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Introduction to Electromagnetic Transient Analysis of Power Systems

Juan A. Martinez-Velasco

1.1 Overview

Electrical power systems are among the most complex, extensive and efficient systems designed to date. The goal of a power system is to generate, transport and distribute the electrical energy demanded by consumers in a safe and reliable way.

Power systems play a crucial role in modern society, and their operation is based on some specific principles. Since electricity cannot be stored in large quantities, the operation of the power system must achieve a permanent balance between its production in power stations and its consumption by loads in order to maintain frequency within narrow limits and ensure a reliable service.

Even when the power system is running under normal operation, loads are continually connected and disconnected, and some control actions are required to maintain voltage and frequency within limits. This means that the power system is never operating in a steady state. In addition, unscheduled disturbances can alter the normal operation of the power system, force a change in its configuration, cause failure of some power equipment or cause an interruption of service that can affect a significant percentage of the system demand, such as a blackout.

The analysis and simulation of electromagnetic transients has become a fundamental methodology for understanding the performance of power systems, determining power component ratings, explaining equipment failures or testing protection devices. The study of transients is a mature field that can be used in the design of modern power systems. Since the first steps in this field, a significant effort has been dedicated to the development of new techniques and more powerful software tools. Sophisticated models, complex solution techniques and powerful simulation tools have been developed to perform studies that are of paramount importance in the design of modern power systems. The first developments of transients tools were mostly aimed at calculating overvoltages. Presently, these tools are applied in a myriad of studies (e.g. FACTS and custom power applications, protective relay

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performance, power quality studies) for which detailed models and accurate solutions can be extremely important.

Transient phenomena in power systems are associated with disturbances caused by faults, switching operations, lightning strikes or load variations. These phenomena can stress and damage power equipment. The paramount importance of their study relates to the effects they can have on system performance or the failures they can cause to power equipment.

Two types of stress can be caused by transient phenomena in power systems: (1) overcurrents, which can damage power equipment due to excessive heat dissipation, and (2) overvoltages, which can cause insulation breakdown (failure through solid or liquid insulation) or flashovers (insulation failure through air). Protection against these stresses is therefore necessary. This protection can be provided by specialized equipment whose operation is aimed at either isolating the power system section where the disturbance has occurred (e.g. a power component failure that causes short-circuit) or limiting the stress across power equipment terminals (e.g. by installing a surge arrester that will mitigate voltage stresses). In addition, a better ability to handle stresses caused by transient phenomena can be also achieved through good design of power equipment (e.g. by shielding overhead transmission lines to limit flashovers caused by direct lightning strikes). That is, although the power system operates most of the time under normal operating conditions, its design must enable it to cope with the consequences of transient phenomena.

In order to provide adequate protection against both types of stresses, it is fundamental to know their origin, calculate their main characteristics and estimate the most adverse operating conditions. A rigorous and accurate analysis of transients in power systems is difficult due to the size of the system, the complexity of the interaction between power devices and the physical phenomena that need to be analysed. Presently, the study and simulation of transients in actual power systems is carried out with the aid of a computer.

Aspects that contribute to this complexity are the variety of causes, the nature of the physical phenomena and the timescale of the power system transients.

Disturbances can be external (lightning strikes) or internal (faults, switching operations, load variations).

Power system transients can be electromagnetic, when it is necessary to analyse the interaction between the (electric) energy stored in capacitors and the (magnetic) energy stored in inductors, or electromechanical, when the analysis involves the interaction between the electric energy stored in circuit elements and the mechanical energy stored in rotating machines.

Physical phenomena associated with transients make it necessary to examine the power system over a time interval as short as a few nanoseconds or as long as several minutes.

This latter aspect is a challenge for the analysis and simulation of power system transients, since the behaviour of power equipment is very dependent on the transient phenomena: it depends on the range of frequencies associated to transients. An accurate mathematical representation of any power device over the whole frequency range of transients is very difficult, and for most components is not practically possible.

Despite the powerful numerical techniques, simulation tools and graphical user interfaces currently available, those involved in electromagnetic transients studies, sooner or later, face the limitations of models available in transients packages, the lack of reliable data and conversion procedures for parameter estimation or insufficient studies for validating models.

Figure 1.1 presents a typical procedure when simulating electromagnetic transients in power systems. The entire procedure implies four steps, that are summarized as follows:

1. The selection of the study zone and the most adequate representation of each component involved in the transient

The system zone is selected, taking into account the frequency range of the transients to be simulated: the higher the frequencies, the smaller the zone modelled. In general, it is advisable to minimize the study zone, because a larger number of components does not necessarily increase

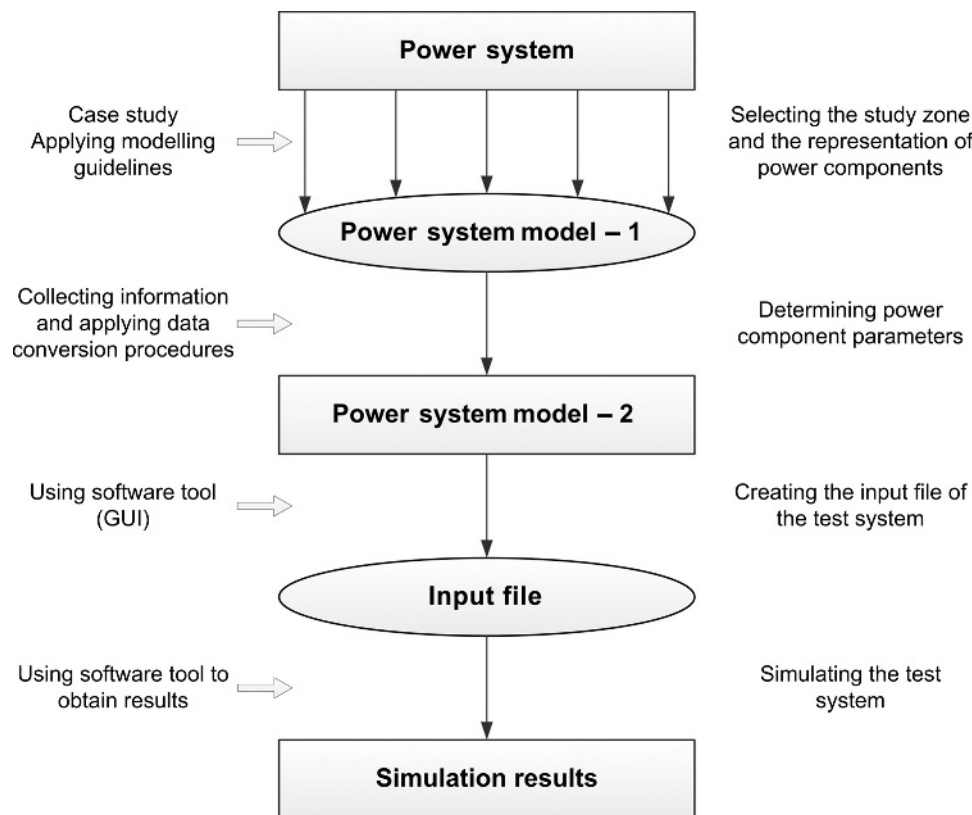


Figure 1.1 Simulation of electromagnetic transients in power systems.

accuracy; instead it will increase the simulation time, and there will be a higher probability of insufficient or incorrect modelling. Although many works have been dedicated to providing guidelines on these aspects [1–3], some expertise is usually needed to choose the study zone and the models.

2. The estimation of parameters to be specified in the mathematical models

Once the mathematical model has been selected, it is necessary to collect the information that could be useful for obtaining the values of parameters to be specified. For some components, these values can be derived from the geometry; for other components these values are not readily available and they must be deduced by testing the component in the laboratory or carrying out field measurements. In such case, a data conversion procedure will be required to derive the final parameter values. Details of parameter determination for some power components were presented in [4].

Interestingly, an idealized/simplified representation of some components may be considered when the system to be simulated is too complex. This representation will enable the data file to be edited and the analysis of the simulation results to be simplified.

A sensitivity study should be carried out if one or several parameters cannot be accurately determined. Results derived from such a study will show what parameters are of concern.

3. The application of a simulation tool

The steadily increasing capabilities of hardware and software tools have led to the development of powerful simulation tools that can cope with large and complex power systems. Modern software for

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transient analysis incorporates powerful and friendly graphical user interfaces that can be very useful when creating the input file of the test system model.

4. The analysis of simulation results

Simulation of electromagnetic transients can be used, among other things, for determining component ratings (e.g. insulation levels or energy absorption capabilities), testing control and protection systems, validating power component representations or understanding equipment failures. A deep analysis of simulation results is an important aspect of the entire procedure, since each of these studies may involve an iterative procedure in which models and parameters values must be adjusted.

Pioneering work in this field was presented in [2, 5, 6]; see also [7]. Readers interested in electromagnetic transient analysis can consult other specialized literature [8–15].

1.2 Scope of the Book

This book provides a basic background to the main solution techniques presently applied to the calculation of electromagnetic transients, gives details of the main applications of the most popular transient tools (insulation coordination, power electronics applications, protection) and discusses new developments (e.g. dynamic average models, interfacing techniques) mostly aimed at overcoming some limitations of the present software tools.

The main topics to be covered by this book are as follows:

Solution Methods and Simulation Tools: The analysis of electromagnetic transients in power systems can be performed in either the time or the frequency domain. Although time-domain solution methods are the most common option, frequency-domain analysis offers certain features that complement the advantages of time-domain analysis [16–18]. In addition, the calculation of the steady state of a power system, prior to the calculation of a transient process, is usually performed in the frequency domain.

Tools for electromagnetic transient simulation are classified into two main categories [19]: off-line and real-time. The purpose of an off-line simulation tool is to conduct simulations on a generic computer. Off-line tools are designed to use numerical methods and programming techniques without any time constraint and can be made as precise as possible within the available data, models and related mathematics. Real-time (on-line) simulation tools are capable of generating results in synchronism with a real-time clock, and have the advantage of being capable of interfacing with physical devices and of maintaining data exchanges within the real-time clock [20, 21]. Computations in real time, imposes important restrictions on the design of such tools, but they can be extremely useful for testing and designing power equipment.

The chapters dedicated to these topics detail currently applied methods for steady-state and transient solution of power systems and control systems, they provide an overview of simulation tools and methods for the computation of electromagnetic transients, including practical examples, and they discuss limitations.

Although parallel computation is covered in the chapters related to real-time simulation, readers interested in the computation of electromagnetic transients using a multicore environment are advised to consult reference [22].

Modelling and Parameter Determination: Despite the powerful numerical techniques, simulation tools and graphical user interfaces currently available, a lack of reliable data, standard tests and conversion procedures generally makes the determination of parameters one of the most challenging aspects of creating a model [4]. Although there is no specific chapter of this book dedicated to these topics, many issues connected to modelling guidelines are presented in several chapters, and two annexes covering

aspects related to the development of models and calculation of parameters for electromagnetic transients studies have been included:

- **Fitting Techniques:** When parameter determination is based on a frequency response test, a data conversion procedure is usually required, in which a fitting procedure is always needed. Although similar fitting techniques can be used for all power components whose behaviour can be derived from a frequency response test, the optimal procedure to be applied in each case is different. Annex A presents the application of fitting techniques for extracting rational models of lines, cables and transformers from frequency response tests [23].
- **Dynamic System Equivalents:** A common practice when dealing with large power systems in transient studies is to divide the system into a study zone, where transient phenomena occur, and an external system encompassing the rest of the system. The study zone is represented in detail, while the rest of the system is modelled by an equivalent. Given the frequency range with which transients are generated, there is a need for suitable techniques that could accurately determine the parameters of the external equivalent system from low- to high-frequency behaviours. Annex B reviews current techniques for obtaining dynamic system equivalents [24].

Readers interested in modelling guidelines and parameter determination for electromagnetic transients studies can consult references [1–7].

Overvoltage Calculations: An overvoltage is a voltage having a crest value exceeding the corresponding crest of the maximum system voltage. Overvoltages can occur with very wide range of waveshapes and durations. Types and shapes of overvoltages, as well as their causes, are well known; they are classified in standards (IEC, IEEE). The magnitude of external lightning overvoltages remains essentially independent of the system design, whereas that of internal switching overvoltages increases with the operating voltage of the system. The estimation of overvoltages is fundamental to the insulation design of power components, and to the selection of protection devices [25, 26]. Chapter 5 summarizes the different types of overvoltages and their causes, provides modelling guidelines for digital simulation using a time-domain tool (e.g. an EMTP-like tool) and presents some illustrative cases of any type of voltage stress in power systems.

Power Electronics Applications: Power electronics applications have quickly spread to all voltage levels, from extra high voltage (EHV) transmission to low voltage circuits in end-user facilities. They include high-voltage DC (HVDC) systems [27], flexible AC transmission systems (FACTS) [28], custom power devices [29], high-power AC to DC converters, converter-based drive technologies, instantaneous backup power systems and power-electronic interfaces for integration of distributed energy resources (DER) [30]. Power electronics modelling and simulation are especially important for a concept validation and design iteration during new product development. Four chapters of this book have been dedicated to the simulation of power electronics components. They provide general modelling guidelines and procedures for simulation of the main power electronics applications using a time-domain tool (e.g. an EMTP-like tool), and present several case studies.

Dynamic Average Modelling: Detailed switching models of power electronics converters are computationally intensive and can be the bottleneck for system-level studies with a large number of components and controllers. These drawbacks have led to the development of the so-called dynamic average-value models (AVM) in which the effect of fast switching is neglected or averaged within a prototypical switching interval [31]. The resulting models are computationally efficient and can run orders of magnitudes faster than the original models. Chapter 10 describes methods of constructing AVMs and demonstrates their advantages with some practical examples.

Protection Systems: Protection systems are critical power system components and their behaviour is an important part of power system response to a transient event. A system aimed at protecting against over-currents consists of three major parts: instrument transformers (current, wound electromagnetic voltage, and coupling capacitor voltage transformers), protective relays, and circuit breakers [32–34]. Chapter 11 summarizes models for instrument transformers and different types of relays (electromechanical, static/electronic, microprocessor-based), and presents some illustrative cases of protection systems.

Smart Grids: The smart grid may be seen as an upgrade of the current power system, in which present and new functionalities will monitor, protect and automatically optimize the operation of its interconnected elements to maintain a reliable and secure environment. The smart grid will offer better management of energy consumption by the use of advanced two-way metering infrastructure and real-time communication; improved power reliability and quality; enhanced security by reducing outages and cascading problems; and better integration of DERs. Although the smart grid will build upon the basic design of the current power grid, it will have features essential to its operation that will involve monitors, sensors, switching devices and sophisticated two-way communication systems that will allow it to be a highly automated power delivery system [35, 36].

The complete model of an actual smart grid should include the representation of: (1) conventional power components that will generate and transmit the electric energy, (2) various types of power-electronic interfaces, loads and DERs, plus their corresponding controllers, and (3) the two-way communication system. To date, there is no software tool capable of coping with such a complex model, although some work is in progress [37].

Chapter 12 presents the application of time-domain solution techniques to the study of large actual distribution systems. The chapter covers the study of DER integration and its possible effects on system reliability and voltage violations, the application of system reconfigurations by large numbers of switching operations to exploit the advantage of automation and self-healing capabilities and the analysis of distribution system overvoltages. The chapter also describes some experiences with the development of industrial-grade translators for interfacing Power-Flow programs with EMTP-like tools, which can facilitate the simulation of electromagnetic transients to utilities.

Interfacing Techniques: Interfacing an electromagnetic transient tool with external programs or algorithms expands their applicability to areas where techniques are available through the external agent (program or algorithm) [38–40]. Chapter 13 describes methods for interfacing a transient simulation tool with other mathematical algorithms to extend their application for both analysis and design of complex power systems.

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