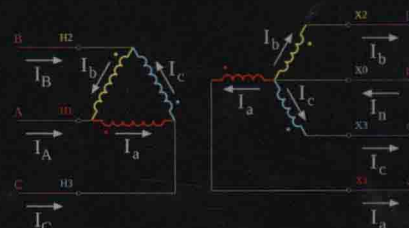
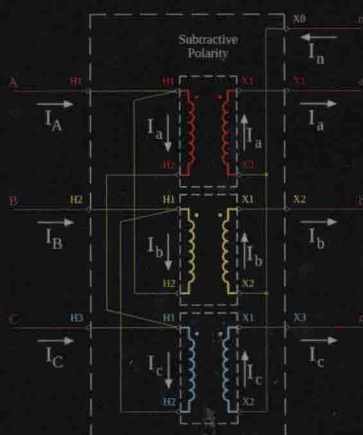


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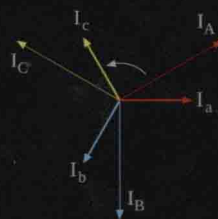
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PREFACE

SINCE THE RELEASE of the first edition in October 2001, I have received many comments from readers saying how helpful the text was while preparing for and taking the Professional Engineering (PE) examination. Truth be told, I never really thought about the PE exam while preparing the first edition manuscript. My objective was simply to produce a book useful to both students and practitioners. When the National Council of Examiners for Engineering and Surveying (NCEES) restructured the Electrical Engineering PE exam in April 2009 creating a power-specific exam, I saw the relevance of aligning this text more with the new exam format.

Several new topics, including arc flash hazard and lighting systems, have been added to this edition, keeping current with the latest trends and practices in the power field. More depth and some derivations have also been added to other sections, such as an in-depth exploration of the per-unit system, additional material on motor application, a thorough analysis of AC power in both the time and phasor domains, and an intuitive development of three-phase symmetrical components. I have never believed in deriving an equation simply for the sake of deriving it (that is a great exercise for mathematicians, but engineers should focus their efforts on application of the formula), but AC power and symmetrical components are exceptions to my tenet on derivations since these are so widely used by power engineers, and complete comprehension, in my opinion, requires going through the step-by-step development. Enhancements such as these should add to the level of understanding of critical power engineering concepts for many students.

Practitioners in the electric power industry will also find this book useful both as a reference and as a means of filling in gaps in their understanding of key concepts. Based largely on practices in the United States, this book references primarily US standards and codes. Often times, similar standards and codes have been developed and adopted abroad, and readers outside the United States are encouraged to investigate local standards and codes. Similarly, customary US units of measurements, as are commonly encountered in the United States, are used throughout the book.

The material covered in this book will be a valuable reference for the practicing power engineer, but will be just as helpful to the engineering student pursuing a career in the power industry. Few US universities have comprehensive programs in electric power that align with industry requirements. Narrowing the gap between what topics are taught at the university and what skills are needed by industry should be made a very high priority, both in academia and in industry. A close academia–industry partnership is needed to accomplish such a lofty goal. It is my hope that this book will help narrow the gap and forge the partnership. Developing new courses based on *Industrial Power Distribution* and incorporating the book into existing courses will facilitate the alignment of the academic curriculum with industry needs.

Over 370 students at the University of South Florida and many more through short courses conducted worldwide have studied the contents of the first edition, and as a result, many constructive comments were made. Between those comments and the expertise of the manuscript reviewers, I believe the second edition of *Industrial Power Distribution* will be a valuable resource for engineering students and practicing power engineers alike, and will help create an academic environment better able to address the needs of the electric power industry.

Ralph E. Fehr, III

PREFACE TO THE FIRST EDITION

ELECTRICITY has been an essential part of our lives since the late nineteenth century. During the early twentieth century, electricity routinely began replacing steam as the primary power source in industrial plants. As factories became larger and more complex, so did their power requirements. As such, engineers were faced with a new challenge: how to distribute electricity safely, reliably, and economically within the industrial facility. Although this challenge has been addressed for over a century, the theories, requirements, and procedures for safe, reliable, and economical industrial power distribution have not been presented in textbook form. This work attempts to do so by drawing on more than a hundred years of lessons learned and refinements in the electrical power distribution field.

The book begins by analyzing the source of the electricity—the utility system. Requirements including the delivery voltage and the topology of the source are explored, along with their impact on the operation and reliability of the industrial facility. Next, a powerful calculation method using the per-unit system is reviewed, and this method is applied extensively throughout the text. Other power source issues such as short circuit availability and transformer sizing are discussed, followed by a brief presentation on metering methods.

The next topic covered is medium-voltage distribution systems within the industrial facility. Guidelines for selecting the optimum voltage are presented. Various transformer connections are analyzed to determine their effects on the behavior of the electrical system. Ferroresonance and methods of eliminating its undesirable effects are introduced. Methods of conductor sizing consistent with the National Electrical Code (NEC) also are presented.

Two chapters are devoted to the calculation of fault currents and the sizing of protective equipment such as circuit breakers and fuses. The method of symmetrical components is used to analyze unbalanced fault conditions.

Switchgear and motor control centers, two types of equipment used extensively to distribute electricity within industrial facilities, are examined in detail including specification and selection requirements. Raceway design including conduit, duct banks, and cable tray is covered consistent with NEC specifications.

Methods of motor starting and motor control are discussed, and a detailed tutorial on ladder logic is included. The application of shunt capacitors for power factor correction rounds out the text.

Useful engineering data is presented in the appendices. This data, including units of measurement, circuit analysis techniques, impedance data, ampacity data

reprinted from the NEC, and conduit data, provides a valuable reference source for the engineer.

The material in this book serves not only as an informative textbook, but also as a concise reference book. Objectives are clearly stated at the beginning of each chapter, and a succinct summary is presented at the end of each chapter. Questions to test the reader's comprehension of important concepts and problems to check the reader's ability to apply theory to solve practical problems are provided for each chapter.

This text is designed for use at either the upper-division undergraduate or graduate level. An understanding of basic power system analysis is the only prerequisite necessary to comprehend fully the material presented in this book.

Ralph E. Fehr, III

ACKNOWLEDGMENTS

THE AUTHOR wishes to thank the many people who contributed their expertise and insight to this book, particularly the technical reviewers of the first edition: Ralph D. Painter, the late Charles Concordia, and the late Joseph P. Skala.

Mr. Painter has been a resident of Florida for over 50 years. He earned BSEE and ME degrees from the University of South Florida, and a JD degree from Stetson University College of Law. He is a senior member of the IEEE, a registered professional engineer in Florida, a Master Electrician in the City of Tampa, and a member of the Florida Bar. Mr. Painter has been employed by Tampa Electric Company for over 40 years in various engineering positions related to power plant electrical system operation, maintenance, and design and regulatory compliance. He is currently Manager—FERC Compliance.

Dr. Concordia needs no introduction to the members of the power engineering community. He worked for over 40 years for the General Electric Company in Schenectady and later as a consultant, making countless contributions to the areas of system analysis and machine design. He was awarded the prestigious IEEE Medal of Honor in 1999 and has worked in the electric power industry for over 70 years. His accomplishments in the area of electric power are astonishing, and his willingness to share his expertise and experience are deeply appreciated.

Mr. Skala had been a dear friend and colleague since I arrived in Florida in 1992. His interest in teaching encouraged me to become more involved in academia. He retired as a power systems engineer with a 30-year background in the utility industry, including transmission and substation design, transmission and distribution maintenance, system planning, and research and development. His extensive experience allowed him to build a tremendous base of expertise, from which I have received benefits many times. Mr. Skala was recognized for his creativity and innovation, both as an engineer and as an educator. For 20 years, he has taught electrical engineering and mathematics courses in the State of Florida University System. As a teacher, he established the graduate power systems program at the University of South Florida and co-founded the DiNapoli-Skala Families Scholarship at St. Petersburg Junior College, which provides assistance to students with a demonstrated financial need. Mr. Skala's contributions to the power industry and academia were many, and through them, he will live on.

I would also like to thank two additional electrical engineers who were instrumental in the development of this book. My father, Ralph E. Fehr, II, worked as an electrical power engineer for over 33 years. He was a registered professional engineer in Pennsylvania, was active as a member and section/committee chairman of the IEEE, and served on numerous technical committees of the Pennsylvania Electric Association. My uncle, Arthur R. Hill, taught electrical engineering and electrical

engineering technology courses at the Berks Campus of the Pennsylvania State University for over 36 years. He also prepared electrical and electronics training and testing programs for several industries. In addition to reviewing the manuscript of this book, my father and uncle provided a supportive academic environment and guided me into the field of engineering.

Key contributors to the second edition include Serge Beauzile (Lakeland Electric Co.), Marcel Bertran (GE Energy Services), Thomas Blair (Tampa Electric Co.), Dave Darden (Tampa Electric Co.), Craig Kalhoefer (Harold Hart & Associates, Inc.), Michael Milbert (Engineering Consultant), John Raksany (University of Wisconsin—Madison), Titipong Samakpong (Provincial Electricity Authority of Thailand), and Harianto Suryo (Lakeland Electric Co.).

And a special thank you to Karen Fehr and Margaret McMullen, who read every page of this second edition manuscript and helped to make this book the best it could be.

ABOUT THE AUTHOR

RALPH E. FEHR III, earned a Bachelor of Science degree in Electrical Engineering from the Pennsylvania State University in 1983, a Master of Engineering degree in Electrical Engineering (Power) from the University of Colorado at Boulder in 1987, and a Doctor of Philosophy in Electrical Engineering from the University of South Florida in 2005. He has worked in the generation engineering field, designing power distribution and control systems for nuclear and fossil-fired power plants. Dr. Fehr also has worked for electric utilities for more than 15 years in the operations, planning, and design areas including transmission, distribution, and substation engineering.

Teaching always has been an important aspect of Dr. Fehr's career. On an adjunct basis, he has taught courses ranging from computer operating systems to mathematics to power system analysis for several institutions including the University of New Mexico at Albuquerque, St. Petersburg (Florida) Junior College, and the University of South Florida at Tampa. He has also taught short courses in the power engineering area domestically and abroad for the Pennsylvania State University and the University of Wisconsin–Madison. Since 1996, he also has taught a review course for professional engineer examination candidates. Dr. Fehr has expanded the power engineering program at the University of South Florida with the goal of producing a greater number of proficient engineering graduates for the power industry.

Dr. Fehr is a senior member of the Institute of Electrical and Electronics Engineers (IEEE) and is a registered professional engineer in New Mexico and Florida. His biography was published in *Who's Who in Science and Engineering*. He also received the 2010 Joseph Biedenbach Award from IEEE Region 3 as Outstanding Engineering Educator from the southeast United States. He currently serves on the Electrical Engineering Faculty at the University of South Florida, where he oversees the school's power engineering program.

CONTENTS

<i>PREFACE</i>	xi
<i>PREFACE TO THE FIRST EDITION</i>	xiii
<i>ACKNOWLEDGMENTS</i>	xv
<i>ABOUT THE AUTHOR</i>	xvii

CHAPTER 1	<i>UTILITY SOURCE</i>	1
------------------	------------------------------	----------

1.1	Electrical Safety	1
1.2	Delivery Voltage	3
1.3	One-Line Diagrams	4
1.4	Zones of Protection	5
1.5	Source Configuration	6
1.6	The Per-Unit System	14
1.7	Power in AC Systems	18
1.8	Voltage Drop Calculations	20
1.9	Short-Circuit Availability	22
1.10	Conductor Sizing	23
1.11	Transformer Sizing	26
1.12	Liquid-Immersed Transformer kVA Ratings	30
	Summary	32
	For Further Reading	33
	Questions	33
	Problems	34

CHAPTER 2	<i>INSTRUMENT TRANSFORMERS AND METERING</i>	37
------------------	--	-----------

2.1	Definitions	37
2.2	Instrument Transformers	39
	2.2.1 Fundamentals	39
	2.2.2 Correction Factors	46
	2.2.3 Burden Calculations	47
	2.2.4 ANSI Accuracy Classes	49
2.3	Metering Fundamentals	49
2.4	Watthour Metering	50
	2.4.1 Single-Stator Watthour Metering	50
	2.4.2 Multi-Stator Watthour Metering	52
2.5	Demand Metering	52
	2.5.1 Kilowatt Demand	53
	2.5.2 Kilovar and kVA Demand	53
2.6	Pulse-Operated Meters	54

2.7	Time-of-Use Meters	54
2.8	Special Metering	55
2.8.1	Voltage and Current Metering	55
2.8.2	Var and Q Metering	57
2.8.3	Compensating Metering	59
2.8.4	Totalizing Metering	60
2.8.5	Pulse Recorders	60
2.9	Digital Metering	61
2.10	Smart Meters	61
	Summary	62
	For Further Reading	63
	Questions	63
	Problems	64

CHAPTER 3 TRANSFORMER CONNECTIONS

65

3.1	Voltage Selection	65
3.2	Ideal Transformer Model	66
3.3	Transformer Fundamentals	68
3.4	Transformer Circuit Model	71
3.5	Single-Phase Transformer Connections	71
3.6	Three-Phase Transformer Connections	73
3.6.1	Delta–Delta	74
3.6.2	Wye–Wye	76
3.6.3	Delta–Wye	78
3.6.4	Wye–Delta	82
3.6.5	Open Delta–Open Delta	82
3.6.6	Open Wye–Open Delta	86
3.7	Two-Phase Transformer Connections	88
3.7.1	T-Connection (Scott Connection)	89
3.8	Six-Phase Transformer Connections	92
3.9	Transformer Phase Shifts	93
3.10	Grounding Transformers	95
3.10.1	Wye–Delta	96
3.10.2	Zig–Zag Connection	96
3.11	Ferroresonance	97
	Summary	98
	For Further Reading	98
	Questions	99
	Problems	99

CHAPTER 4 FAULT CALCULATIONS

101

4.1	Overview	101
4.2	Types of Faults	102
4.3	Data Preparation	103
4.4	First-Cycle Symmetrical Current Calculations	105
4.5	Contact-Parting Symmetrical Current Calculations	112
4.6	Analyzing Unbalanced Systems	113
4.7	Physical Example of Vector Components	114

4.8	Application of Symmetrical Components to a Three-Phase Power System	116
4.9	Electrical Characteristics of the Sequence Currents	121
4.10	Sequence Networks	124
4.11	Short-Circuit Faults	134
4.11.1	Three-Phase Fault	134
4.11.2	Line-to-Ground Fault	136
4.11.3	Double Line-to-Ground Fault	138
4.11.4	Line-to-Line Fault	141
4.12	Open-Circuit Faults	143
4.12.1	One-Line-Open Fault	143
4.12.2	Two-Lines-Open Fault	147
	Summary	150
	For Further Reading	150
	Questions	151
	Problems	152

CHAPTER 5 *PROTECTIVE DEVICE SELECTION AND COORDINATION*
155

5.1	Overview	155
5.2	Power Circuit Breaker Selection	158
5.3	Fused Low-Voltage Circuit Breaker Selection	160
5.4	Molded-Case Circuit Breaker Selection	162
5.5	Medium-Voltage Fuse Selection	163
5.6	Current-Limiting Fuse Selection	166
5.7	Low-Voltage Fuse Selection	168
5.8	Overcurrent Device Coordination	169
5.9	Summary	174
	For Further Reading	175
	Questions	175
	Problems	176

CHAPTER 6 *RACEWAY DESIGN*
179

6.1	Overview	179
6.2	Conduit and Duct Systems	181
6.2.1	Pulling Tension	187
6.2.2	Sidewall Pressure	188
6.2.3	Design Examples	189
6.3	Cable Tray Systems	194
6.3.1	Design Example	202
	Summary	203
	For Further Reading	203
	Questions	204
	Problems	204

CHAPTER 7 *SWITCHGEAR AND MOTOR CONTROL CENTERS*
207

7.1	Overview	207
7.2	NEMA Enclosures	208

7.3	Switchgear	208
7.3.1	Source Transfer	213
7.3.2	Configuration	214
7.3.3	Ratings	215
7.3.4	Circuit Breakers	217
7.4	Motor Control Centers	222
7.4.1	Configuration	223
7.4.2	Ratings	223
7.4.3	Starters	223
7.4.4	Protection	225
7.5	ARC Flash Hazard	226
	Summary	231
	For Further Reading	232
	Questions	233
	Problems	233

CHAPTER 8 LADDER LOGIC**235**

8.1	Fundamentals	235
8.2	Considerations When Designing Logic	236
8.3	Logic Implementation	239
8.4	Seal-In Circuits	240
8.5	Interlocks	243
8.6	Remote Control and Indication	245
8.7	Reversing Starters	246
8.8	Jogging	248
8.9	Plugging	250
	Summary	251
	For Further Reading	251
	Questions	251
	Problems	252

CHAPTER 9 MOTOR APPLICATION**255**

9.1	Fundamentals	255
9.2	Energy Conversion and Losses	259
9.3	Speed-Torque Curves	260
9.4	Motor Starting Time	263
9.5	Cable Sizing	264
9.6	Motor Protection	265
9.7	Circuit Protection	266
9.8	Winding Protection	266
9.9	Motor Starting Methods	267
9.9.1	Across-the-Line	267
9.9.2	Reduced Voltage Starting	267
9.9.3	Wye-Delta Starting	276
9.9.4	Part-Winding Starting	278
9.9.5	Solid-State Starting Options	278
	Summary	283
	For Further Reading	283