + \mathbf{L}\frac{d}{dt}\mathbf{i} \qquad \text{Eq. 2-2}$$

where bold characters are used to represent vectors and matrices, the vector $\mathbf{v}$ stands for winding voltages, the vector $\mathbf{i}$ is for winding currents, $\mathbf{Z}$ is the matrix impedance (complex, steady-state), $\mathbf{R}$ is the resistance matrix, and $\mathbf{L}$ is the inductance matrix. The model now includes coupling between different phases. The differences in core design among different types of transformers are not accounted for because all core designs receive the same mathematical treatment.

The initial reference on transformer data calculation and modeling is given by [15] (see also [16]). This approach was also used to develop the BCTRAN function. The BCTRAN model is only for linear representation of the transformer, and the nonlinear magnetization branch must be externally connected using a nonlinear device. It can be connected to the low-voltage winding side as shown in Figure 2-9. The idea is to connect magnetization to the winding closest to the core; however, such a connection is not necessarily topologically correct (see, for example, shell-form design with pancake windings). In some cases, the location of the magnetization branch can lead to considerable error (see [20]). The presence of the magnetization branch (core model) on the low voltage winding in BCTRAN causes currents to circulate in both high-voltage and low-voltage winding resistances, resulting in higher losses and modification of time constants in transients.

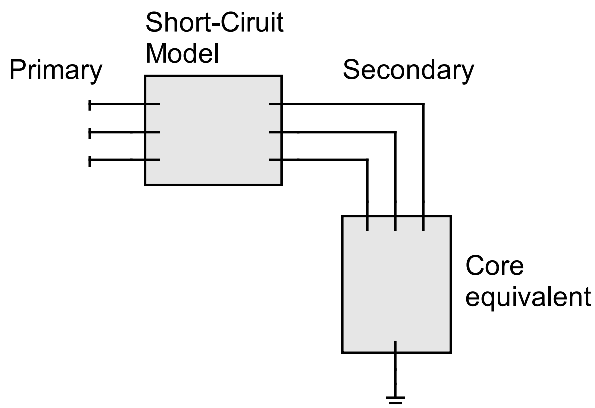

Figure 2-9
Basic Matrix and Core Representation for a Three-Phase Transformer (Two Windings)

The BCTRAN module setup in EMTP-RV is shown in Figures 2-10, 2-11, and 2-12. It consists of a coupled multiphase branch system with identified winding connections. The required data inputs are: positive sequence excitation test, zero sequence excitation test, and short-circuit tests for all winding pairs.

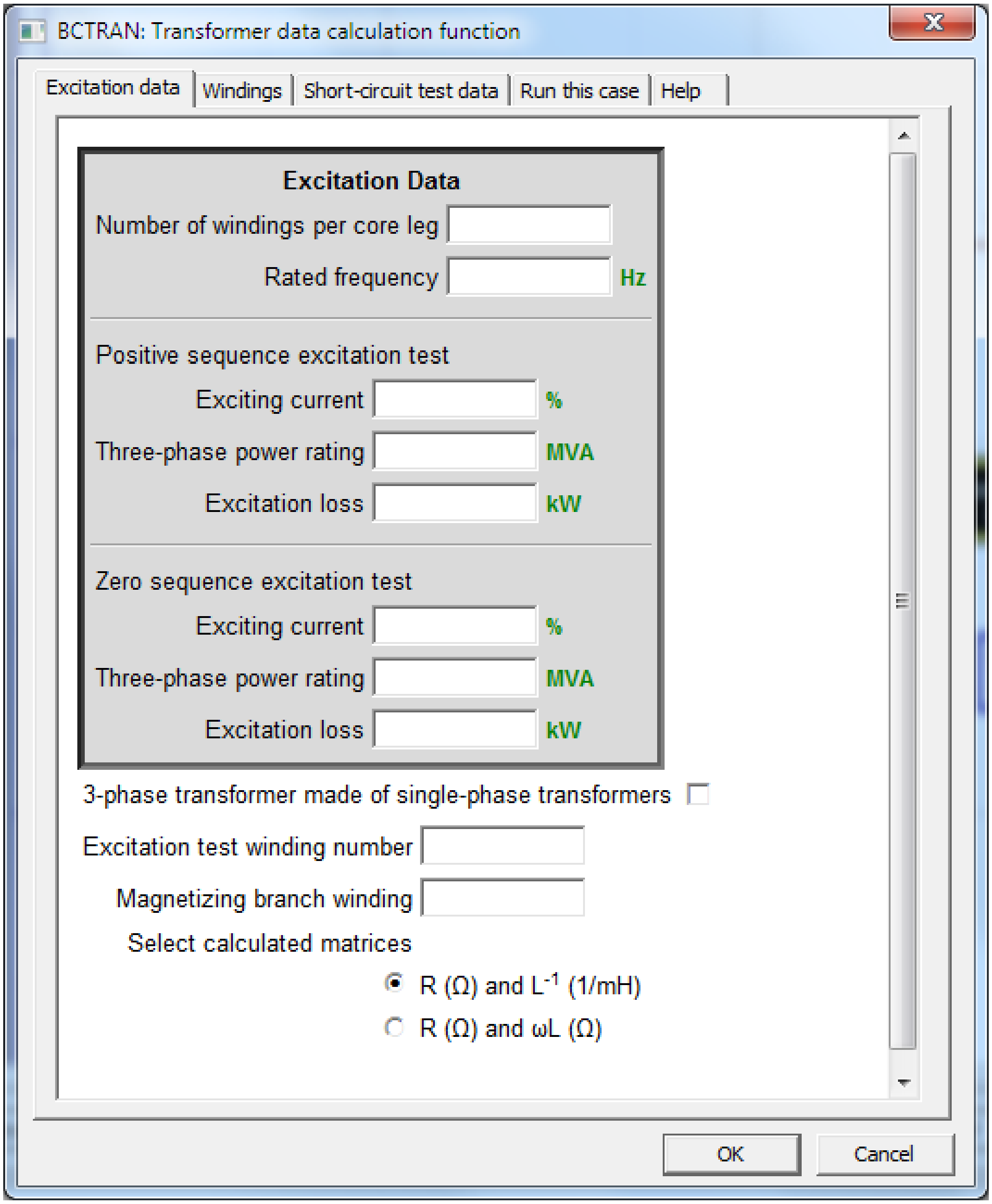

Figure 2-10
BCTRAN Data Calculation Module in EMTP-RV (Part 1 of 3)

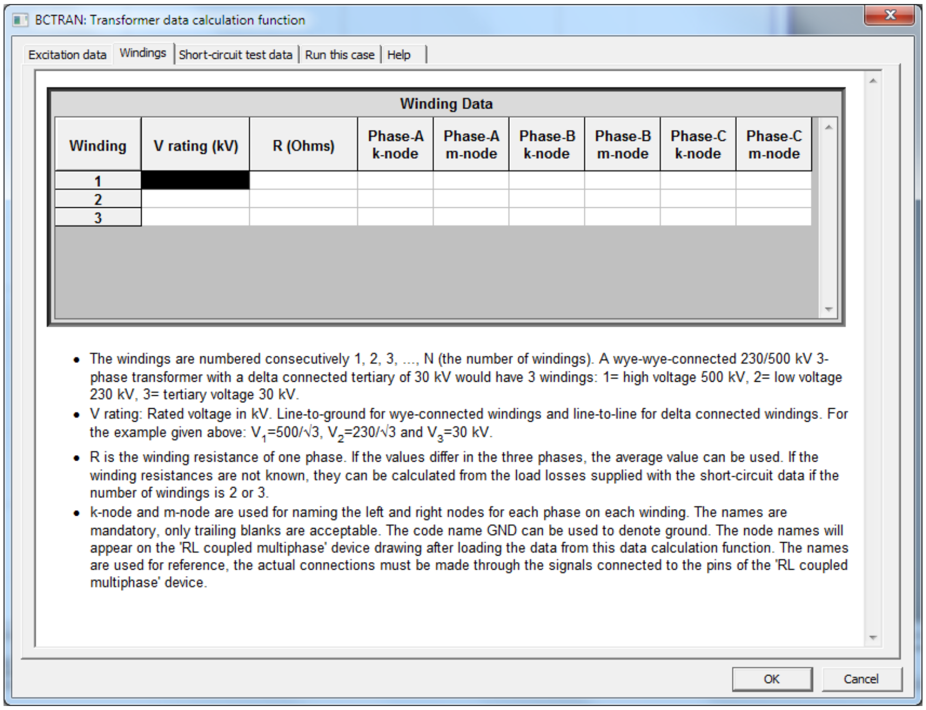

Figure 2-11
BCTRAN Data Calculation Module in EMTP-RV (Part 2 of 3)

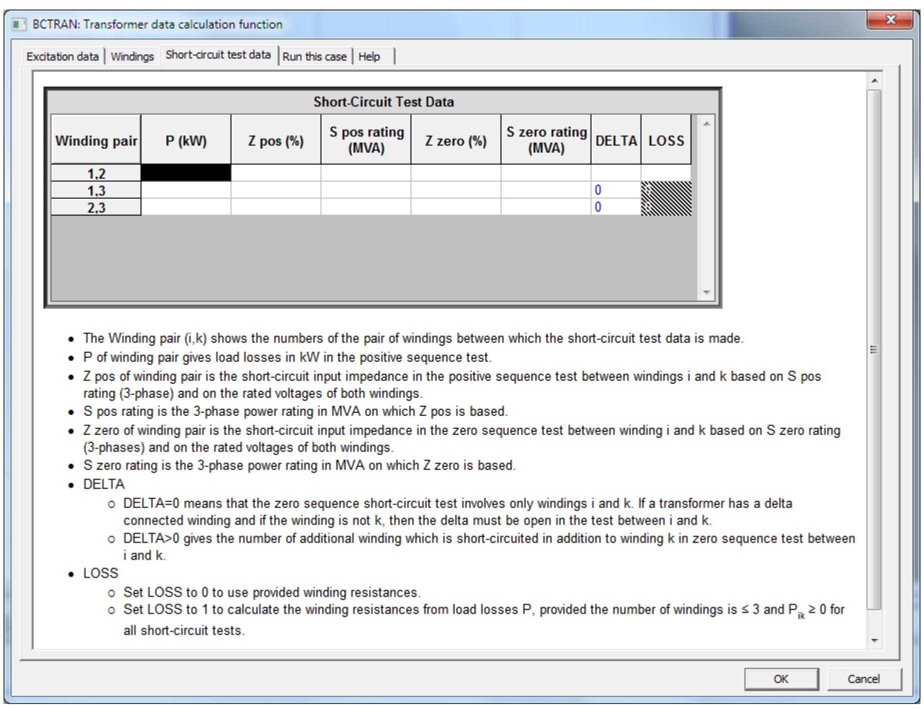

Figure 2-12
BCTRAN Data Calculation Module in EMTP-RV (Part 3 of 3)

In addition to BCTRAN, EMTP-RV includes a data calculation function named TRELEG [16]. It also uses short-circuit tests for all winding pairs. While both models require similar data inputs for comparable modeling accuracy, there are fundamental differences in their formulations. TRELEG creates an impedance matrix from specified input data, whereas BCTRAN builds an admittance matrix. From the equivalent circuit of a coupled RL-branch, if the excitation (test) current is neglected, then the impedance matrix is ill-conditioned. However, the (singular) admittance matrix exists. As a result, TRELEG cannot be used if the excitation current is neglected.

Both BCTRAN and TRELEG assume complete symmetry among phases, reflecting identical leakage impedance and excitation current for each phase. For the three-phase core-form units, windings on the outer core legs are indistinguishable from those on the center leg. The magnetizing branches are incorporated as uncoupled elements, connected at specified winding terminals. Therefore, the sequence components of magnetizing currents appear electrically inseparable. In reality these components are physically associated with separate flux components displaced in space.

However, many manufacturers do not offer the zero-sequence excitation test. In that case, it is possible to estimate the zero-sequence excitation current using the following formula [16]:

$$\frac{I_0}{I_1} = \frac{1+k}{1-2k} \qquad \textbf{Eq. 2-3}$$

where k is found from the flux distribution inside the transformer when only phase-a is excited. The following typical values of k can be used according to transformer type:

- Three limbs: $k = 0.4985$ and $I_0/I_1 = 499.5$
- Five limbs: $k = 1/3$ and $I_0/I_1 = 4$
- Shell-form: $k = 1/3$ and $I_0/I_1 = 4$
- If, for example, $I_1 = 0.19\%$ then $I_0 \approx 100\%$

Despite its limitations, BCTRAN is often used for modeling transformers because it requires minimal data to perform EMT-type studies.

Topological Models

A good summary on transformer models for low- and mid-frequency transients is presented in [22]. This document describes various limitations on available models. It also presents an overview on topology-based models. Topology-based models include the duality-based and geometric models.

Duality Principles

Topologically correct equivalent circuit models can be derived from a magnetic circuit model using the principle of duality. In this approach, saturation is included in each individual core leg. It also includes interphase magnetic coupling and leakage effects.

Duality is based on the correspondence between electric and magnetic circuits [23]-[25]. Voltage, current, and inductance in electric circuits correspond to time-derivative of flux, MMF, and reluctance, respectively, in magnetic circuits.

Publication [23] demonstrates that it is not possible to derive a dual circuit for transformers with more than four windings because the resulting circuit is non-planar. The extension of the principle of duality for non-planar networks is available in [26], but it is rather complicated.

As explained in [27] (see Chapter 4 on Transformers), it is possible to derive the PI-model of a single-phase transformer for both core- and shell-form designs, using the duality principle. The process of obtaining the dual electric equivalent circuits from flux paths is presented in [27]. The PI-model can also be related to the T-model (STC) when internal construction information is not available.

To establish a topological electrical equivalent circuit of a transformer, it is first needed to discretize the transformer magnetic circuit as shown in Figure 2-13 for the three-legged core case with three windings per core leg. A possible electric equivalent circuit version is shown in Figure 2-14 (see [20]). In this circuit, nonlinear inductances correspond to iron flux paths in the magnetic circuit. Each core limb is modeled individually. A detailed description of circuit parameters can be found in [20]. The inductors L_k represent the pair of top and bottom horizontal yokes, and each L_b represents a wound limb. The inductors L_0 represent the return flux path through air, outside the core, and around the windings. In the three-limb case, the return path includes the transformer tank, whereas in the five-limb it is mostly confined to the outer limbs. The inductors located between L_0 and L_b on each phase are used to model winding leakages through air. An interface between leakage flux and magnetizing flux is established through the internal nodes α and β. Typical values for L_h , L_x and L_y can be found in [12]. These inductors account for unequal flux linkage among winding turns.

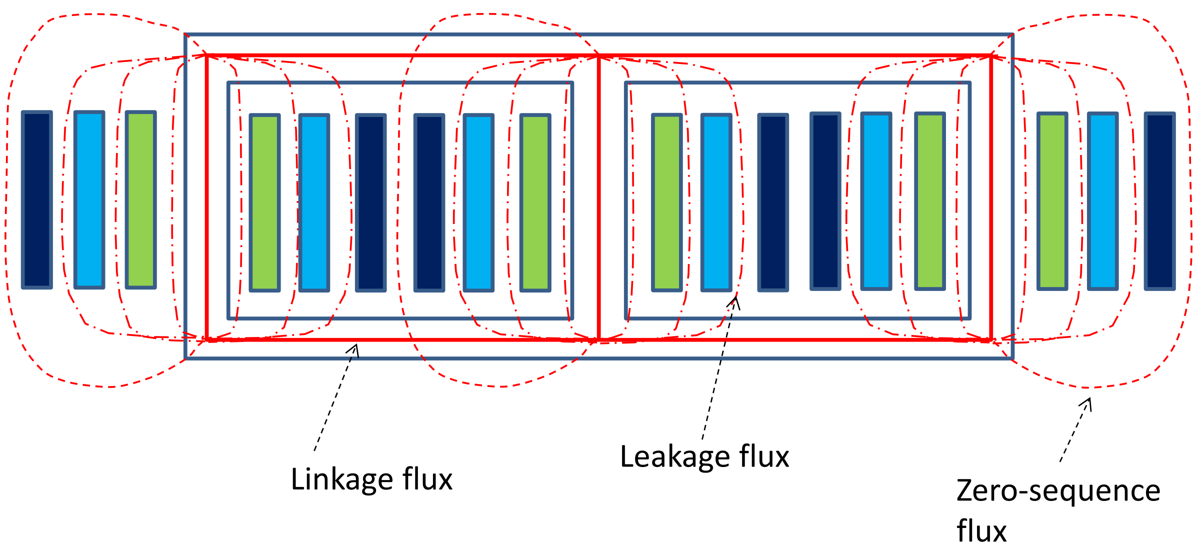

Figure 2-13
Discretized Flux Paths for a Three-Legged Core-Form Transformer

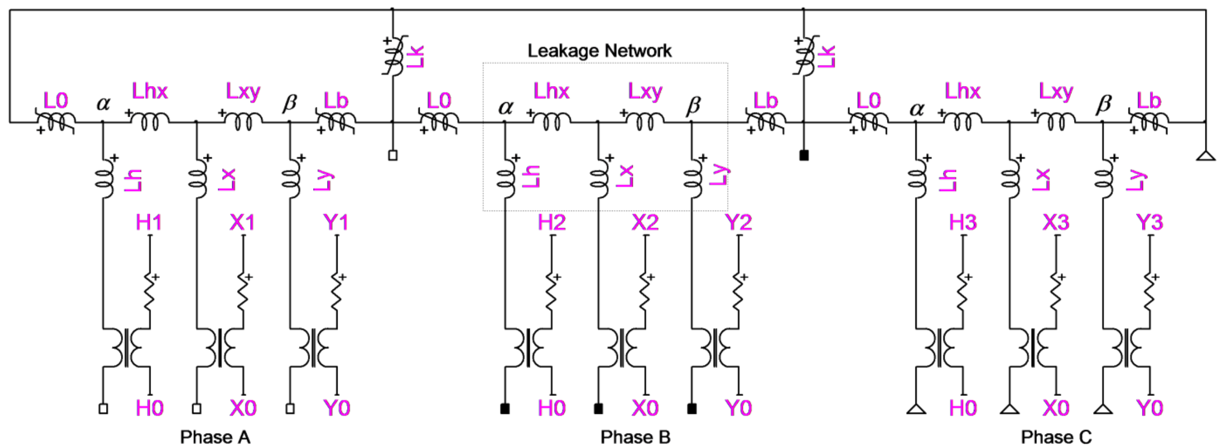

Figure 2-14
Electric Equivalent Circuit for Magnetic Coupling for a Three-Legged Core-Form Transformer

Ideal transformers link the leakage network with the topological core model. These transformers provide topological isolation from the electrical network, permit arbitrary winding connections, and provide the incorporation of windings turns ratio.

The inductors L_k and L_b are typically much larger than the remaining inductors. L_h and L_y are negligible. A schematic representation of the model is given in Figure 2-15. This model is used in the TOPMAG data calculation function of EMTP-RV.

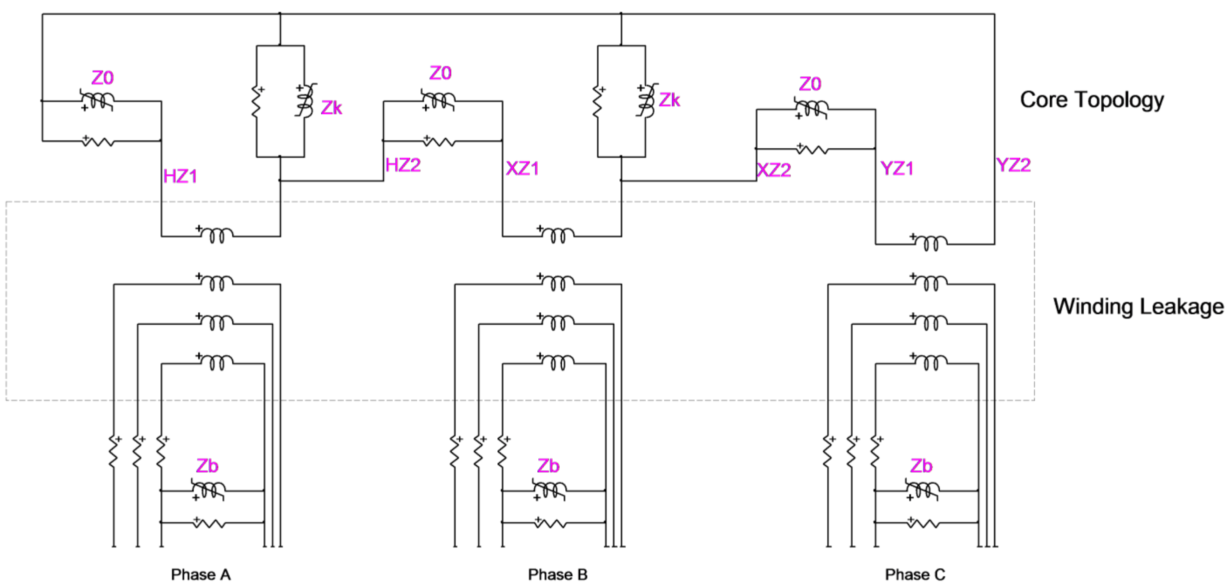

Figure 2-15
Schematic Representation of a Three-Phase and Three-Winding Core-Form Transformer (TOPMAG Model)

Another approach to the same problem is presented in Figure 2-16. The corresponding electric circuit is shown in Figure 2-17. In Figure 2-16, ℜ represents reluctance and ℑ stands for magnetomotive force. Further details on these schematics can be found in [77].

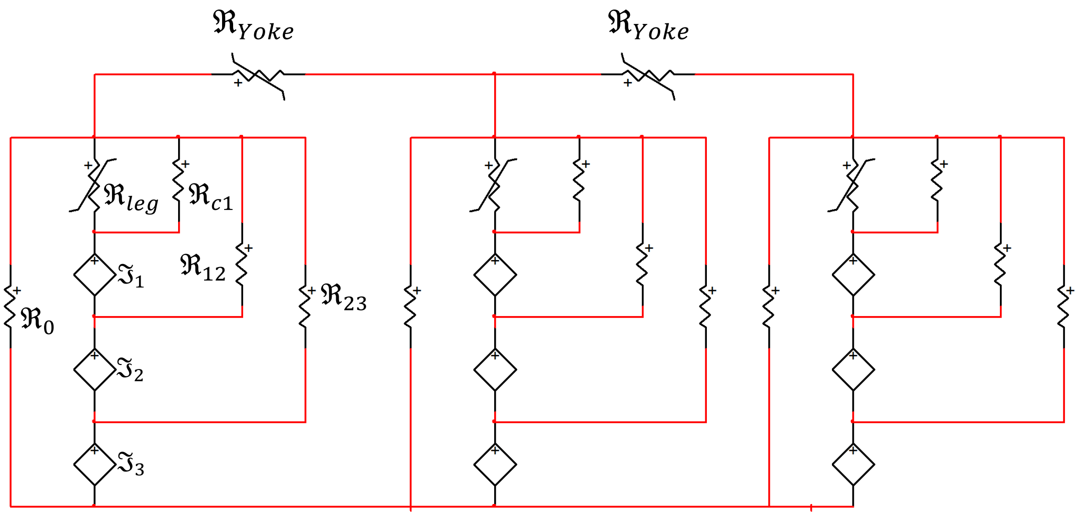

Figure 2-16
Equivalent Magnetic Circuit for Figure 2-13

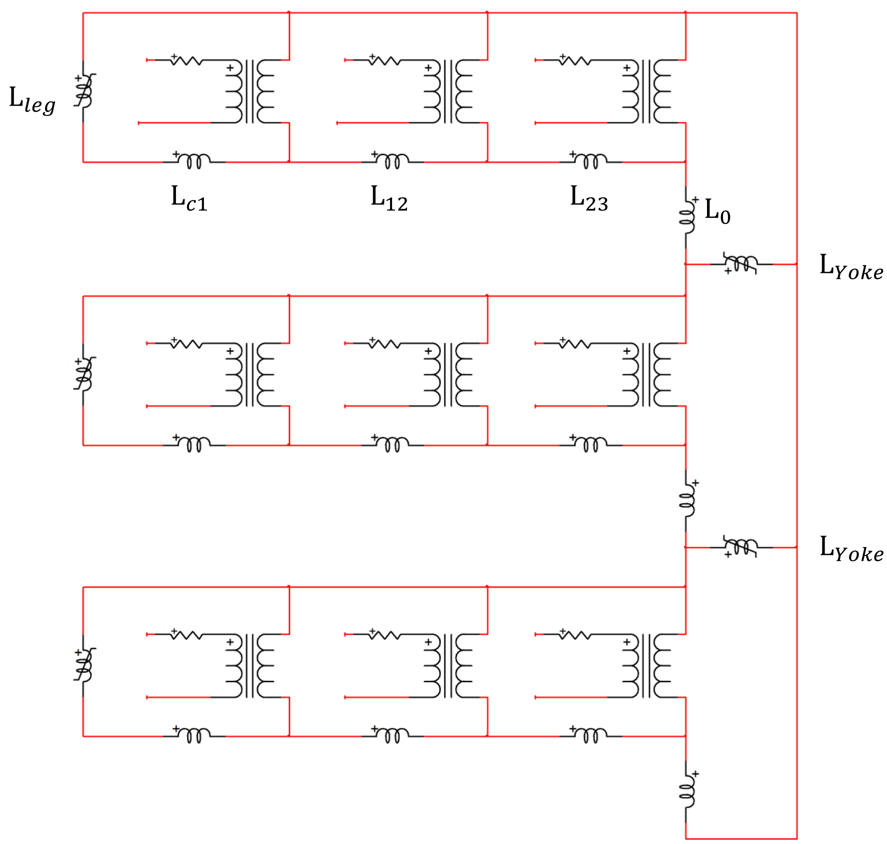

Figure 2-17
Equivalent Electric Circuit Resulting from Duality Transformation of Figure 2-16

Duality-derived equivalents for three-phase (two-windings) and three-legged stacked core (three- and five-legged) transformers are presented in [13] and [27]. The models based on duality for three-phase and three-winding transformers for the core- and shell-form cases are also discussed in [13] and [28].

Geometric Models

The geometric models are based on the generic formulation:

$$\mathbf{v} = \mathbf{R}\,\mathbf{i} + \frac{d}{dt}\boldsymbol{\varphi} \qquad \textbf{Eq. 2-4}$$

where $\boldsymbol{\varphi}$ is the vector of flux linkages. This approach also considers core topology, but the solution passes through a mathematical formulation and not a circuit-based representation. The list of such models includes [29]-[38].

Duality-Based Model: Dick-Watson

This duality-based model was created for three-winding, three-phase, core-form (three-leg stacked core) transformers [12]. This model is based on the calculation of transformer parameters from measurements. Inductance values are calculated from short-circuit tests. A new hysteresis model is also proposed. The flux paths used in this model are questionable.

This model is not implemented in industrial-grade, EMT-type simulation software.

Duality-Based Model: Arturi

This model [39] was developed to simulate a five-legged, three-phase transformer in highly saturated conditions. One of the objectives was to study mechanical stresses on windings during energization to see if the model produces higher accuracy compared to classical models. The same approach was also used for the case of an autotransformer.

The nonlinear inductances of this model are found from $B(H)$ curves of core material using geometrical dimensions. The modeling approach is not generalized. The $B(H)$ curves are only related to ferromagnetic material and do not account for the transformer magnetic circuit topology (internal gaps).

This model is not implemented in industrial-grade, EMT-type simulation software.

Duality-Based Model: de Leon-Semlyen

This model is presented initially in [14] and then in [41]-[43]. The model developed for a three-phase, three-legged core is very detailed for low-frequency transients. In this model, winding and core losses are frequency dependent. De Leon–Semlyen uses a Foster equivalent circuit to model frequency dependence in windings and a Cauer equivalent circuit for the core. The details on fitting procedures for the parameters of equivalent circuits are found in [14] and [43].

This model also includes winding capacitances. Leakage inductances are calculated using the image method. For low-frequency transients, the leakage inductances and winding capacitances are reduced to an equivalent.

According to [22], this model is very accurate for low-frequency and mid-frequency applications, but the determination of its parameters is complicated. Transformer manufacturers do not generally provide the frequency response required for the derivation of Foster and Cauer networks. Additionally, detailed geometrical data is required for the calculation of leakage inductances. The model does not include hysteresis effects, and the idea of including them with saturation in the Cauer equivalent circuit for core laminations [44] appears complicated. In [45], the duality principle is used to derive the eddy current phenomena in the windings of a coil using the Cauer model.

This model is not currently implemented in industrial-grade, EMT-type simulation software.

Duality-Based Model: TOPMAG

This model [20] was the first to use separate leakage inductances and core representation. The circuit derived from duality is shown in Figure 2-14. The BCTRAN approach is used to calculate separate leakage impedances from the core.

TOPMAG accommodates three-phase, five-limbed units and three-phase, three-limbed units. The leakage model permits arbitrary winding arrangements with proper short-circuit tests. One limitation in the formulation for three-limbed units is that it cannot accommodate short-circuit tests with more than one closed delta winding [20].

A table in [20] compares BCTRAN and TRELEG to TOPMAG for a three-phase, three-limb transformer case. Only zero-sequence, short-circuit impedance predictions are compared against measurements because positive-sequence results are almost identical with all models. The following conclusions are derived in [20] and [21] for three-limb transformers:

- BCTRAN does not properly recognize the role of zero-sequence magnetizing impedance in short-circuit tests, which may result into lower leakage impedances.
- BCTRAN does not always account for the fact that zero-sequence tests are not reciprocal. TRELEG can accommodate test data correctly.
- Greater differences are predicted for multi-legged designs not equipped with delta windings, as well as studies requiring more rigorous accommodations of core non-linearities and core losses.

In many cases, it is still possible to improve the accuracy of BCTRAN against available measurements by manipulating the zero-sequence test parameters. Equation (3) can be used to compensate for the lack of current zero-sequence excitation data. Appropriate placement of the nonlinear saturation (or hysteresis) branch in the BCTRAN model can allow deriving sufficiently accurate results for energization and harmonic studies.

The current version of TOPMAG cannot handle shell-form transformers. The topological formulation for shell-form units is important for GIC studies because they are vulnerable to core saturation in the presence of zero-sequence currents.

A major difficulty in TOPMAG is calculating the nonlinear inductances in Z_0 and Z_k (see Figure 2-15). There are no support routines or clearly defined methods for obtaining these inductances. Additionally, many assumptions made for the TOPMAG code remain to be clarified.

The TOPMAG setup in EMTP-RV uses the standard input of data for excitation tests (positive-sequence and zero-sequence excitation tests) and in the short-circuit test data in Figure 2-18. Default values are used for geometrical data. The duality winding connection points (example) are shown in Figure 2-14. The calculated default duality winding data is only linear.

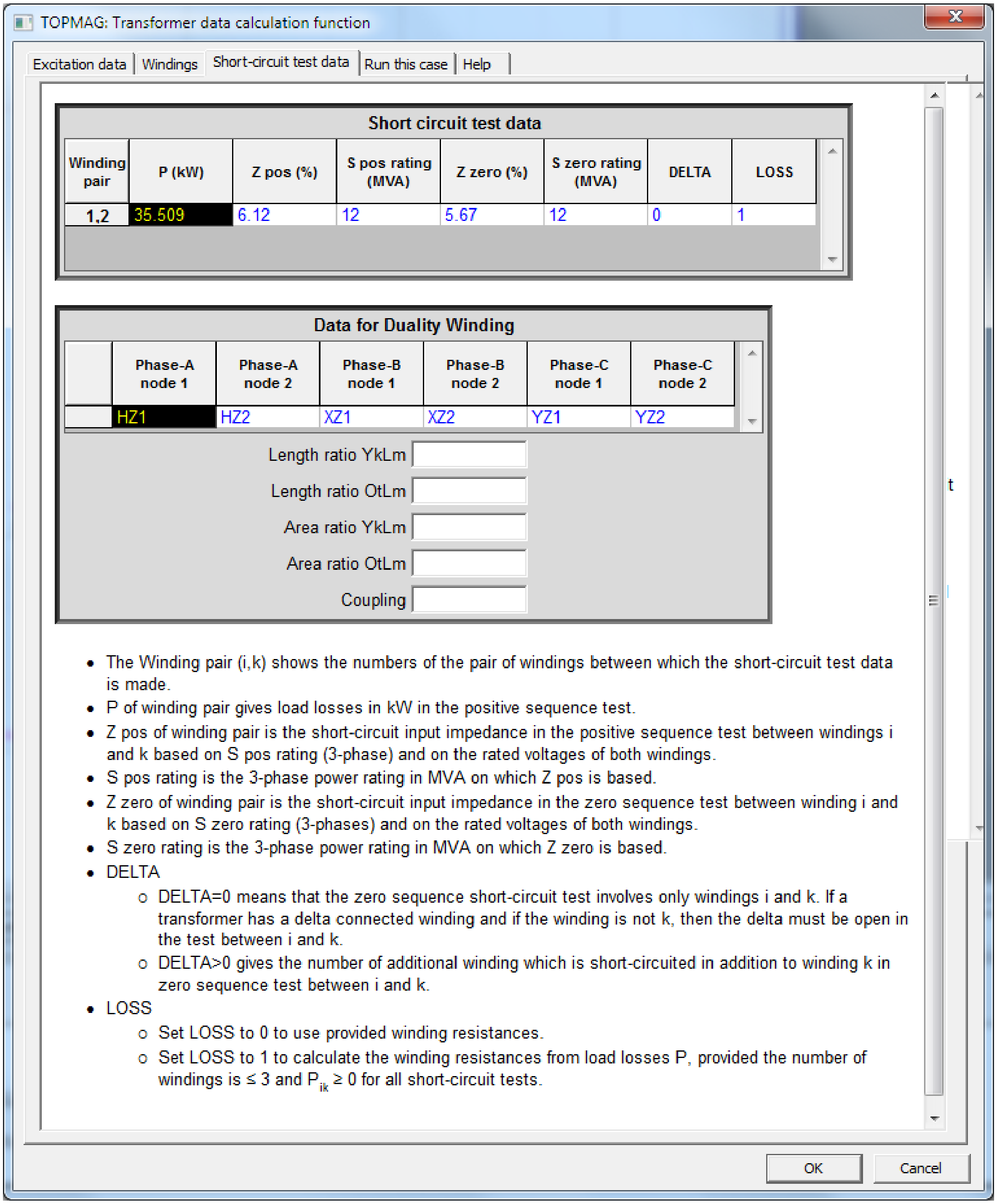

Figure 2-18
Short-Circuit Test Data for TOPMAG Module in EMTP-RV

In EMTP-RV, it is also possible to use an eddy current data calculation function [21] for insertion into the model duality winding nodes. The data requirements of this function are complicated.

Topological Mode UMEC

Instead of duality, the UMEC model uses the Hopkinson analogy (geometrical approach) [46] and [47] (see also example in [48]). The UMEC model was first presented in [49] and then in subsequent papers [33], [49], and [50]. This model was developed to replace classical modeling approaches used in EMTDC.

UMEC uses the normalized core, where only the relative dimensions of the core are needed (e.g., the ratio between yoke and limb lengths), instead of using absolute values. To avoid interfacing problems with electric circuits, the model is reduced to a multi-port Norton equivalent. This is where the researchers compute the admittances and current sources from magnetic circuit equations linearized at the operating point in time-domain.

UMEC uses the Hopkinson analogy to represent the magnetic circuit, which eliminates the duality approach's requirement for a planar magnetic circuit. However, in the derivation of the flux paths, as well as in the magnetic circuits for the three- and five-legged transformers, the windings are considered separated from one another when they should be concentric (for the cylindrical winding case). This separation is similar to the approach used to divide the leakage flux for the single-phase two-winding model. According to [11], the separation of leakage flux is not valid for three-phase transformers.

It is demonstrated in [52]-[54] that this model does not give good results.

Duality-Based Model: Hybrid

The hybrid transformer model [55] implemented in ATP (www.emtp.org) combines the leakage inductance matrix with a duality-based topologically correct representation of the core. It assumes that the leakage inductances are much smaller than the core inductances and can be separated into two distinct blocks. The idea is similar to TOPMAG, but the equivalent core circuit is not the same (see Fig. 7 in [55]). This model was initially developed for a five-legged transformer [48] based on initial work presented in [56]. The model has been extended to three-legged and shell-form transformers. The details can be found in [55]. Benchmark and laboratory measurements are also available in [57]. Related material on model development and testing can be found in [58]-[65]. Work on parameter estimation is available in [66].

The saturation curves (nonlinear inductances) of this model are based on [67] and [68]. The case of delta-connected transformers is accounted for in [69]. The saturation curves are related to core dimensions and can be accurately calculated from available measurements. Further details on parameter estimation procedures can be found in [52] and [53]. It is possible to estimate parameters from typical data, from test reports, or from geometrical data.

The leakage reactance calculation in this model can be based on winding geometry (see [66] and [70]-[72]) using a classical approach. Windings of unequal heights can be accommodated using an average value of heights [73]. However, this approach creates considerable error when the coils are of different heights and located far from the core [14]. This is due to the fact that radial and axial fluxes are neglected. Recent research at the École Polytechnique de Montréal validates this finding with a finite-element method for a 360-MVA, shell-form, single-phase, two-winding transformer.

This model is superior to TOPMAG because it offers flexibility in the type of input data and provides functional procedures for derivation of parameters. On the other hand, [74] argues that the separation of leakage inductances from the core model is valid when the core is not saturated and will yield wrong results in heavy saturation.

Hysteresis was included in [75] using the hysteresis modeling approach presented in [76]. This hysteresis model is also referred to as the Type-96 model due to its reference in initial EMTP codes.

Duality-Based Model: Chiesa

The model proposed in [74], [77], and [78] attempts to improve the saturation effects in the hybrid model. Publication [74] explains that the lumping of leakage inductances outside the core model would result into inaccuracies for heavy saturation during transformer energization studies or GIC studies. The hybrid (also called XFMR) transformer model encounters limitations at extreme saturation and for the representation of the hysteretic behavior of the core.

This model is derived from the magnetic equivalent circuit using duality and without separating the leakage inductances from the core equivalent circuit. It is similar to the hybrid transformer model, except for the core's nonlinear inductors which include the hysteresis phenomenon modeling by using a modified Jiles-Atherton model detailed in [79] and [80]. As explained in [81], a crucial element of the transformer model for transient analysis is the representation of the core. The modeling of nonlinear hysteretic inductors is required to accurately represent the transformer core.

In this model, the leakage flux had to be neglected to derive the scalar magnetic equations. It does not make this model more topologically valid than the hybrid model. More work is required to study the improvements proposed by this model. It is not implemented in industrial-grade, EMT-type simulation software.

Several transformer models (STC, BCTRAN, UMEC, and hybrid) are compared in [54] for inrush current prediction accuracy in a three-phase, shell-form transformer. The evaluation is based on field measurements for a 96-MVA transformer. The transformer is energized from its primary 400-kV Y-grounded winding. The secondary side consists of three 6.8-kV delta-coupled windings. The STC and BCTRAN models are able to reproduce correctly the first peak on one of the phases, but they fail to reproduce the other phases and overall shapes. In the case of UMEC, significant errors occur if its data is not conditioned. As a result, the hybrid model is the most accurate and can match both the inrush current and waveform shape in the first periods of simulation.

None of the models (including hybrid) studied in [54] are able to match the current decay of measurements. Further research is needed to improve this aspect through better loss modeling. A potential solution to this problem is to use frequency-dependent winding resistances to represent accurate topological losses.

Eddy Current Losses

The changes in magnetic flux flows are the causes of hysteresis and eddy losses. Hysteresis loss happens due to the cyclic reversal of flux in the magnetic circuit. Eddy losses in the steel are caused by currents induced by the flow of magnetic flux in a conducting material.

In steady-state conditions, eddy currents produce losses, but they can have a contributing damping effect during transients.

Series winding losses are frequency dependent [27]. Winding resistances can be adjusted for accuracy by including eddy currents in windings, skin effect, and stray losses. A formula for the ac resistance of windings is given in [82].

A Foster equivalent can be used to accurately model winding resistance and leakage inductance as a function of frequency [27]. This equivalent can be derived from frequency response tests.

The excitation losses obtained from excitation tests are iron-core losses, because the I^2R losses are relatively small for low excitation current values. An approximate linear representation for iron-core losses can be obtained using a shunt resistance R_m as in Figure 2-5. Eddy current losses are proportional to the square of magnetic flux and frequency. Frequency-dependent eddy current representation is proposed in [83]. In this case, R_m is replaced by a number of parallel RL branches.

Models based on Foster or Cauer equivalent circuits are proposed in [43] and [82]. Other frequency-dependent eddy current models for magnetization impedance can be found in [84] and [85].

A complete literature review on eddy currents is presented in [27].

The stray losses [7] are a term given to additional losses in the transformer. They include winding eddy losses and losses due to the effects of leakage flux entering internal metallic structures.

Representation of Transformer Magnetization

Transformer magnetization aspects have been discussed as part of transformer models. Further details are covered in this section.

Magnetization (hysteresis and saturation) is a key aspect in the analysis of GIC effects on transformers. During a GIC event, DC current flows into transformer windings and results into severe half-cycle saturation. As a consequence, the transformer draws a large asymmetrical exciting current, resulting in increased reactive power consumption and significant harmonic levels. The harmonic currents and extent of saturation depend on the magnetic core. This means that GIC studies must include accurate representation of magnetizing characteristics of transformers.

Hydro-Québec in Québec (Canada) has contributed several papers on the effects of DC currents in power transformers. GIC observations and studies on the Hydro-Québec system are presented in [4]. The saturation time of transformers under DC excitation is discussed in [86]. The objective is to define the time taken by a transformer to saturate due to DC bias. A simple nonlinear inductance model is used to study the envelope of magnetizing current as a function of time. Related studies are presented in [87]-[91] (see other references in [86]).

EMT-type tools usually provide a hysteretic loop function and a magnetizing curve function of flux-current crossing zero. These functions are in time-domain. As explained earlier for the STC model, basic flux-current data can be calculated from manufacturer measurements. In most cases, the manufacturer provides RMS-voltage versus RMS-current characteristics, which can be converted into a flux-current function in time-domain. The nonlinear flux-current function can be represented as a piecewise nonlinear function and solved within surrounding network equations. It is essential to apply a simultaneous nonlinear solution method to achieve accurate simulations. EMTP-RV, for example, is capable of solving all nonlinear devices simultaneously with network equations.

The representation of hysteresis loops is important to account for losses and remanence. There are numerous methods in the literature for modeling ferromagnetic hysteresis loops. Useful bibliographic reviews are presented in [22], [92] and [93]. The models are based on curve fitting without particular considerations on underlying physics. The most accurate models are macroscopic models. The classical magnetization models are [93]: Stoner-Wolhfarth, Jiles-Atherton (JA), Globus and Preisach. The JA and Preisach models are preferred [81] for their capability to model minor loops and de-energization. They can estimate the remanent magnetization.

The JA model has been preferred mainly because the model parameters can be calculated with fitting procedures [79] and [94] (without specific measurements). The Preisach model is preferred if measurements are available. Detailed implementation and analysis of the Preisach model in EMT-type tools is presented in [95]-[98].

The model presented in [76] (fitting based, Type-96) is often used in many EMT-type tools. A modified version of this model is also available in EMTP-RV. Its advantage is the simple data input, but it is considered as less accurate (see analysis in [98]). Some limitations of the original Type-96 model have been eliminated in its recent implementation in EMTP-RV. It remains to be studied in the context of GIC applications. Publication [75] (hybrid model) also reports that it uses the hysteresis modeling method of Type-96 for the topological transformer model.

A hysteretic reactor model implementation based on [12],[21] is presented in [99]. Another fitting approach based model is presented in [100]. These models are currently available in EMTP-RV. These models rely on measurements of the magnetization characteristic.

In [54], the magnetization curve is fitted to a modified Frolich equation [75]. The accurate estimation of the final slope in saturation has a significant impact on the accuracy of inrush current estimation.

A contribution directly related to GIC studies with the JA model is presented in [80]. In this model, the JA-based hysteresis model is extended to include eddy current losses. The simulation of a single-phase, two-winding transformer is validated with measurements.

A simplified method based on equivalent magnetizing curve is used in [101] (see also [102]) to estimate harmonic currents and reactive power consumption. The proposed method is based on the transformer's nameplate and core design. Presented simulation results are validated with field measurements [103],[104], and [105]. Unfortunately, it is impossible to reproduce and verify the results presented in [101] due to the paper's lack of data.

Different magnetization curves are proposed in [101] to characterize the performance of three-phase, shell-form transformers; three-phase, three-legged core transformers; and three-phase, five-legged core transformers. The derived graphs show the relationship between exciting current harmonics and GIC for different core designs. The variation of reactive power consumption as a function of GIC is also presented.

The idea of [101] is based on the fact that duality-based or FEM-based transformer models are accurate but complicated and require detailed design data and measurements that are generally not available. That is why it's a practical and realistic approach to estimate harmonic currents and reactive power consumption from transformer nameplate data. Simplified modeling formulas are used from basic nameplate data: rated voltage, rated power, winding voltages, core configuration and typical excitation current percentage. Unfortunately there is insufficient data in this paper to reproduce the various findings.

The characterization of current harmonics caused by GIC is presented in [106]. This document presents several analysis results for single-phase and three-phase transformers. Some of the conclusions provided in [106] are summarized below.

For the single-phase transformer case, normalization of GIC on a rated phase-current basis is more satisfactory than on a multiple-of-exciting current basis. The paper suggests applying rated-current basis for the generic curves relating GIC effects to a per-unit GIC magnitude for design variations using a particular core configuration.

Air-core reactance is the slope of the saturation curve in the fully saturated region of the transformer. It is a function of winding geometry (between 0.3 to 0.8 pu approximately). Figure 5 in [106] presents the impact of the magnitude of air-core reactance on flux offset.

Offset saturation results in substantial fundamental frequency exciting current in phase with flux and 90° phase lag with voltage. This current acts as reactive load. In [106] reactive power at a given GIC magnitude is directly proportional to AC voltage.

The exciting current of transformers saturated by GIC contains even and odd harmonic orders. The magnitude decreases with increasing harmonic order. The harmonic magnitude versus GIC characteristics are sensitive to the transformer winding air-core reactance.

GIC saturates transformers, and its harmonic current component phase angles are directly related to the fundamental voltage phase [106]. This means that when harmonics propagate into the network, they tend to constructively and destructively interfere at various system locations. It is necessary to perform system-wide analysis of harmonics during GIC disturbances [106].

In the case of three-phase transformers [106], the magnetic circuit behavior when submitted to GIC, becomes more complicated. A three-phase shell-form transformer saturation affects two phases at one time. In a five-leg core-form transformer, the yokes interconnecting the main legs and the outer legs saturate during GIC and create complicated magnetic interaction between the phases. In a three-leg core-form transformer, the zero-sequence flux returns outside of the core. Due to related low permeance, a given amount of GIC creates a relatively small amount of zero-sequence DC flux. This means that a large amount of GIC is required to saturate the main-leg fluxes [107].

Saturation of three-leg transformers [108] should consider the transformer structural members that can supply sufficient return path permeance to allow main leg saturation. This aspect requires further investigation.

Flux offset versus GIC curves for shell-form and five-leg core-form transformers is presented in [106]. Negative- and zero-sequence fundamental frequency exciting current components are also analyzed in [106] for shell-form and five-leg core-form transformers.

The approach used to generate results in [106] is based on lumped magnetic circuit models. This resembles the duality approach with some simplifications. Time-domain constant flux sources (DC flux component superimposed on the fundamental frequency AC flux) represent the windings, and linear/nonlinear reluctance branches model the magnetic circuit. The reluctances are estimated from transformer physical characteristics. The presented models include single-phase, three-phase five-leg core-form and three-phase shell-form transformers. Unfortunately, there is not enough data in [106] to reproduce the models and simulation results.

3 CONCLUSIONS

This report presents a literature survey on transformer models for the simulation and analysis of electromagnetic transients. The targeted frequency range includes low and mid-frequency transients. The transformer models are suitable for studying GIC impact on power systems with numerical methods used in electromagnetic transients type (EMT-type) simulation tools. The presented transformer model types include divided leakage flux, matrix representation, and topological models.

In theory the most accurate models are the topological models. Most topological models are based on the duality principle that allows deriving an electrical circuit equivalent from magnetic equations. An important issue in these models remains the inclusion of leakage flux. The leakage flux representation problem is the source of numerous topological model variants in the literature.

Although some of the duality-based models are considered to be accurate in the literature, there is no clear consensus supported by validation and manufacturer tests for verifying the underlying modeling assumptions.

Sophisticated duality based models have complicated data input requirements. Such data is not available in most cases. Although some modeling approaches are capable of substituting for the lack of data and offer various alternatives, the level of accuracy remains related to the availability of measurements and transformer design details.

A key aspect in GIC is the modeling of transformer magnetization. Nonlinear inductances with or without hysteresis effects are used for this aspect. The topological models may provide inaccurate results in saturation, and further research is needed in this aspect.

Proposed future work is to deliver templates with simplified models for the most common transformer design types using basic nameplate data. It must be assumed that detailed design data and measurements are not available in most practical cases. In addition to topological models, the authors also propose to conduct research on simplified models using available magnetization characteristic and short-circuit tests. The developed models should provide transformer performance analysis with sensitivity to parameters for GIC applications.

Finally, there is an urgent need to work with transformer manufacturers to gather significant amounts of data and develop models that the industry can confidently use for typical transformer types.

4
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