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J. ARRILLAGA • N. R. WATSON

# COMPUTER MODELLING OF ELECTRICAL POWER SYSTEMS

Second Edition

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# COMPUTER MODELLING OF ELECTRICAL POWER SYSTEMS

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# PREFACE

This book describes the use of component models and efficient computational techniques in the development of computer programs representing the steady and dynamic states of electrical power systems.

The content, although directed to practising engineers, should also be appropriate for advanced power system courses at final year degree and masters levels.

Some basic knowledge of power system theory, matrix analysis and numerical techniques is presumed, and specific references are given to help the uninitiated to pick up the relevant material.

An introductory chapter describes the main computational and transmission system developments justifying the purpose of the book. This is followed by two chapters describing the modelling of power transmission systems, one on conventional plant components and the other on FACTS devices and HVDC links.

A general-purpose single-phase a.c. load-flow program is described in Chapter 4 with particular reference to the Newton Fast-Decoupled algorithm. The load-flow subject is extended in Chapter 5 with the description of algorithms for the incorporation of FACTS and HVDC transmission in conventional programs.

The remaining chapters consider the power system in the dynamic state. Chapter 6 covers the subject of electromagnetic transients with reference to the EMTP method, and provides examples of its application to fast transients and general power system disturbances. Attention is also given to the representation of power electronic components.

Chapter 7 describes electromechanical models of a.c. power system plant and their use in multi-machine transient stability studies.

Finally, a combination of the electromechanical and electromagnetic models described in Chapters 6 and 7 is presented in Chapter 8 for the assessment of Transient Stability in systems containing HVDC links and/or FACTS devices.

The authors should like to acknowledge the considerable help received from their earlier and present colleagues, both at UMIST (Manchester) and University of Canterbury (New Zealand). In particular they wish to single out E Acha, G Anderson, C P Arnold, G Bathurst, P S Bodger, A Brameller, H W Dommel, B J Harker, M D Heffernan, B C Smith, B Stott, K S Turner and A R Wood. They also wish to thank Mrs G M Arrillaga for her active participation in the preparation of the manuscript.

**J Arrillaga**
**N R Watson**

# CONTENTS

# *1*

# INTRODUCTION

## 1.1 General Background

The first edition of this book described the development of FORTRAN based power system programs for implementation in the mainframe computer technology of the 1970s. Since then, the ubiquitous personal computer (PC) has become the workhorse of most power system engineers and the new edition takes this fact into account.

Nevertheless, the basic algorithms have remained largely unchanged; what has altered in the past two decades is the general acceptance of power electronic devices for the control of power flow and its related stability improvement. Both high voltage d.c. and FACTS technologies are now an integral part of modern power transmission systems. Their incorporation in power system analysis is not straightforward, however, and this new edition describes suitable models of these devices.

The primary subject of computer modelling is the load flow problem, which finds application in all phases of power system analysis. Due to space limitations, only the solution of the basic load flow equations is normally considered. It is acknowledged, however, that the load flow problem is not restricted to the solution of the basic continuously differentiable equations. There is probably not a single routine program in use anywhere that does not model other features. Such features often have more influence on convergence than the performance of the basic algorithm.

The most successful contribution to the load flow problem still is the application of Newton–Raphson and derived algorithms. These were finally established with the development of programming techniques for the efficient handling of large matrices and, in particular, the sparsity-oriented ordered-elimination methods. The Newton algorithm was first enhanced by taking advantage of the decoupling characteristics of power flow and, finally, by the use of reasonable approximations directed towards the use of constant Jacobian matrices.

In dynamic studies, a significant modelling tool has been the application of implicit integration techniques which allow the differential equations to be algebraized and then incorporated with the network algebraic equations to be solved simultaneously. The use of implicit trapezoidal integration has proved to be very stable, permitting step lengths greater than the smallest time constant of the system. This technique allows detailed representation of synchronous machines with their voltage regulators and governors, induction motors and non-linear loads, such as FACTS and HVDC converters.

Trapezoidal integration is also an integral part of the Electromagnetic Transient Programs (EMTP). With the availability of cheap computer power the EMTP has become universally accepted for the solution of all sorts of transient problems and constitutes the main addition to the present edition.

In particular, electromagnetic transient programs are now used extensively for the analysis of system disturbances and in power system protection design. The availability of fast EMTP solutions, and particularly the possibility of Real Time Digital Simulators (RTDS) to interface with real protection hardware, has diminished the use of conventional fault simulation, based on quasi-steady-state linear system behaviour. The increasing presence of power electronic devices, for which conventional fault simulation is totally inadequate, has added to the demise of the earlier programs. However, the Fault Level ($MVA_f$) at points of common coupling and the Short Circuit Ratio (SCR) at nodes with converter equipment are still derived from Fault Simulation. Thus in the new edition a concise version of the earlier Faulted System Studies chapter has been included as an appendix.

## 1.2 The New Computer Environment

Earlier implementations of power system programs were severely restricted by the lack of flexibility of mainframe computers as well as limitations in graphical support, memory and storage space. Now the evolution of computer technology has removed most of these limitations, and made the PC a universal platform for power system simulation.

Abundance of cheap memory and new operating systems permit the computers to accommodate large executable code with extensive data storage. In addition, the utilisation of virtual memory technology (paging to hard disks) has eliminated the traditional limitation of insufficient memory space for executable binary and simulation data. The dynamic memory allocation facility has also enabled optimised usage of the memory space. Application code can be made relocatable and dynamically loaded into the memory and called from the main program only when it is needed. Therefore, memory space is released immediately when it is no longer required.

Traditionally, power system programs have been designed using a single programming language, Fortran being the dominant language. However, there is little graphic support available through Fortran and, hence, many power system programs lack a graphical user interface. Therefore, a text-based database file is commonly used, allowing users to construct the database by typing in the power system data using an ordinary text editor. Manual database editing has the advantage that data errors are often immediately obvious.

Recent advancements in software development tools have made it possible for the program binary generated by different compilers on different programming languages to be able to interact with each other. This enables programmers to exploit the strengths of different languages in the development of single computer software. The software can be separated into a graphical user interface and a simulation engine. The graphical user interface and the simulation engine have different development tools requirements and, hence, different languages are chosen to construct them. Fortran is retained as the language of the simulation engine, due mainly to its implicit handling of complex-number arithmetic. Normally, the simulation engine is also programmed using basic Fortran commands (i.e. avoiding extended features of some Fortran compilers) so that it is transportable across different operating systems/platforms.

## 1.3 Transmission System Developments

Large increases in transmission distances and voltage level, as well as national and international interconnections, have resulted in a more sophisticated means of active and reactive power control.

HVDC links and FACTS devices have now been generally accepted to achieve more flexible power transmission and their incorporation in conventional power system programs presents a challenge to power system modelling. Moreover, considering the large power ratings of such devices, their presence exercises considerable influence on the rest of the system and must be accurately represented.

Whenever possible, any equivalent models used to simulate the power electronic components should involve traditional power system concepts for easy incorporation within existing power system programs. However, the number of degrees of freedom of d.c. power transmission and FACTS is higher and any attempt to model the behaviour in the more restricted a.c. framework will have limited applications.

Long-distance transmission presents voltage and power balancing problems which can only be accurately assessed by using correspondingly accurate models of power transmission plant in the phase frame of reference. With reference to power system disturbances, the behaviour of FACTS and HVDC transmission cannot be accurately modelled by conventional fault study or stability programs. Disturbances are best simulated with electromagnetic transient programs. Thus the modelling of linear and non-linear components, as well as the frequency dependence of transmission lines for use in the electromagnetic transient programs have received considerable attention in recent times and are given extensive coverage in this edition of the book.

## 1.4 Theoretical Models and Computer Programs

The transition from power system analysis to efficient computer programs is a very laborious exercise. Present commercial programs are the result of considerable skills and many engineering years. Thus, newcomers to the power system area usually acquire existing commercial packages rather than building their own. However, they need to understand their capabilities and limitations to be able to incorporate new components and more advanced hardware technologies.

Instruction manuals provide full information on the practical structure of the programs but lack the technical background necessary for the user to perform the inevitable modifications required in the long run.

It is almost expected that a specialist book of this type should provide a comprehensive survey and comparison of the various conventional alternatives. Such an approach, although academically satisfying, would detract from the main object of the book and would occupy invaluable space. Instead, up-to-date modelling techniques generally recognized as efficient are described from theoretical and practical considerations.

# 2

# TRANSMISSION SYSTEMS

## 2.1 Introduction

The conventional power transmission system is a complex network of passive components, mainly transmission lines and transformers, and its behaviour is commonly assessed using equivalent circuits consisting of inductance, capacitance and resistance.

This chapter deals with the derivation of these equivalent circuits and with the formation of the system admittance matrix relating the current and voltage at every node of the transmission system.

Among the many alternative ways of describing transmission systems to comply with Kirchhoff's laws, two methods, mesh and nodal analysis, are normally used. The latter has been found to be particularly suitable for digital computer work, and is almost exclusively used for routine network calculations.

The nodal approach has the following advantages:

- The numbering of nodes, performed directly from a system diagram, is very simple.
- Data preparation is easy.
- The number of variables and equations is usually less than with the mesh method for power networks.
- Network crossover branches present no difficulty.
- Parallel branches do not increase the number of variables or equations.
- Node voltages are available directly from the solution, and branch currents are easily calculated.
- Off-nominal transformer taps can easily be represented.

## 2.2 Linear Transformation Techniques

Linear transformation techniques are used to enable the admittance matrix of any network to be found in a systematic manner. Consider, for the purposes of illustration, the network drawn in Figure 2.1.

Five steps are necessary to form the network admittance matrix by linear transformation, i.e.

(i) Label the nodes in the original network.

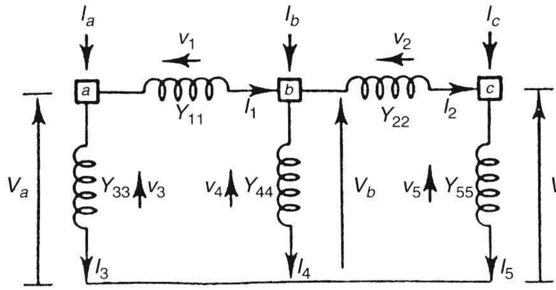


**Figure 2.1** Actual connected network

(ii) Number, in any order, the branches and branch admittances.

(iii) Form the primitive network admittance matrix by inspection.

This matrix relates the nodal injected currents to the node voltages of the primitive network. The primitive network is also drawn by inspection of the actual network. It consists of the unconnected branches of the original network with a current equal to the original branch current injected into the corresponding node of the primitive network. The voltages across the primitive network branches then equal those across the same branch in the actual network.

The primitive network for Figure 2.1 is shown in Figure 2.2.

The primitive admittance matrix relationship is:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{11} & & & & \\ & Y_{22} & & & \\ & & Y_{33} & & \\ & & & Y_{44} & \\ & & & & Y_{55} \end{bmatrix}}_{[Y_{\mathrm{PRIM}}]} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix}. \tag{2.1}$$

Off-diagonal terms are present where mutual coupling between branches is present.

(iv) Form the connection matrix $[C]$.

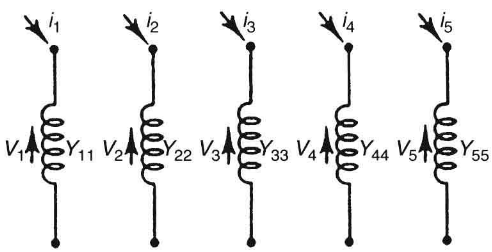


**Figure 2.2** Primitive or unconnected network