可靠性工程原理

郭永基　编著

清华大学出版社　Springer

(京)新登字 158 号

内 容 简 介

本书系统地讲述了可靠性工程原理,其特点是:强调基础,反映新成果,重视应用,适宜自学。全书共分 8 章。前 5 章介绍原理,后 3 章介绍几种典型应用。第 1 章介绍了可靠性工程的内容和分析方法。第 2 章介绍了指数分布等 7 种典型故障函数和强度应力模型。第 3 章介绍了不可修复系统的可靠性评估方法,包括串联系统、并联系统、表决系统等可靠性模型,以及用最小路集和最小割集分析系统可靠性的方法。第 4 章和第 5 章介绍了马尔柯夫过程和马尔柯夫链的基本原理和基本方程以及可修复系统可靠性的分析方法。第 6 章介绍了软件可靠性。第 7 章介绍了可靠性与经济性的协调。第 8 章介绍了电力变压器的可靠性。

本书可作为工程、管理、科学等有关系科的本科、研究生学习可靠性工程时的教材或参考书,也可供政府或企业的领导、工程师、经济师、大学教师阅读参考。

书　　名: 可靠性工程原理
作　　者: 郭永基　编著
出 版 者: 清华大学出版社(北京清华大学学研大厦,邮编 100084)
　　http:// www .tup .tsinghua .edu .cn
责任编辑: 王一玲
印 刷 者: 北京通县大中印刷厂
发 行 者: 新华书店总店北京发行所
开　　本: 787×1092 1/ 16　印张: 17 .5　字数: 351 千字
版　　次: 2002 年 1 月第 1 版　2002 年 12 月第 2 次印刷
书　　号: ISBN 7-302-04918-1/ TB・38
印　　数: 4001～6000
定　　价: 24 .00 元

前　言

可靠性是元件、产品或系统的完整性的最佳度量。可靠性是元件、产品、系统在规定环境下,规定时间内,规定条件下无故障地完成其规定功能的概率。

可靠性工程提供了理论和实用的工具,使元件、产品或系统在规定环境下,规定时间内,规定条件下无故障地完成其功能的概率和能力得以评定、预测、设计和试验。

科技进步推动生产复杂产品并形成越来越多的复杂系统,例如装配生产线、通信设备、计算设备、防污染设备、原子能电站、家用取暖及制冷设备、电力系统。这些产品和系统建造费用昂贵,若在运行中出现故障则损失更大。可靠性评估的作用日显重要。

近十年作者为清华大学的电气工程与其他工程系科的高年级学生及一年级研究生开设"可靠性工程原理"课程。这门课颇受学生欢迎。本书就是在《可靠性工程原理》讲义的基础上出版的。该讲义获1996年清华大学优秀教材奖。

本书融入了作者在清华大学近十年积累的科研成果和教学经验,具有强调基础、反映新成果、重视应用、适宜自学的特点。书中反映了作者大量的科研成果,如基于对数正态分布的强度应力模型、变压器寿命评估、停电损失费用估计、中国产电比数值等。全书精选了约200道例题,以帮助读者理解基本概念和自学。约110道习题的解答附在书末。因此,本书也可作为有志进入现代可靠性领域的工程师们的参考书。

本书共有8章。

第1章是可靠性工程领域的概论,介绍了可靠性和可靠性工程的基本概念。

第2章讨论了广泛应用的一些故障函数,包括二项分布、泊松分布、指数分布、威布尔分布、正态分布、对数正态分布和极值分布等,并介绍了强度—应力模型。

第3章讨论了不可修复系统的可靠性估计方法,包括串联系统、并联系统、储备系统、表决系统的可靠性评估方法。还介绍了用最小路集法和最小割集法求复杂系统可靠性的方法。讨论了故障树分析法和故障模式、影响和危险度分析法。

第4章介绍马尔柯夫过程和马尔柯夫链。讨论了求解瞬时状态概率和平稳状态概率的方法。

第5章介绍了应用马尔柯夫过程评估可修复系统可靠性的方法。讨论了频率和持续时间法,混合乘积法。介绍了串联结构、并联结构、r/n结构的近似等值。还讨论了共同模式故障。

第6章介绍了软件可靠性。给出了软件可靠性的基本定义及指标。介绍了运行

可靠性、系统性能可靠性、可靠性增长函数。

第 7 章介绍可靠性和经济的协调。包括冗余经济学、修理和维修经济学,以及评估停电损失费用的各种办法。

第 8 章介绍电力变压器的可靠性。介绍了评估电力变压器可靠性指标的统计方法以及基于检测老化过程中聚合度的中小型变压器寿命评估方法。

作者对帮助出版此书的个人及单位致谢。程林博士、博士研究生张鹏、宋云亭校读了全书手稿。清华大学选修过我的课程的学生也曾对讲义提出过改进的意见。清华大学教材基金资助了本书的出版工作,在此表示感谢。

最后,感谢我的夫人朱爱菁教授的帮助。

郭永基 教授
2001 年 4 月
清华大学

Preface

Reliability is the best quantitive measure of the integrity of a designed component, product or system .

Reliability is the probability that components, products, or systems will perform their designed-for functions without failure in specified environments for desired periods under specified conditions .

Reliability engineering provides the theoretical and practical tools whereby the probability and capability of components, products, or systems to perform their required functions without failure in specified environments for desired periods under specified conditions, can be specified, predicted, designed and tested .

Scientific and technological advances produce or form more and more complex products and systems, for example, assembly lines, communication equipment, numerically machine tools, antipollution equipment, atomic energy plants, homeheating and cooling machines, electric power systems . These products and systems are massively expensive to build, and even more expensive if they fail to operate as designed . Reliability evaluation takes on an ever increasing importance . The emphasis placed on quality and reliability of products further stresses the need for studying, quantifying and innovating to improve the reliability of engineering systems .

Recent 10 years, the author lectured the course *Principle of Reliability Engineering* at the senior-elective level in Electrical Engineering Department, Tsinghua University . This course is welcomed by students .

This book is published based on lecture note *Principle of Reliability Engineering* which was awarded excellent lecture note prize by Tsinghua University in 1996 . The materials contained in the book have evolved over a period of 10 years of teaching experiences . This book is characterized by four features: emphasis on fundamentals, reflection of new advances in science and technology, emphasis on applications, suitability of self-study . Newest scientific research results achieved by the author are reflected in this book . These materials include strength-stress model based on lognormal distribution, lifetime evaluation of transformer based on degree of polymerization, outage cost evaluation, statistical

values of ratio of output value to unit energy consumption . Nearly 200 carefully selected examples and problems are included to illustrate the basic concepts and to assist readers in self-study . Answers to all 110 problems are given at the end of the text . Thus, this book can also serve as reference for practicing engineers who is entering the field of reliability .

There are 8 chapters in this text .

Chapter 1 contains an introduction to the field of reliability engineering . Basic concepts of reliability and reliability engineering are introduced .

Chapter 2 discusses the important distributions that have found widely applications in modeling reliability functions . These distributions are: Binomial distribution, Poison distribution, Exponential distribution, Normal distribution, Weibull distribution, Lognormal distribution, Extreme-value distribution .

Chapter 3 discusses methods for reliability evaluation of non-repairable systems, including series system, parallel system, standby system, voting system . Determination of complex system reliability using minimum path sets and minimum cut sets is introduced . Fault Tree Analysis (FTA), Failure Mode, Effects and Criticality Analysis (FMECA) are discussed .

Chapter 4 introduces Markov process and Markov chain . Methods for determining transient state probabilities and steady state probabilities are discussed .

Chapter 5 introduces methods for reliability evaluation of repairable systems using Markov process . Frequency and duration technique and mixed product approach are discussed . Approximation of series structure, parallel structure, r/n structure is introduced . Common-mode failure modeling is discussed .

Chapter 6 introduces software reliability . Basic definitions of software reliability are introduced . Reliability indices of software are mentioned . Run reliability, system performance reliability, reliability growth function are introduced .

Chapter 7 introduces coordination of reliability and economics . Redundancy economics, repair and maintenance economics are introduced . Methods for evaluation of outage cost in different countries are mentioned . New methods for evaluating outage cost are presented .

Chapter 8 introduces power transformers reliability . Evaluation of reliability indices of power transformers based on statistics are introduced . Evaluation of lifetime of small and medium size transformers based on detection of degree of

polymerization by accelerated lifetime experiments is presented .

My sincere thanks to the following individuals and organization who provided help for preparing this book . Doctor Chen Lin, Doctoral Candidates Zhang Peng and Song Yuntin proofread the manuscript of whole book . Students of Tsinghua University who elected my course provided comments for improvement of the text . Foundation of text books of Tsinghua University sponsors the publication of this book .

Finally my special thanks to my wife Prof . Zhu Aijing for her patience and assistance in making the writing of this book possible .

Prof . Guo Yongji
April 2001
Tsinghua University

作 者 简 介

郭永基,男,广东潮阳人。毕业于　华大学电机系。在原苏联列宁格勒工业大学(今圣彼得堡国立技术大学)获技术科学博士学位。历任清华大学助教、讲师、副教授、教授,第五届校学位委员会委员兼电机系学位委员会主席。现为清华大学教授,博士生导师,中国电工技术学会电工产品可靠性研究会副理事长,燕山大学兼职教授,美国 IEEE 高级会员。长期从事电力系统及其自动化、电力系统及电工产品可靠性和故障诊断的教学和研究工作。曾主持和参加多项科研课题,获多项创新成果。在《电机及电力系统稳定分析和控制》项目中,首次提出了考虑电机惯性常数、电网电压及负荷特性的发电机自励磁分析理论,绘制了新的自励区,并经物理模拟试验证实。该项目属国际领先水平,获 1988 年国家自然科学二等奖和国家教委科技进步一等奖。在《提高全密封油浸变压器可靠性的研究》项目中,提出了基于聚合度的中小型变压器寿命评估理论和实验方法,测定 SBS9 变压器的期望寿命为 20 年。该项目属国际先进水平,获国家教委 1996 年科技进步三等奖。在《电力系统及设备可靠性理论及应用》项目中,发表了论文近 20 篇,著作 2 部,该项目属国际先进水平,获教育部 1998 年科技进步三等奖。在《华北和东北电力系统互联后东北 500kV 及 220kV 主系统可靠性的研究》项目中,首次提出基于蒙特卡洛模拟法评估及多重故障的大规模电力系统可靠性的算法及软件;并从理论上阐明大模型电力系统考虑多重故障的重要性。实践中,该项目解决了华北—东北联网后东北电力系统的可靠性评估。该项目属国际先进水平,获教育部 1999 年科技进步三等奖。在《持续高效开展继续教育》项目中,对继续教育作出了重要贡献,获 1997 年北京市教学成果二等奖。在《干式变压器三个关键技术问题的研究》项目中开发了干式变压器电磁优化设计软件和基于二维温度场偏微分方程数值解的干变温度场分析软件,确定了线圈的最热点。进行了环氧树脂样品的加速寿命试验。该项目属国际先进水平,获北京市 2000 年科技进步三等奖。2000 年起主持了《田湾核电站外部电力系统可靠性研究》及《龙滩水电站电气主接线可靠性评估》等国家重点项目,取得高水平的研究成果。

为本科及研究生开设课程 8 门。已培养博士及硕士 18 名。著有《电力系统新进展》、《电力系统可靠性原理和应用》(上、下册),合著有《串联电容引起的交流电机自激》、《中国电力百科全书·电力系统卷》(一版、二版)、《中国电机工程师手册·基础卷》,合译有《电力系统可靠性》、《自动控制系统可靠性的理论基础》。发表论文 100 余篇。被《科学引用索引(SCI)》及《工程索引(EI)》引录 20 篇次。代表性论文有《基于蒙特卡洛法的大电力系统可靠性评估》、《概率电压稳定分析》、《配电系统可靠性评估》、《中小型变压器寿命评估》。事迹被收入英国出版的《世界名人字典》,我国出版的《中国专家大辞典》、《中华人物辞海》、《世界文化名人辞海》等。

About the author

Guo yongji, male, born in Guangdong Province. He graduated from Tsinghua University in Electrical Engineering Department. He received degree of Doctor of Technical Sciences at former Leningrad Polytechnical Institute, Leningrad, USSR (now Saint Petersburg National Technical University, Saint Petersburg, Russia). He was appointed in Tsinghua University as assistant, lecturer, associate Professor, Professor, member of 5th Academic Degree Commission of Tsinghua University and Chairman of Academic Degree Sub-commission of Electrical Engineering Department. Now he is appointed as a professor, supervisor of doctoral candidates, Vice-Chairman of Reliability Society of Electrical Products and Equipment, China Electrotechnology Society. He is an IEEE senior member.

Professor Guo for a long time engages in research and teaching works in the field of power systems and its automation, power systems and equipment reliability, diagnosis of equipment. He directed and directs tens of scientific research projects and achieves lots of creative results. In project <*Analysis and control of electrical machines and power systems*>, he presents analytical theory of A. C. machine self-excitation with consideration of machine interia constant, network voltage and load characteristics and is verified by physical simulation experiments. This project is estimated as lead level in the world, and received 2nd grade State Nature Science award issued by State Science and Technology Commission and 1st grade scientific and technological progress award issued by State Education Commission in 1988. Prof. Guo proposes new methodology for lifetime evaluation of small and medium size transformers based on detecting degree of polymerization by accelerated experiments of insulated papers. Expected lifetime of SBS9 transformer is evaluated as 20 years by using the method presented. This project was estimated as international advanced level, and received 3rd grade scientific and technological progress award issued by State Education Commission in 1996.

Prof. Guo received 3rd grade scientific and technological progress award issued by State Education Ministry in 1997 based on acheivements of project *A study of fundalmentals of power systems and equipment reliability* which evolves 2

monographes and 20 scientific papers .

Prof . Guo received 2nd grade teaching acheivements award issued by Beijing city Government due to contributions on continuing education . Prof . Guo received 3rd grade scientific and technological progress award issued by State Education Ministry in 1999 based on achievements of project *North-East China* 500kV *and* 220kV *bulk power system reliability evaluation considering interconnection of North China and North-East China power systems* . In this project, algorithm and software for large scale system are developed based on Monte-Carlo simulation which are successfully applied to interconnection of North China and North-East China Power Systems . Necessity of considering multiple contingencies for reliability evaluation is verified theoretically . The results of this project is estimated as international advanced level in technology .

Prof . Guo received 3rd grade scientific and technologyical progress award issued by Beijing City Government due to achievements of project A study of 3 key technical problems of dry type transformers . In this project, softwares for electromagnetic optimum design of dry type transformer, software for temperature distribution calculation of dry type transformes based on Poison temperature field partial differential equations are developed . Hotest points of windings of dry type transformers are determined by using the software .

Prof . Guo lectured 8 courses at undergraduate and graduate levels . He has cultivated 18 masters and doctors . He is author of books *Advances in Power Systems*, *Fundamentals and Applications of Power System Reliability* (Vol Ⅰ, Vol Ⅱ) . He is a co-author of books *Self-excitation of AC motors connected to distribution lines with series compensation*, *China Electric Power Encyclopedia— Power System Volume* (First Edition), *China Electric Power Encyclopedia— Power System Volume* (Second Edition), *Handbook of Electrical Engineers— Fundamentals volume* . Prof . Guo is co-author of translated books *Power System Reliability*, *Fundamentals of reliability of automatic control systems* . Prof . Guo delivered more than 100 scientific journal papers, among them 20 papers are cited by SCI and EI . His representative papers are: *Composite System reliability evaluation based on Monte-Carlo simulation considering failures screening*, *Probabilistic Voltage stability analysis*, *Distribution reliability evaluation*, *Lifetime evaluation of medium and small size transformers* . His biography is published in *Didctionary of Whos Who in the World* by UK, *Dictionary of Chinese Experts*, *Chinese Talents Dictionary and Grobal Curtural Celebrities Dictionary* .

目　　录

Contents