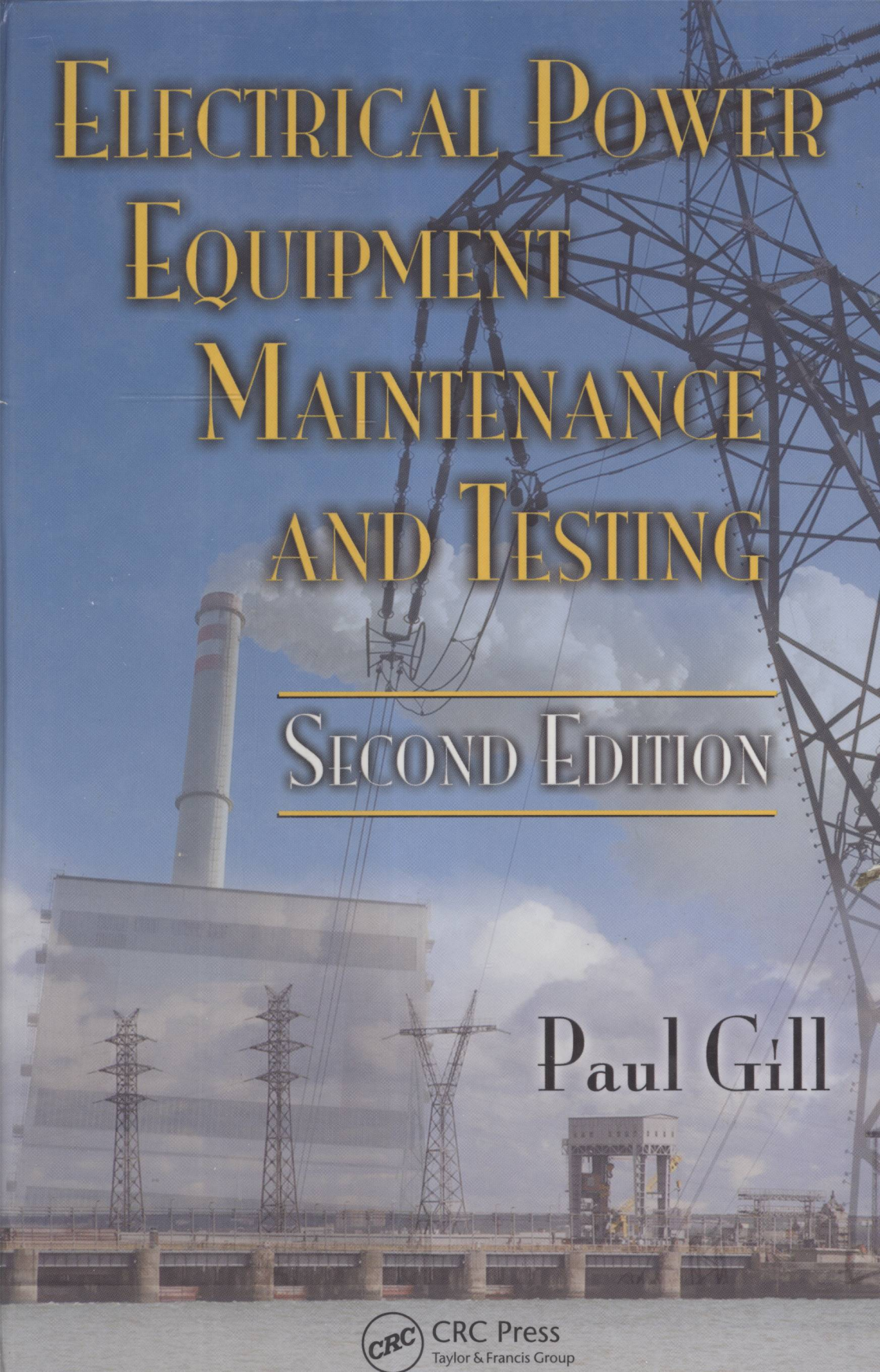
Electrical Power Equipment Maintenance and Testing

Second Edition

Paul Gill



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ELECTRICAL POWER EQUIPMENT MAINTENANCE AND TESTING

SECOND EDITION

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This textbook and instructions offered in it are designed to acquaint students and readers with accepted good practice for maintenance, operation, and testing of electrical equipment and/or systems. This book does not purport to be complete nor is it intended to be specific for the products of any manufacturer, testing procedures, or maintenance routines. The publisher, the author, companies, and other organizations referenced in this book will not accept any responsibility and liability whatsoever for work undertaken on the basis of this text. The sole purpose of this book is to impart knowledge on the subjects covered in the book. All work undertaken based on this text is the sole responsibility of the reader and user of the book. The manufacturer's operating, maintenance, and testing procedures are the only reliable guide in any specific instance and, therefore, they should be consulted before undertaking any work on electrical equipment.

The contents of this book do not represent a U.S. Nuclear Regulatory Commission (USNRC) position on the subjects covered in the book.

Dedication

In memory of my parents—Jasbir Singh and Amar Kaur

To my wife Patricia—for her patience and understanding to make this work possible

To my children/spouses—Shaun/Debra, Rajan/Larie, Jason/Deanna, and Rania/Alden and to my beautiful grandchildren Collin, Andrew, Ryan, Timothy, Owen, Henry, Jack, Maya, Chani, Paul, and Lauryn who keep me young and bring boundless joy to my journey in life

Series Introduction

When the first edition of this book was published 10 years ago, it was a particularly timely addition to the Marcel Dekker series on power system engineering. The power industry was beginning to be challenged by "aging infrastructures"—areas within local and regional power grids where a good deal of equipment was quite old and in a few cases much deteriorated. Maintenance, particularly testing to determine condition and prescribe proper service and refurbishment, was receiving more attention than it had in decades.

But now, more than ever, there are factors beyond just the need to evaluate old equipment that are creating a heightened focus on sound maintenance and testing throughout the electric power industry. Equipment manufacturers have honed computer-aided design models to the point where they can shave design margins and engineer wear and deterioration rates with great precision, all to the purpose of reducing first cost, something they are forced to do in a world where much of the market buys mostly on the basis of lowest first cost. This means that comprehensive testing and "by the book" maintenance of equipment are critical earlier in the life cycle, because today's new equipment has little margin for skipped maintenance or continued deterioration; it works well only if maintained in good condition. In addition, new materials, designs, and testing methods mean the proper matching of testing and maintenance to specific equipment is more intricate and involved than ever. New technologies like online condition monitoring create opportunities to improve operations and efficiency. Finally, evolving concerns and standards, such as those regarding arc-flash, create a need for renewed focus in some areas.

Electric Power Equipment Maintenance and Testing, Second Edition is a thorough update of the first edition, with revised material and additions throughout, including new discussions on arc-flash, online condition monitoring, uninterruptible power supply testing, motor vibration analysis, and current industry safety requirements to name just a few. In addition, it has two new chapters that provide enhanced focus on a pair of critical areas in power system testing: testing and commissioning of protective relays and instrument transformers; and power quality and harmonics, and their effects on electrical equipment.

As the editor of the Power Engineering Series, I am proud to include *Electric Power and Equipment Maintenance and Testing, Second Edition* among this important group of books. During the past decade, I found the first edition to be among those I most often used in my work. This second edition is as well organized and indexed as the first, so that it will make a good reference in day-to-day work, with key material easy to find and concisely presented. Yet it is written in an accessible, linear style so that it is also a good tutorial

for those who are not familiar with the material. Since these are qualities I strive for in my books, I know how difficult it is for an author to achieve them well and as a result value Paul Gill's new book all the more.

Like all the books in the Power Engineering Series, *Electric Power Equipment Maintenance and Testing, Second Edition* puts modern technology in a context of proven, practical application; useful as a reference book as well as for self-study and advanced classroom use. The Power Engineering Series includes books covering the entire field of power engineering, in all of its specialties and subgenres, all aimed at providing practicing power engineers with the knowledge and techniques they need to meet the electric industry's challenges in the twenty-first century.

H. Lee Willis

Foreword

Paul Gill's original book, *Electrical Equipment Testing and Maintenance* (1982), and the first edition, *Electrical Power Equipment Maintenance and Testing* published in 1997, were the first two books that addressed the practical aspects of electrical testing and maintenance of power system equipment and apparatus. Both books presented testing methodologies and engineering basics on the subject of electrical testing and maintenance in one volume. Considered the electrical testing and maintenance "bible," *Electrical Power Equipment Maintenance and Testing* has been the leading treatise on the subject and an essential reference book for engineers and technicians concerned with the maintenance and testing of electrical power system equipment and apparatus. Both of these textbooks were a must read for the plant electrical engineer and plant maintenance technician as well as for electrical engineering graduates and students. The first edition has become a required reading for institutions offering electrical testing and maintenance curricula. The first edition has also been an invaluable aid for technicians studying for the InterNational Electrical Testing Association's (NETA) levels II, III, and IV test technician examinations and is a valued reference for engineers and technicians in the electrical testing industry.

The second edition contains major revisions and is an improvement of the first edition. It represents a great deal of effort and study on the part of the author to compile, sort, and apply information and data supplied by manufacturers and allied industries together with that made available by relevant industry standards, institutions, and associations. The second edition is an invaluable book for practicing engineers, technicians, managers, and others who are involved in the testing, maintenance, and care of electrical equipment and apparatus, as well as engineering students pursuing further studies in this field. This new book has been substantially enhanced by the addition of updated information on various subjects.

For example, Chapter 1 has been revised to include information on reliability centered maintenance (RCM), insulating materials and insulation systems of electrical equipment, causes of insulation failure and failure modes of electrical equipment, temperature ratings, and the relationship between maintenance and arc-flash hazard. Chapter 5 has been revised to include the latest tests performed on transformers including online monitoring tests. Chapter 6 has been revised to include cable degradation and diagnostic online and off-line tests such as PF, VLF, and partial discharge; summary/comparison of various field tests; and latest trends in cable diagnostic testing. Major revisions have been made to Chapter 7; the section on circuit breaker time travel has been expanded to fully cover how the test is to be conducted and evaluated, and the protective relays and instrument transformers previously covered in this chapter are now covered in a separate chapter. The revisions to Chapter 8 include assessing service life and endurance requirements for low-voltage breakers, mechanical

maintenance factors such as lubrication, electrical maintenance factors, and information on how to conduct thermographic surveys. The original Chapter 9 now covers testing and commissioning of protective relays and instrument transformers. Instrument transformers and electromechanical, solid-state, static and microprocessor relays including event reporting have been covered in greater detail with examples in Chapter 9. Chapter 10 now covers motors and generators, and it has been revised to include an extensive guide on preventative maintenance of motors and variable frequency drives. In this chapter, a discussion section has been added on the online and off-line partial discharge testing and vibration analysis of motors. A new Chapter 12 has been added to cover power quality and hormonic issues and their relationship to predictive maintenance since many causes of equipment failure are being attributed to poor power quality. A new Chapter 13 covers the contents of the original Chapter 11. This chapter now includes a detailed discussion on arc-flash hazard regulatory basis, and how to perform an arc-flash hazard study.

The revised second edition contains a wealth of new information, along with the original information in the first edition, with tables, formulas, diagrams, line drawings, and photographs. Also, in this book, the text has been consolidated under each subject heading to facilitate easier reading and to locate information. The original chapters have been updated to include the latest information on testing and test methods and two new chapters have been added to cover additional subjects. The whole book has been organized to make it reader-friendly. The information contained herein will prove even more useful than that contained in the first edition. The reader will find this book an invaluable resource on insulation materials and systems, aging stressors and failure modes of power equipment, and for routine field (in situ) testing of electrical power system equipment and apparatus. Also, in the revised second edition, the author has superbly explained the relationship between poor power quality and harmonics resulting from the application of nonlinear loads, and how it can impact insulation systems of power apparatus. In this book, the author has explained various rules of thumb that exist in the industry for evaluating insulation test results and why they should not be followed blindly. We believe this is the only book that makes a significant attempt to address this issue. We congratulate Gill for superbly improving on an excellent original book. We wholeheartedly recommend the new book to the reader.

Alan D. Peterson
Technical Committee Chairman
InterNational Electrical Testing Association

Jayne Tanz
Executive Director
InterNational Electrical Testing Association

Preface

This edition has been devoted to the subject of maintenance and testing of electrical power equipment and apparatus. It covers all types of apparatus and equipment found in electrical power systems serving industrial and commercial facilities, large institutional complexes and office buildings, and utility type substations and generating plants. This book is an outgrowth of my work teaching courses on maintenance and testing of electrical power system apparatus and equipment over the last 30 years. Electrical equipment maintenance and testing are subjects that have assumed greater importance these days because of the detailed attention they are receiving from professional societies, insurance companies, government regulators, manufacturers, and owners. There exists considerable interest among people who operate and maintain electrical power systems in a wide range of topics relating to equipment maintenance and testing. This is because *condition and reliability* are directly related to *maintenance and testing.* To obtain maximum life from electrical equipment, maintain its reliability, and minimize repair costs, it is necessary to service and test it periodically to predict its condition. More attention is being directed to the maintenance and safe operation of electrical equipment. Many municipalities are mandating regulations and codes for periodic inspection and testing of large electrical facilities under their jurisdictions; the federal government has passed laws for the maintenance of commercial nuclear power plants (maintenance rule), and insurance companies are basing their premiums on the quality of a facility's maintenance program and equipment condition. Attitudes are changing and it is no longer true that maintenance is something the industry must tolerate and learn to live with; preventive and predictive maintenance instead of "necessary" maintenance is now the preferable option and is being increasingly adopted.

In the past, the subject of electrical equipment maintenance and testing was promoted mostly by electrical power equipment and electrical test equipment manufacturers, utilities, and professional societies and organizations, such as the IEEE, ANSI, NEMA, and others. These bodies and entities continue to publish a majority of the requirements for maintenance and testing. To the best of my knowledge, there is no comprehensive book that addresses this subject to the level previous editions of my book have covered. There are other books on the market that address maintenance of individual equipment but I am not aware of any book that covers the subject as comprehensively as this book does. Although many of the basic principles, including theory and practices, have not been affected by the latest technological advancements in this field, there have been changes in the practices of certain applications and instrumentation. In this revised edition, I have attempted to consolidate and coordinate the latest advances in the field into

a comprehensive and understandable text. In addition, this book provides a guide for evaluating the test results of each category of testing. This information is not usually found in other publications, and I consider it the strength of this book.

This book also provides practical information on the maintenance and testing of electrical equipment for maintenance personnel who install and maintain such equipment. The scope of this book is both very broad and specialized. Therefore, to carry out the test procedures and maintenance practices discussed in this book, one must either have or acquire the necessary knowledge to carry them out successfully and safely. The original Chapter 1 has been expanded to include information on reliability center maintenance (RCM), insulating materials and insulation systems of electrical equipment, causes of insulation failures and failure modes of electrical equipment, temperature ratings, and the relationship between maintenance and arc-flash hazard analysis. It retains the original material on dielectric theory, testing methods, and maintenance planning. The new material provides a clear understanding concerning what fails within power equipment and how the equipment fails. Once a clear understanding of the failure modes of equipment is established, correct maintenance strategies can be developed to address such failures before they happen. Also, an extensive discussion has been undertaken on the basis of maintenance of protective devices and how such maintenance, or lack of such maintenance, will impact the arc-flash hazard exposure, hazard labeling of equipment, and personnel protective equipment. Chapter 2 has been devoted to testing with direct current (DC) voltage of various types of electrical equipment and apparatus, including its advantages and disadvantages. Chapter 3 deals with testing with alternating current (AC) voltage, for example, power factor (Doble) and dissipation factor (Tan Delta) test methods. Advantages as well as limitations of the AC voltage methods are discussed to provide a thorough understanding of this subject. Chapter 4 covers the testing of oil and insulating fluids used in electrical apparatus such as transformers and circuit breakers. The description of maintenance and test methods includes typical problems found in these types of insulation systems.

In Chapter 5, information on transformer maintenance and testing, including installation, application, and operation as it relates to the reliability of transformers, is discussed. This chapter has been expanded to include the latest tests performed on transformers including online monitoring and diagnostic tests. Chapter 6 has been devoted to the discussion of cables, including their construction, application, failure modes, and testing, as well as cable fault locating methods. The section on cable testing in this revision now includes information on cable degradation and diagnostic tests; online and off-line tests such as PF, VLF, partial discharge, and AC resonance; a summary of comparison of various field tests; and latest trends in cable diagnostic testing. Chapter 7 has been revised to solely cover inspection, maintenance, and testing of medium- and high-voltage switchgear and control power. Information has also been provided on the rating system used for circuit breakers and how these are selected and applied in switchgear

applications. Additional information has been provided on circuit breaker time travel analysis to explain this test in more detail and how this test can be used to ensure the reliability of medium- and high-voltage breakers. Chapter 8 is devoted to the maintenance and testing of low-voltage (below 1000 V) switchgear and circuit breakers. This chapter provides information on Underwriters Laboratories' testing, labeling, and verification of these breakers in the field. Additional information has been provided in this chapter on assessing service life and endurance requirement for low-voltage breakers, mechanical maintenance factors such as lubrication, electrical maintenance factors, and information on how to conduct thermographic surveys.

A new Chapter 9 covers instrument transformers and testing and commissioning of protective relays. The information in this chapter explains the theory, application, and testing of instrument transformers, and electromechanical, solid-state, static, and microprocessor relays. The commissioning of microprocessor relays including event reporting has been covered in greater detail with examples of commissioning microprocessor relays in this chapter. The protective relays, especially microprocessor relays, are an important part of the power system; hence they are retained in the respective chapter in this edition. The maintenance and testing of motors and generators, including the makeup of the insulation systems used in these machines and their temperature rating system, are covered in the new Chapter 10. This chapter has been revised to include an extensive guide on preventative maintenance of motors and variable frequency drives. In this chapter, a detailed discussion has been added on online and off-line partial discharge testing and vibration analysis of motors. The original Chapter 10 has been renumbered as Chapter 11, which covers electrical power system grounding and ground resistance measurements. Various grounding systems are described to provide an understanding on what is a good ground and how to obtain it. A new Chapter 12 has been added in this revision to cover power quality and harmonic issues and their relationship to predictive maintenance since many of the causes of equipment failures are now being attributed to poor power quality and harmonics. It is expected that the information in this chapter will help the reader understand poor power quality and how it can affect the health and reliability of electrical equipment and apparatus. It is hoped that the monitoring of power quality will receive the required attention so corrective actions can be implemented to minimize equipment degradation and failures.

On-site safety and switching practices required during maintenance and testing of electrical equipment are now covered in Chapter 13, as are National Electrical Code (NEC), National Safety Code, and OSHA requirements as they relate to the maintenance and testing of electrical equipment as well as arc-flash hazard analysis and exposure. A new section has been added in this chapter on arc-flash hazard regulatory basis, what it is, and how to perform an arc-flash hazard study.

It is hoped that this book will serve as a practical guide that engineers and technicians can use for the maintenance and testing of electrical equipment. To make this book useful, many tables, test connection diagrams, and

photographs are provided throughout the book. One of the complicated aspects of testing is the interpretation of test results—it is difficult to judge how good or bad test results are unless the previous year's test results are available for comparison. Various minimum values are used as rules of thumb for assessing the relative health of the insulation of electrical equipment. In this book, I have provided some insights on these rules of thumb and why they should not be followed blindly. It is my belief that the knack for interpreting test results can be gained only by acquiring this knowledge and hopefully this book fulfills this need. To a great extent this is the only book that makes a significant attempt to address this issue.

I hope that this book may prove useful both to budding and experienced engineers alike. With this book they can acquire the needed knowledge and application to pursue further studies in this field. I believe that most aspects of this subject that were thought to be necessary are covered in this revision. It is possible that some aspects of this subject are not covered, or in detail to the extent necessary for a good understanding of the subject. I would welcome and appreciate any suggestions from readers to make this book even more useful and current.

Paul Gill, P.E.

Acknowledgments

This book is based on my notes and my previous two volumes, *Electrical Equipment Testing and Maintenance* (1982), and *Electrical Power Equipment Maintenance and Testing* (1997), which were used in teaching a course on electrical equipment maintenance and testing at the George Washington University and at IBEW Local 26. The production of a book requires the cooperation and effort of many people and institutions. It is difficult to appropriately acknowledge all the organizations and individuals who helped in the development of a book of this type.

I would particularly like to thank the major electrical manufacturers, testing services companies, electrical test equipment manufacturers, various private and government organizations, and professional societies and organizations for making information available. Where possible, I have tried to give recognition to the source of the information obtained.

I wish to acknowledge explicitly the following organizations and persons for their review and support in the development of this book. The staff of Megger Incorporated, Valley Forge, Pennsylvania (formerly AVO International, Dallas, Texas) reviewed and provided comments on Chapters 2 and 6. Additionally, I thank the various staff at Megger Incorporated for helping to teach cable fault locating in a course on maintenance and testing at the George Washington University and providing review comments on the section on cable fault locating in Chapter 6. The information on power factor testing in Chapter 3 is based on the Double Engineering Company's literature and their past contributions in teaching maintenance and testing courses at the George Washington University. I am also grateful to them for reviewing and commenting on Chapter 3. The information in Chapter 4 on dissolved gas analysis is condensed from the IEEE std. C57.104-1991. I thank the personnel of Baron USA, Inc., Cookville, Tennessee for providing an overall review and comments on Chapter 4. Alan Peterson of Utility Services and chairman of the NETA Technical Committee peer-reviewed many chapters for this revision and I thank him for his support. The information on ground resistance measurements and testing was supplied by AEMC Instruments, Boston, Massachusetts, and for which I thank them.

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I also wish to thank Alan D. Peterson and Jayne Tanz of the InterNational Electrical Testing Association for writing the Foreword and recommending the book. Finally, I thank all my students who have taken the maintenance and testing course at the George Washington University and the IBEW Local 26 who made it possible for me to teach and write this book in the first place.