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parameter determination

procedures for modeling system transients

POWER SYSTEM TRANSIENT analysis is usually performed using computer simulation packages like the electromagnetic transients program (EMTP). Scaled modeling using transient network analyzers (TNAs) is still done but decreasingly so as computer simulation models have become significantly more precise and efficient in the last decade. In several modeling applications, computer-based simulation is actually much more precise than TNA. There is also a family of tools based on computerized real-time simulations, which are normally used for testing real control system components or devices such as relays. Although there are several common links, this "Techtorial" column targets only nonreal-time simulations.

Engineers and researchers who perform transient simulations typically spend only a small amount of their total project time actually running the simulations. The bulk of their time is spent obtaining parameters for component models, benchmarking the component models to confirm proper behaviors, constructing the overall system model, and benchmarking the overall system model to verify overall behavior.

Only after the component models and the overall system representation have been verified can one confidently proceed to run meaningful simulations. This is an iterative process. If there are some transient event records to compare against, more model benchmarking and adjustment may be required.

This column deals with parameter determination and is aimed at reviewing the procedures to be performed for deriving the mathematical representation data of the most important power components in electromagnetic transient simulations. It presents a conveniently arranged summary on the current status and practice in this field and emphasizes needed improvements for alleviating and augmenting the precision of modeling tasks in detailed transient analysis.

Figure 1 shows a flowchart of the procedure suggested for obtaining the complete representation of a power component.

- ✔ First, choose the mathematical model.
- ✔ Second, collect the information that could be useful to determine the values of the parameters to be specified.
- ✔ Third, decide whether the available data are enough, or not enough, to derive all parameters.

Note that the procedure depicted in Figure 1 assumes that the values of the parameters to be specified in some mathematical descriptions are not necessarily readily available. Also, they must be deduced from other information using a data conversion procedure.

Modeling Guidelines

An accurate representation of a power component is essential for reliable

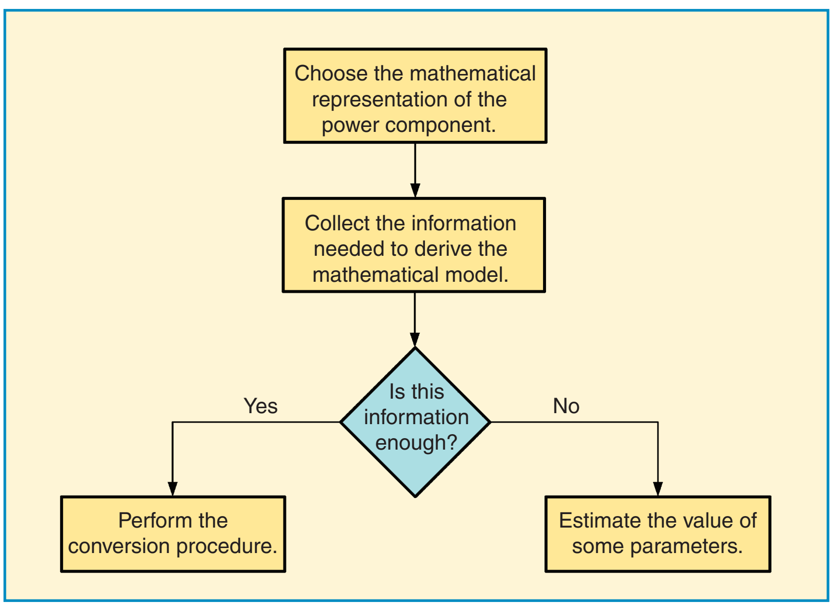

figure 1. The procedure to obtain a complete representation of a power component.

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table 1. Origin and frequency ranges of transients in power systems.

Origin	Frequency Range
Ferroresonance	0.1 Hz–1 kHz
Load rejection	0.1 Hz–3 kHz
Fault clearing	50 Hz–3 kHz
Line switching	50 Hz–20 kHz
Transient recovery voltages	50 Hz–100 kHz
Lightning overvoltages	10 kHz–3 MHz
Disconnector switching in GIS	100 kHz–50 MHz

transient analysis. The simulation of transient phenomena may require a representation of network components valid for a frequency range that varies from dc to several megahertz. Although the ultimate objective in research is to provide wideband models, an acceptable representation of each component throughout this frequency range is very difficult and for most components is not practically possible. In some cases, even if the wideband version is available, it may suffer from computational inefficiency or require more complex data.

The modeling of power components that take into account the frequency-dependence of parameters can be currently achieved through mathematical models accurate enough for a specific range of frequencies. Each range of frequencies usually corresponds to some particular transient phenomena. In one of the most accepted classifications, proposed by the International Electrotechnical Commission (IEC) and CIGRE, frequency ranges are classified into four groups: low-frequency oscillations (from 0.1 Hz–3 kHz), slow-front surges (from 50/60 Hz–20 kHz), fast-front surges (from 10 kHz–3 MHz), and very-fast-front surges (from 100 kHz–50 MHz). Note that there is overlap between frequency ranges.

If a representation is already available for each frequency, the selection of the model may suppose an iterative procedure: the model must be selected based on the frequency range of the transients to be simulated; however, the frequency ranges of the test case are not usually known before performing the simulation. This task can be alleviated by looking into widely accepted classification tables. Table 1 shows a list of common transient phenomena.

Several reports on modeling guidelines for time-domain digital simulations have been produced during the last few years.

- ✔ The document written by the CIGRE WG (Working Group) 33-02 covers the most important power components and proposes the representation of each component, taking into account the frequency range of the transient phenomena to be simulated.

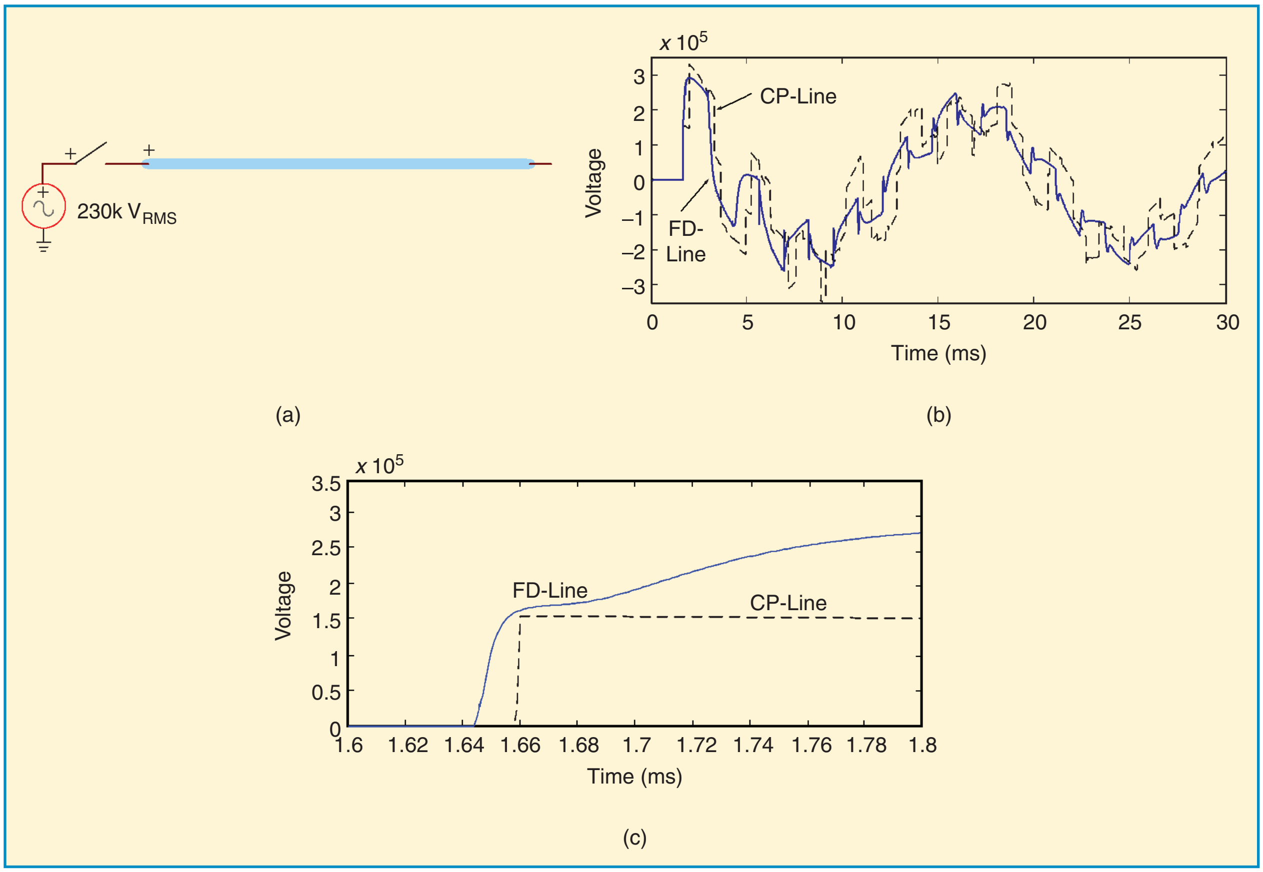

figure 2. Comparative modeling of lines: FD and CP models: (a) scheme of the test case: 230-kV line; (b) voltage at the end of the line; and (c) voltage at the end of the line (zoomed on the initial wave).

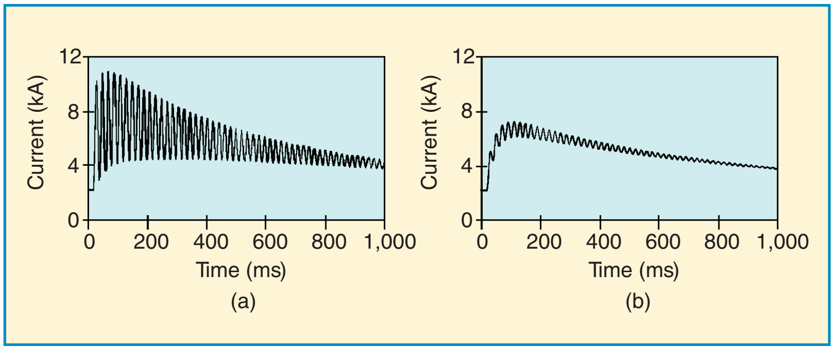

figure 3. Field winding current in a synchronous generator during a three-phase short-circuit: (a) the field current when coupling between the rotor d-axis circuits is assumed and (b) the field current when coupling between the rotor d-axis circuits is neglected.

- ✔ The documents produced by the IEEE WG on Modeling and Analysis of System Transients Using Digital Programs and its task forces present modeling guidelines for several particular types of studies.
- ✔ The fourth part of the IEC standard 60071 (TR 60071-4) provides modeling guidelines for insulation coordination studies when using numerical simulation, e.g., EMTP-like tools.

The simulation of a transient phenomenon implies not only the selection of the model to be implemented for calculations but the selection of the system area that must be represented and, in many instances, the method-deterministic/probabilistic to be used. The method selection is out of the scope of this column. Listed below are a few practical rules to be considered when selecting models and the system area in digital simulations of electromagnetic transients.

1) The system zone to be represented depends on the frequency range of the transients—the higher the frequencies, the smaller the zone modeled.
2) Irrespective of the transient phenomena to be reproduced, the user should try to optimize (i.e., minimize) the part of the system represented. Although modern applications allow representing very large networks through advanced graphical user interfaces, an increased number of components does not necessarily mean increased precision since there could be a higher probability of insufficient or wrong modeling. In addition, a very detailed representation of a system will usually require longer simulation time.
3) Losses are the most difficult modeling aspect. Although there are cases where losses do not play a critical role, since their effect on maximum voltages and oscillation frequencies is very limited,

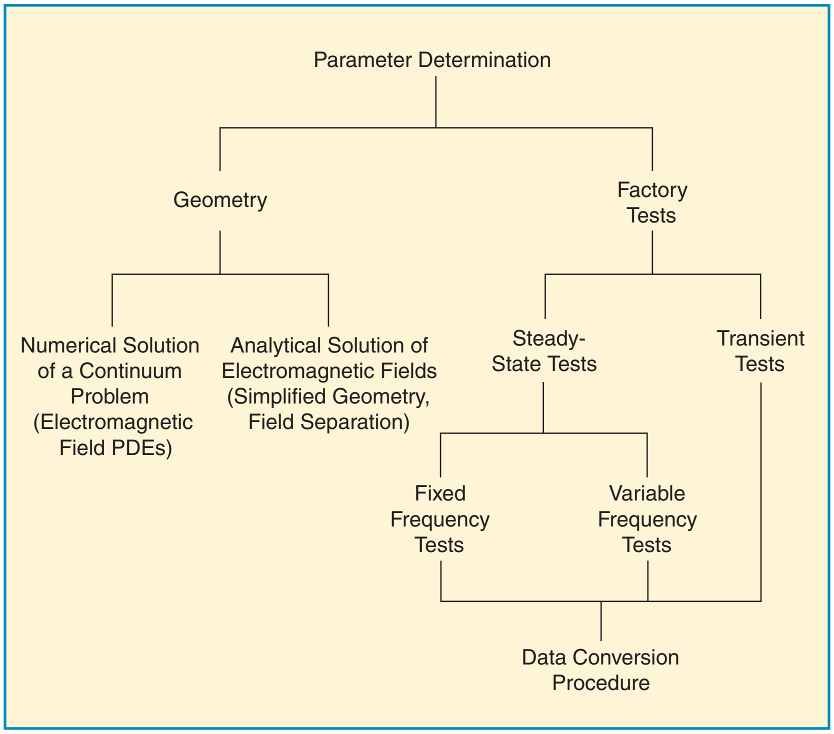

figure 4. The classification of methods for parameter determination.

there are other cases for which losses are critical in defining the magnitude of overvoltages. Cases where losses are particularly important include ferroresonance, dynamic overvoltage conditions involving harmonic resonance, and capacitor bank switching.

4) If the system to be simulated is too complex, a first approach based on an idealized representation of some components is recommended. Such representation will facilitate the edition of the data and simplify the analysis of simulation results.
5) If one or several parameters cannot be accurately determined, a sensitivity study could be very useful since the results derived from such an approach will show whether these parameters are of concern or their influence is of secondary importance.

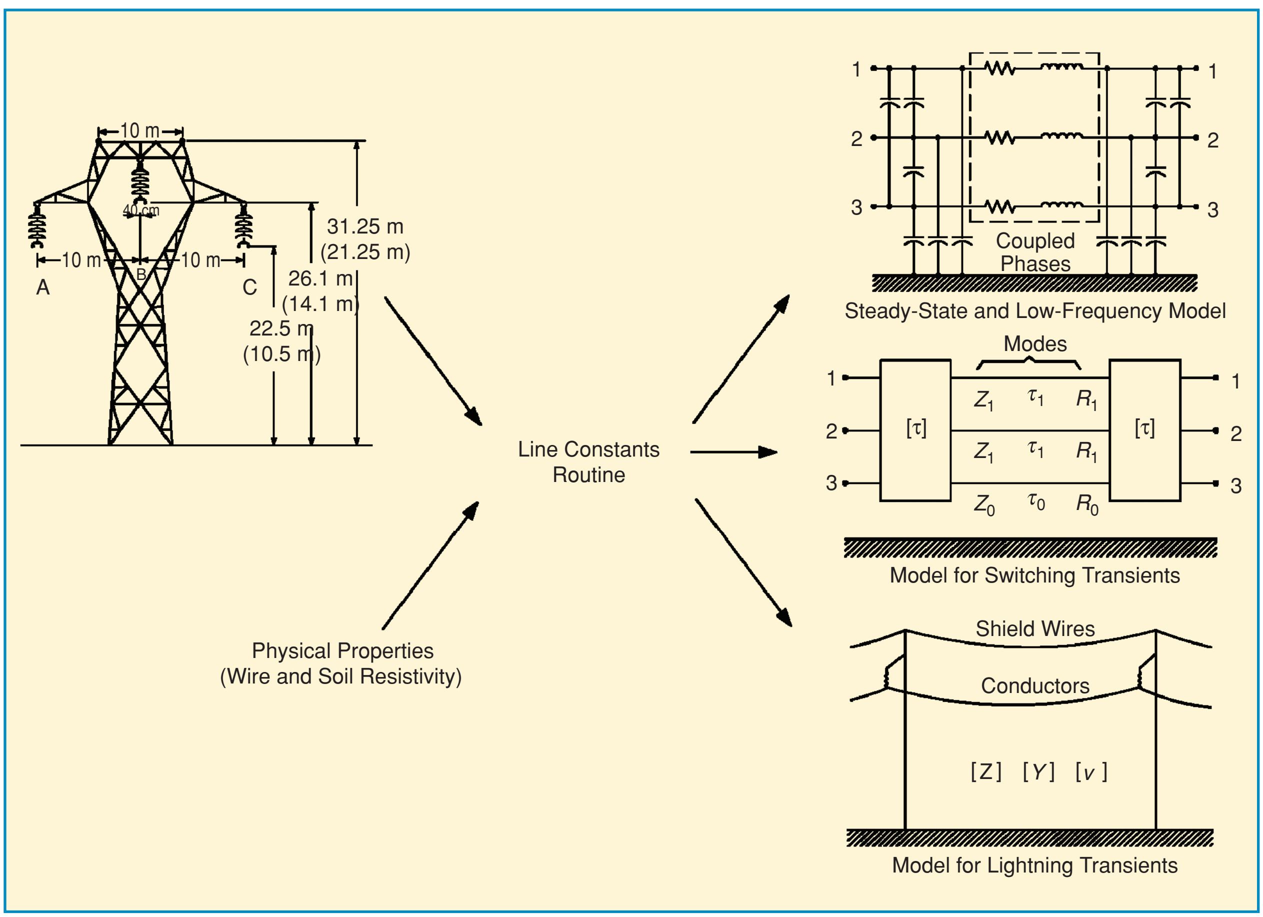

figure 5. The application of a line constants routine to obtain overhead line models.

Figure 2 shows a test case used for illustrating the differences between simulation results from two different line models: the constant parameter line (CP-line) and the frequency-dependent line (FD-line). The three-phase breaker is closed to energize the line. It is apparent that the CP-line has less damping and results in higher overvoltage. Zooming on the initial waveform appearing at the end of the line indicates that the more precise FD-line model has a higher propagation velocity.

Frequency-dependent modeling is essential in lightning studies. In breaker performance studies, since the breaker arc voltage excites all circuit frequencies, it is important to apply frequency-dependent models even for substation bus-bar sections where the breaker is studied.

Figure 3 shows the field current in a synchronous generator during a three-phase short circuit at the armature terminals obtained with two different models. The first model assumes a coupling between the two rotor circuits located on the *d*-axis (field and damping windings), while this coupling has been neglected in the simulation of the second case. Although the differences are important, both modeling approaches can be acceptable if the main goal is to obtain the short circuit current in the armature windings or the rotor angular velocity with respect to the synchronous velocity.

Parameter Determination

Given the different design and operation principles of the most important power components, various techniques can be used to analyze their behavior.

The following paragraphs discuss the effects that must be represented in mathematical models and the approaches that can be used to determine the parameters, without covering the determination of parameters needed to represent mechanical systems, control systems, or semiconductor models.

The mathematical model of the most important components of a power system (lines, cables, transformers, rotating machines, arresters, and breakers) must represent the effects of electromagnetic fields and losses.

- ✔ Electromagnetic field effects are, in general, represented using a circuit approach: magnetic field effects are represented by means of inductors and the coupling between them, while electric field effects are replaced by capacitors. In increased precision models, such as distributed parameter transmission lines, parameters cannot be lumped, and mathematical models are based on solving differential equations with matrix coupling.
- ✔ Losses can be caused in windings, cores, or insulations. Other sources of losses are corona in overhead lines or screens and sheaths in insulated cables. As for electromagnetic field effects, they are represented using a circuit approach. In many situations, losses cannot be separated from electromagnetic fields. Skin effect is caused by the magnetic field

constrained in windings and produces frequency-dependent winding losses; core losses depend on the peak magnetic flux and the frequency of this field; corona losses are caused when the electric field exceeds the inception corona voltage; and insulation losses are caused by the electric field and show an almost linear behavior. Approaches that can be used to represent losses would include: a resistor (with either linear or nonlinear behavior), a hysteresis cycle, or a combination of various types of circuit elements. More sophisticated loss models must include frequency dependence.

The parameters used to represent electromagnetic field effects and losses can be deduced using the following techniques:

- ✔ Techniques based on geometry, for instance, a numerical solution aimed at solving the partial-differential equations of the electromagnetic fields developed within the component and based on the finite element method (FEM), a numerical technique that can be used with most components. However, simpler techniques have been also developed, for example, an analytical solution based on a simplified geometry and on the separation of the electric and magnetic field being used for lines and cables. Factory measurements can be needed to obtain material properties (that is, resistivity, permeability, and permittivity), although these values very often can be obtained from standards or manufacturer catalogues. If the behavior of the component is assumed linear, permeabilities are approximated by that of the vacuum. If the behavior of the component is nonlinear (that is, ferromagnetic materials do saturate), factory tests can be used to obtain saturation curves/hysteresis cycles. However, factories rarely provide complete saturation data. Saturation curves are generally made by the calculation of the air-core impedance (saturated slope) and flux-axis intercept level. In some cases, tests are used to generate the early part of the curve before hard saturation.
- ✔ Factory tests, mainly with transformers and rotating machines. Tests developed with this purpose can be grouped as follows:
  - steady-state tests, which can be classified into two groups: fixed-frequency tests (no load and short-circuit tests are frequently used) and variable-frequency tests (frequency-response tests).
  - transient tests, e.g., those performed to obtain parameters of the equivalent electric circuits of a synchronous machine.

When parameter determination is based on factory tests (for example, a frequency-response test), a data conversion procedure can be required; that is, in many cases, parameters to be specified in a given model are not directly provided by factory measurements.

Figure 4 shows a flowchart on the parameter determination approach presented above.

Some common approaches followed to obtain the mathematical model for lines and synchronous machines when using time-domain simulation tools will clarify the above discussion.

Parameters and/or mathematical models needed for representing an overhead line in simulation packages are obtained by means of a "supporting function," which is available in most EMTP-like tools and can be named, for the sake of generality, as *line constants (LC) routine*. LC routine users must enter the physical parameters of the line and select the desired model. The following data must be input: (x, y) coordinates of each conductor and shield wire, bundle spacing and orientations, sag of phase conductors and shield wires, phase and circuit designation of each conductor, phase rotation at transposition structures, physical dimensions of each conductor, dc resistance of each conductor (including shield wires), and ground resistivity of the ground return path. Note that all the above information, except conductor resistances and ground resistivity, is from geometric line dimensions. The following models can be created: lumped-parameter equivalent or nominal pi-circuits, at the specified frequency; constant distributed-parameter model at the specified frequency; and frequency-dependent distributed parameter model, fitted for a given frequency range (see Figure 5). In addition, the following information usually becomes available: the capacitance or the susceptance matrix; the series impedance matrix; resistance, inductance, and capacitance per unit length for zero and positive sequences, at a given frequency or for the specified frequency range; surge impedance, attenuation, propagation velocity, and wavelength for zero and positive sequences, at a given frequency or for a specified frequency range. Line matrices can be provided for the system of physical conductors, the system of equivalent phase conductors, or with symmetrical components of the equivalent phase conductors. Note that the model created by the LC routine represents only phase conductors and, if required, shield wires, while in some simulations the representation of other parts is also needed. For instance, towers, insulators, grounding impedances, and, ultimately, corona models are needed when calculating lightning overvoltages in overhead transmission lines.

The conversion procedures that have been proposed for the determination of the electrical parameters to be specified in the equivalent circuits of a synchronous machine use data from several sources, for example, short-circuit tests or standstill frequency response (SSFR) tests. The diagram shown in Figure 6 illustrates the determination of the electrical parameters of a synchronous machine from SSFR tests. Low-voltage frequency-response tests at standstill are becoming a widely used alternative to short-circuit tests due to their advantages: they can be performed either in the factory or on site at a relatively low cost; equivalent circuits of high order can be derived, and the identification of field responses is possible. The equivalent circuits depicted in Figure 6 are valid for representing a synchronous machine in low-frequency transients, for example, transient stability studies; however, the information provided by SSFR tests can be also used to obtain more complex equivalent circuits.

There are two important exceptions worth mentioning: circuit breakers and arresters. The approaches usually followed for the determination of parameters to be specified in the most common models proposed for these two components are discussed below.

- ✔ The currently available approach for accurate analysis of a circuit

table 2. Some international standards.

Component	IEEE Standards	IEC Standards
Line	IEEE Std. 738-1993, "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors." IEEE Std. 1243-1997, "IEEE Guide for Improving the Lightning Performance of Transmission Lines." IEEE Std. 1410-1997, "IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines."	IEC 61089, "Round Wire Concentric Lay Overhead Electrical Stranded Conductors," 1991. IEC 61597, "Overhead Electrical Conductors—Calculation Methods for Stranded Bare Conductors," 1997.
Cable	IEEE Std. 575-1988, "IEEE Guide for the Application of Sheath-Bonding Methods for Single-Conductor Cables and the Calculation of Induced Voltages and Currents in Cable Sheaths." IEEE Std. 635-1989, "IEEE Guide for Selection and Design of Aluminum Sheaths for Power Cables." IEEE Std. 848-1996, "IEEE Standard Procedure for the Determination of the Ampacity Derating of Fire-Protected Cables." IEEE Std. 844-2000, "IEEE Recommended Practice for Electrical Impedance, Induction, and Skin Effect Heating of Pipelines and Vessels."	IEC 60141-X, "Tests on Oil-Filled and Gas-Pressure Cables and Their Accessories," 1980. IEC 60228, "Conductors of Insulated Cables," 2004. IEC 60287-X, "Electric Cables. Calculation of the Current Rating," 2001. IEC 60840, "Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 30 kV ($U_m = 36$ kV) up to 150 kV ($U_m = 170$ KV)—Test Methods and Requirements," 2004.
Transformer	IEEE Std. C57.12.00-2000, "IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers." IEEE Std. C57.12.01-1998, "IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid-Cast and/or Resin-Encapsulated Windings." IEEE Std. C57.12.90-1999, "IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers." IEEE Std. C57.12.91-2001, "IEEE Standard Test Code for Dry-Type Distribution and Power Transformers." IEEE Std. C57.123-2002, "IEEE Guide for Transformer Loss Measurement."	IEC 60076-X, "Power Transformers," 2004. IEC 60905, "Loading Guide for Dry-Type Power Transformers," 1987. IEC 60354, "Loading Guide for Oil-Immersed Power Transformers," 1991.
Rotating Machine	IEEE Std. 1110-1991, "IEEE Guide for Synchronous Generator Modeling Practices in Stability Studies." IEEE Std. 115-1995, "IEEE Guide: Test Procedures for Synchronous Machines." IEEE Std. 112-1996, "IEEE Guide: Test Procedure for Polyphase Induction Motors and Generators."	IEC 60034-4, "Rotating Electrical Machines–Part 4: Methods for Determining Synchronous Machine Quantities from Tests," 1985.
MO Surge Arrester	IEEE Std. C62.11-1999, "IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits (> 1 kV)." IEEE Std. C62.22-1997, "IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems."	IEC 60099-4, "Surge Arresters–Part 4: Metal-Oxide Surge Arresters without Gaps for A.C. Systems," 2004.
Circuit Breaker	IEEE Std. C37.04-1999, "IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers." IEEE Std. C37.09-1999, "IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis." IEEE Std. C37.081-1981, "IEEE Guide for Synthetic Fault Testing of AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis." IEEE Std. C37.083-1999, "IEEE Guide for Synthetic Capacitive Current Switching Tests of AC High-Voltage Circuit Breakers."	IEC 60427, "Synthetic Testing of High-Voltage Alternating Current Circuit-Breakers," 2000. IEC 60694, "Common Specifications for High-Voltage Switchgear and Controlgear Standards," 2002. IEC 61233, "High-Voltage Alternating Current Circuit-Breakers—Inductive Load Switching," 1994. IEC 61633, "High-Voltage Alternating Current Circuit-Breakers—Guide for Short Circuit and Switching Test Procedures for Metal-Enclosed and Dead Tank Circuit-Breakers," 1995.

breaker performance during fault clearing is based on using arc equations. Such black-box model equations are able to represent with sufficient precision the dynamic conductance of the arc and predict thermal reignition. Although some typical parameters are available in the literature, there are no readily accessible and general purpose methods for arc model parameter evaluation. In some study cases, it becomes compulsory to perform or require specific laboratory tests for establishing needed parameters. The detailed arc model is useful for predicting arc quenching and arc instability. When such a model becomes numerically unaffordable, approximate voltage-current functions can be used to calculate the breaker's arcing time. In the case of transient recovery voltage studies, a simple ideal switch model can be sufficient.

✔ The MO (metal-oxide) surge arrester is modeled using a set of nonlinear exponential equations. These equations can be found using a readily available fitting function. The original data is deduced from arrester geometry and manufacturer's data. Techniques based on factory measurements for determination of parameters also have been developed. A combination of arrester equations with inductances and resistances can be used to derive an accurate arrester model for both switching and lightning surges.

Factory tests are usually performed according to standards. However, the factory tests defined by standards often do not provide all of the data needed for transient modeling, and there are some cases for which no standard has been proposed to date. This is applicable to both transformers and rotating machines, although the most significant case is related to the representation of three-phase core transformers in low- and midfrequency transients. The simulation of the asymmetrical behavior that can be caused by some transients must be based on models for which no standard has been yet developed, although several tests have been proposed in the specialized literature. Agreement in the engineering community on modeling methods and required data standards should constitute an important thrust towards the establishment of standardized manufacturer tests.

Table 2 lists some international standards (IEEE and IEC) that can be useful to understand factory tests or guidelines for electromagnetic transient models, although some of them do not deal with any of these aspects.

Conclusions

The parameters to be specified in the models that are used in detailed simulations of transients can be derived from geometry or from factory tests or estimated from the values suggested in the literature.

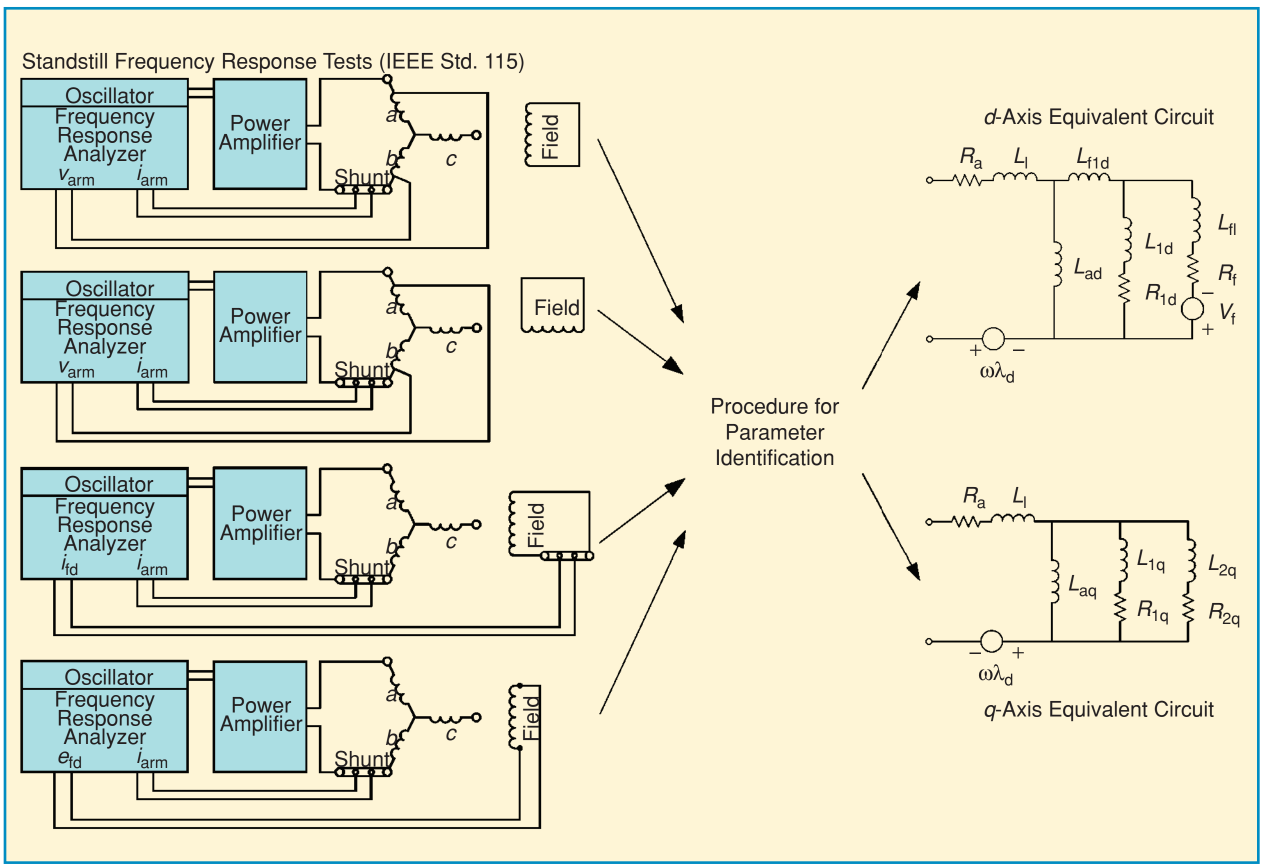

figure 6. The determination of the electrical parameters of a synchronous machine from SSFR tests.

The various approaches that can and often must be used to represent a power component, when considering transients with different frequency ranges, do not require a parameter specification with the same accuracy and detail. The literature on modeling guidelines can help users of transients tools choose the most adequate representation and can provide advice about the parameters that can be of paramount importance.

Present standards cannot solve all problems related to parameter determination. On the other hand, the increasing capabilities of software tools and computers are a challenge for standards developers since more sophisticated and rigorous models can be developed and implemented at lower costs. In many cases, the main limitation to estimate parameters is the lack of reliable tests and conversion procedures.

For Further Reading

"Guidelines for Representation of Network Elements when Calculating Transients," CIGRE WG 33.02, 1990.

A. Gole, J.A. Martinez, and A. Keri (Eds.), "Modeling and Analysis of Power System Transients Using Digital Programs," IEEE Special Publication TP-133-0, IEEE Catalog No. 99TP133-0, 1999.

"Insulation Co-ordination—Part 4: Computational Guide to Insulation Co-ordination and Modeling of Electrical Networks," IEC TR 60071-4, 2004.

Editor's note: The IEEE Power Engineering Society Task Force on Data for Modeling System Transients has prepared several papers on the subject of parameter determination for modeling system transients related to the most important power components (lines, cables, transformers, rotating machines, breakers, arresters, and semiconductors); these papers were published in the July 2005 issue of *IEEE Transactions on Power Delivery*.

Biographies

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Reigh A. Walling received his bachelor's and master's degrees in electric power engineering from Rensselaer Polytechnic Institute, New York, in 1974 and 1979, respectively. He is a principal consultant for GE Energy and is involved in a wide range of distribution, transmission, and generation technologies, including several decades of work in electromagnetic transient simulation. He is a Fellow of the IEEE. p&e