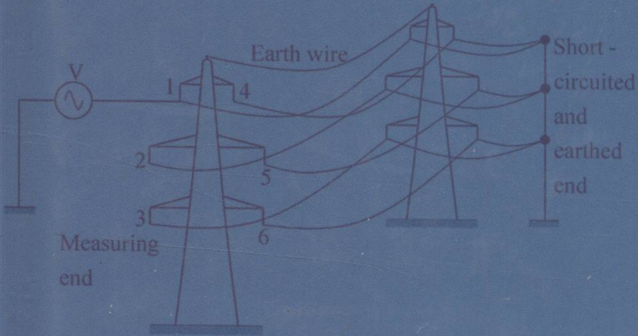
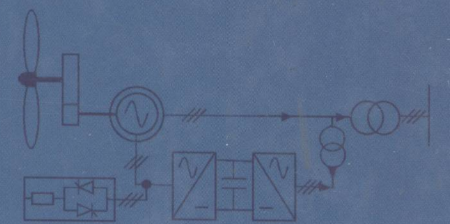
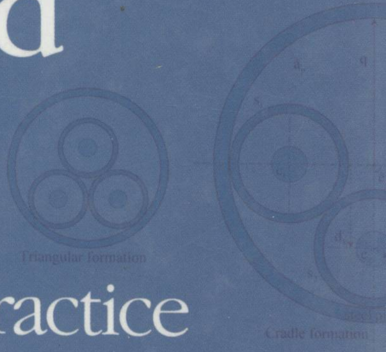
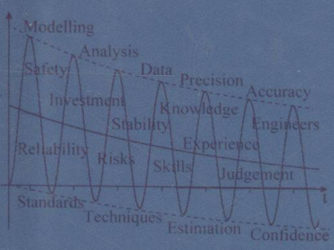




Power Systems Modelling and Fault Analysis



Theory and Practice



Nasser Tleis

Newnes

Power Systems Modelling and Fault Analysis

Theory and Practice

Nasser D. Tleis
BSc, MSc, PhD, CEng, FIEE

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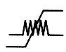
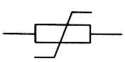
Power Systems Modelling and Fault Analysis

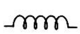
Dedicated to the late Mr Rafik Hariri
former Prime Minister of Lebanon
without whom this book would not have been written

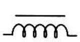
List of electrical symbols

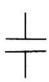
 Resistor

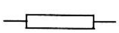
 Resistor with non-linear current/voltage characteristics

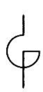
 Varistor or surge arrester with non-linear current/voltage characteristics

 Inductor

 Iron-cored inductor

 Capacitor

 Impedance

 Reactor

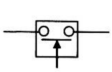
 Short-circuit fault

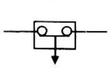
 Normally closed circuit-breaker

 Normally open circuit breaker

 Normally closed disconnector

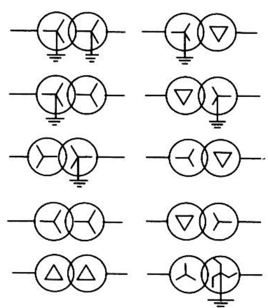
 Normally open disconnector

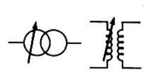
 Fast closing switch

 Fast opening switch

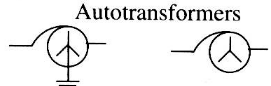
 Fuse

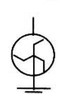
Two-winding transformers of various winding connection arrangements



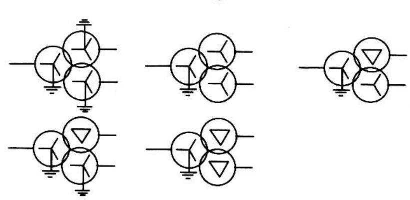
 Variable tap ratio ideal transformer

Autotransformers

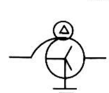


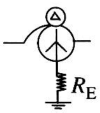
 Interconnected star or zig-zag earthing transformer

Three-winding transformers

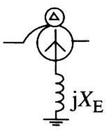


Autotransformers with a delta-connected tertiary winding

 Neutral solidly earthed



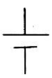
Neutral earthing resistor

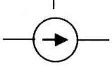


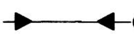
Neutral earthing reactor


AC generator

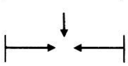

Induction motor

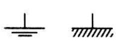

dc voltage source

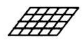

Current source


Cable sealing ends


Spark gap


Triggered spark gap

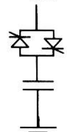

Earth

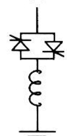

Substation earth mesh/mat or grid

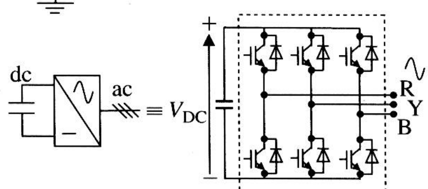

Diode


Thyristor


Insulated gate bipolar transistor (IGBT)


Thyristor switched capacitor


Thyristor controlled reactor



Basic Voltage source converter

Foreword

This is a new era for the electricity sector. The challenges we face in the near future are greater than at any time since the major network development programmes of the mid 20th Century. Thankfully, power transmission technology and its control and protection has made enormous leaps enabling better utilisation of assets, greater efficiency and improved quality of supply. This will help us meet the challenges ahead.

From a technology perspective we are now seeing the construction of new national networks, the formation or integration of regional networks and major network renewal programmes. There is also the need to develop and integrate new generation technologies and implement new control and power electronics solutions in more active and integrated transmission and distribution networks. The technology problem is therefore becoming richer and more complex – and demanding of novel solutions; it also requires a greater understanding of the characteristics and performance of the systems we need to build.

But technology is not the only development over the last few decades. We have also seen the development of a more competitive market place for electricity with second and third generation market models now being implemented, the unbundling of utility companies all providing benefits for consumers.

And crucially we are now understanding the impact of human activity on the environment and seeking to reduce emissions and develop more sustainable networks. This creates new pressures to incorporate the new greener technologies and meet planning and amenity constraints.

From a social perspective we know that electricity has entwined itself into the very heart and veins of society and all the services we now take for granted. We have learnt this lesson very keenly in the opening of the 21st century with rude reminders on what can happen when electricity supplies are lost.

Academia and the industry need to help the next generations of engineers to rise to these challenges. I believe that now is the time for the resurgence in engineering and electrical engineering disciplines; in particular the power generation, transmission and distribution sectors. It is vital that we develop and equip engineers with the verve, excitement, knowledge and talent they require to serve society's needs.

This book fills a major gap in providing the tools for this generation of engineers. It carefully targets the knowledge required by practitioners as well as academics in understanding power systems and their characteristics and how this can be modelled and incorporated into the development of the networks of the future.

Nasser Tleis is distinguished as an academic and a senior manager in the industry. Nasser has been at the forefront in developing academic capability as well as building generations of engineers capable of taking forward this knowledge and experience in the practical application of the techniques. This book captures Nasser's unique blend of the theoretical and applied knowledge to become a reference text and work book for our academics and engineers.

It gives me great pleasure to write the Forward to this book. It comes at a time where its contents are most relevant and I am confident it will bridge a gap between academic treatments and the very real need for application to power systems for the future by a new breed of practitioners.

Nick Winser
Director of Transmission, National Grid
Warwick, United Kingdom

Preface

The objective of this book is to present a practical treatment of modelling of electrical power systems, and the theory and practice of power system fault analysis. The treatment is designed to be sufficiently in-depth and generally adequate to serve the needs of practising electrical power engineers. Practical knowledge of power systems modelling and analysis techniques is essential for power system engineers working in the planning, design, operation, protection and incident analysis of generation, transmission, distribution and industrial power systems.

In many universities, undergraduate levels cover very little electrical engineering and even at postgraduate levels, course contents have become more fundamental, theoretical and basic. Nowadays, many undergraduate and postgraduate university teachers have no or very little practical industrial experience. This book is intended to provide a practical source of material for postgraduate students, researchers and university teachers in electrical power engineering. Further, over the last 20 years or so, the ongoing liberalisation and restructuring of electricity supply industries have been accompanied by significant loss of experienced electrical power engineers, mostly to retirement. Many new engineers entering industry are neither adequately equipped academically nor are they finding many experienced engineers to train them! Technical learned society papers are necessarily concise and specialised. Though not necessarily brief, books on power system modelling and fault analysis generally tend to follow a highly theoretical treatment and lack sufficient practical information and knowledge that leaves the reader with inadequate understanding. In writing this book, one of my aims has been to attempt to bridge a gap between those theoretical books and the specialised technical papers.

The aim of this book is to present practical power system modelling and analysis techniques as applied in modern industry practices. Therefore, strict academic and basic fundamental theories have largely been omitted to save valuable space. Basic knowledge is presumed in the following areas: analysis of three-phase alternating current electrical circuits; theory of electrostatic and electromagnetic fields; calculation of resistance, inductance and capacitance of lines; basic theories of electromagnetic transformers and ac rotating machines, complex phasor algebra, matrix algebra, linear differential equations and Laplace transforms. These basic topics are well covered in many power systems and mathematics textbooks.

In support of the in-depth material I present in this book, I have included a comprehensive and most relevant list of technical references.

I have used SI units throughout and I hope this is not seen as a disadvantage where non-SI units are still in use.

Chapter 1 discusses the nature, causes and effects of faults in power systems, presents fundamental concepts and definitions of short-circuit currents and circuit-breaker interruption as well as a practical treatment of per-unit system of analysis. Chapter 2 presents the theory of symmetrical components and a practical and detailed treatment of the connection of sequence networks under various fault conditions including simultaneous faults. Chapter 3 is concerned with the advanced modelling and analysis of practical multi-conductor overhead lines and cables in the phase coordinates and sequence reference frames. Chapter 4 presents the modelling, in the phase coordinates and sequence reference frames, of transformers, quadrature boosters, phase shifters, series and shunt reactors, series and shunt capacitors, static variable compensators and power system load. Chapter 5 presents the modelling in the phase coordinates, $dq0$ and sequence reference frames of synchronous generators and induction motors. Modern wind turbine generators such as squirrel-cage induction generators, wound rotor doubly fed induction generators and generators connected to the ac grid through power electronics converters are also covered. In Chapters 3–5, practical measurement techniques of the electrical parameters of various power system equipment are presented. The models presented in these three chapters can be used in various power system analysis applications including positive phase sequence (PPS) load flow and PPS transient stability, multiphase unbalanced load flow and multiphase fault analysis, etc. Chapter 6 presents methods for the simulation of short-circuit and open-circuit faults as well as static and dynamic short-circuit analysis techniques in ac power systems. New and strong emphasis is given to the analysis of the time variation of the ac and dc components of short-circuit current. This emphasis is important in generation, transmission and industrial power systems. In addition, the expansion in the connection of small-scale distributed generation in distribution systems is exacerbating short-circuit current problems where switchgear are traditionally not designed either for make duties or for significant dc short-circuit current component.

The emphasis on the analysis of the dc short-circuit current component also reflects the increase in X/R ratios of power system equipment due to the use of higher system voltages and/or more efficient and lower loss transformers. An introduction to modern short-circuit analysis in the phase coordinates frame of reference is given. Chapter 7 describes and highlights the differences among the three international approaches to the analysis of short-circuit currents: the International Electro-technical Commission IEC 60909 Standard, the UK Engineering Recommendation ER G7/4 and the American IEEE C37.010 Standard. Chapter 8 presents the formulation of power system equivalents by network reduction techniques. It discusses uncertainties present in short-circuit analysis, gives an introduction to probabilistic short-circuit analysis and to the theory of quantified risk assessment including safety considerations. Chapter 9 presents practical methods for the control and limitation of high short-circuit currents in power system design, operational planning and real-time operation. In addition, the various technologies of existing and some future short-circuit fault current limiters are described including their applications. Chapter 10 describes the effects of ac currents on the human body and its electrical resistance. It describes the components that make up extended substation earthing systems, and gives an introduction to the analysis of short-circuit earth or ground return current and rise of earth potential. The phenomenon of electrical interference from power lines is discussed and analysis techniques of induced voltages are presented with a particular focus on coupling interference from overhead power lines to metallic pipelines. Two Appendices are included: the first presents the analysis of multi-conductor lines and cables and the second presents typical data for power system equipment.

I have used actual power system equipment data and solved practical examples representing some of the type of problems faced by practising power engineers. I have solved or shown how to solve the examples using hand calculations and electronic calculators. I believe in the 'feel' and unique insight that hand calculations provide which can serve as a good foundation for the power engineer to adequately specify, model, analyse and interpret complex and large power system analysis results.

Many colleagues in National Grid have given me help and encouragement. Mr Andy Stevenson who gave his and National Grid's support at the start of this project, Mr Tony Johnson, Mr Tom Fairey and Dr Andrew Dixon for reviewing various chapters and preparing their figures. I am indebted to Dr Zia Emin for reviewing Chapter 3, for the high quality figures prepared and for our many useful discussions.

Writing this book whilst full-time employed and raising a young family has been difficult. I would like to thank my wife Hanadi for her patience, unfailing support and encouragement throughout. I also want to thank my daughters Serene and Lara for never complaining why I ignored them for such a long time!

Like most books that contain material of a reference nature, the published work is only the visible part of a huge iceberg. It is hoped that the nature of the material and list of references included may give a 'taster' of the size of the invisible iceberg!

Finally, the book may contain errors of a typographical nature or otherwise. Should a second edition be required, I would be grateful to receive your comments and any suggestions for improvements on any aspect of this book on Nasser.Tleis@uk.ngrid.com.

Nasser Tleis
England, UK
June 2007

Biography

Dr Nasser Tleis obtained his PhD degree in Electrical Power Engineering from The University of Manchester Institute of Science and Technology, England, UK in 1989. He joined the Central Electricity Generating Board in London, then the newly formed National Grid Company on privatisation in 1990. He has extensive experience in electrical power engineering in the following areas: power plant performance specification including steady state and transient analysis, substation insulation coordination, planning and design of transmission systems, voltage control strategies and reactive compensation planning, power systems thermal and loadflow analysis, voltage stability, frequency control and stability, transient and dynamic stability including long-term dynamics, faults and short-circuit analysis, multiphase power flow and unbalance analysis, analysis and measurement of harmonic distortion and voltage flicker.

He has worked on the development and validation of dynamic models of generation plant, their excitation and governor control systems, dynamic models for transmission plant control systems as well as developing new power systems analysis techniques. For the last few years, he has led the development of the Great Britain Grid Code specifying the technical connection requirements for new non-synchronous generation technologies, particularly wind turbine generators. He is currently involved in the assessment of the changing technical behaviour of power systems that include a mix of synchronous and non-synchronous generation technologies including the development of steady state, transient and dynamic models. He is a Chartered Engineer and a Fellow of the Institution of Engineering and Technology (formerly Institution of Electrical Engineers).

Contents