Hydropower Process Control
—Theory, Application & Development

Ye Luqing

水力发电过程控制
理 论 、 应 用 及 发 展

叶鲁卿 著

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内容简介

本书是作者近20年来在水力发电领域所取得的研究成果的总结，主要由20世纪80年代以来作者在国内外著名刊物上发表的论文经筛选、补充、编辑而成.这些论文大部分被国际著名索引文献《科学索引》(SCI)、《工程索引》(EI)、《科学文摘》(SA)等引录.

全书共分6章，重点论述了水电机组及水电站的控制、维护以及水电站智能控制-维护-管理系统的理论及应用，内容丰富，具有先进性，极富时代特征.

本书可供水力发电领域的硕士生、博士生及有关工程技术人员阅读参考.

序

本书以水力发电过程之控制为主旨引申到智能控制-维护-管理系统，是水力发电过程现代化代表作的集成.它组编了20世纪80年代以来(主要是90年代以来)作者在国内外发表的论文，补以必要章节而成为一本体系完整的专著.这是我个人从教五十多年来，在国内看到的有关水电控制学科最完整美好的著作.作为一个老水电科教工作者，我由衷地感到欣慰与兴奋!

从飞摆式的机械调速器到今天的微计算机调速器，我真实地看到了先进科学文化的发展方向.本书的具体内容表现了作者在这个科学园地中付出的辛勤劳动和获得的丰硕果实.

我认识作者叶鲁卿教授很久很久了.从他的双十年华到今天的六六花甲，从他当年的座上佼佼到今天的海内外超超，我为他感到骄而不傲，诚而笃实.我不自禁地有诗代序：

神州水力世称骄，
发电过程仔细描．
飞摆当年控失速，
激机此日制精调．
多凭数字创模块，
更化智能作浪潮．
专著斐然海内外，
山河新貌看今朝．

程良骏

2001年8月挥汗书于
华中科技大学之“磊石听涛斋”

PREFACE

This book written with the aim of expounding the control of the hydropower process and the developments, such as intelligent control, maintenance and management system is a monograph in which the papers compiled represent the generalization of the ideas of the modernization of the hydropower process. This book including the papers published at home and abroad in the 80's and mainly 90's and the necessary sections added forms a good and integrated system of writings on the subject of the control of hydropower. I have found this is the best monograph in the fifty years of my teaching. As an old scientific worker in the hydropower field, I feel extremely happy, excited and gratified for the publication of this book.

From the mechanical governor with centrifugal pendulum to the microcomputer-based governor, I looked and saw the direction of the development of advanced science and culture. The concrete content of the book shows the assiduous work and bumper harvest of the author in the scientific garden.

I have known the author for many, many years, from his early 20's to his late 60's and from his being an excellent student in my class to his being a

professor, well-known both at home and abroad. I am very proud of him, a man honest and sincere. So I couldn't help writing a poem to him as a substitute for the preface as follows.

Giving a careful description of the process of
generating electricity,
We take great pride in the achievements in
China's undertaking of hydropower.
Using governors with centrifugal pendulum to
control unqualified speed in the past,
We have microcomputer-based governor to make
precise regulation now.

Depending on digital technique for module
making,
We see the tide of intelligent control, maintenance and
management coming to the fore.

Praising the papers of the author, well-known
at home and abroad,
We admire the completely new look of China
today.

Prof. Cheng Liangjun

In Huazhong University of
Science and Technology
August 2001

前　言

本书系根据笔者20世纪80年代初以来发表或出版的论著筛选编辑而成.一方面,除作少量文字修改外,保留了发表时的原貌,所使用的语种也未作变动;另一方面,又按内容对论文进行了组织编排,按图书体例要求作了形式修改,新写了绪论及个别节次,以使全书构成一个相对完整的体系.从论著发表的时间分布来看,20世纪90年代发表的论文约占总量的80%.

从宏观上来观察,水力发电过程的本质是水能—机械能—电能的转换过程.所谓水力发电过程控制,即是对这一能量转换的全过程进行控制,以实现优质、可靠、高效的目标.水轮发电机组是这种能量转换过程中的核心设备,它的控制具有举足轻重的地位.自然,其"上游"及"下游"还需对水力系统及电力系统进行控制.

从微观上来观察,水力发电过程中存在三个技术领域:控制、维护、管理(这里主要指技术管理).通常,藉控制保证高性能及高质量(如电能质量),藉维护确保设备与系统的可靠性及高可利用率,藉管理求高效益(经济效益及社会效益).从历史及当前的情况考察,这三个领域发展是不平衡的:控制领域应用自动化、信息化技术起步较早,历史最长;管理领域应用自动化、信息化技术是从20世纪80年代计算机普遍应用以来才开始的,如OA,MIS等;维护领域应用自动化、信息化技术相对滞后,长期以来停留在事后维修及计划维修手工化的水平上,只是到了20世纪90年代才开始研制、开发状态维修及预知维修等技术.此外,这三个领域至今基本上是互不联系的"孤岛",而实际上,它们是相互联系、相互制约的.只是到了20世纪90年代,才开始研究这三个领域的集成技术.

水力发电过程是一个水—机—电的复杂生产过程,这本册子

并未对其各个方面进行全面的讨论.本书主要针对水电机组及水电站的控制、维护等分别作了阐述,然后将其引申到智能控制-维护-管理系统.笔者深信,后者是水电站、电力系统及其他企业在21世纪的必然发展趋势.

本书收集的论文和专著章节有:笔者独著、笔者为第一作者、笔者指导的博士生为第一作者笔者为第二作者撰写的论文,以及全文由笔者撰写的论著章节.收集在本书中的论文,绝大部分发表于国内外著名刊物上,国际著名刊物含《IEEE 汇刊·能量转换》(IEEE Transactions on Energy Conversion)、《IEEE 汇刊·电力系统》(IEEE Transactions on Power Systems)、法国的《水力发电》(La Houille Blanche,我国水电界学术前辈们译为《白煤》)、法国《通用电气杂志》(Revue Générale de l'Electricité)、《加拿大电气与计算机工程学报》(Canadian Journal of Electrical and Computer Engineering)、《电力系统研究》(Electric Power System Research)、《电力及能源系统》(Electrical Power and Energy Systems)、Elsevier Science 的 IFAC(国际自动控制联盟)出版物等;国内著名刊物含被 EI 引录的《中国电机工程学报》、《电力系统自动化》等.每篇论著后均标明了发表的刊物或出版社、时间及页码,以及被国际著名索引文献《科学索引》(Science Citation Index, SCI)、《工程索引》(Engineering Index, EI)、英国《科学文摘》(Science Abstracts, SA)等引录的情况.本书中的论文绝大部分均被上述索引引录.据对国际权威刊物《IEEE Transactions on Energy Conversion》连续十年(1989 年至 1998 年)的统计,在水电机组控制领域的论文总量中,笔者及其合作者的论文占 1/3,它们均同时被 SCI、EI 引录.收集在本书中有关水电机组现代控制策略的理论成果获得了教育部 2000 年中国高校自然科学一等奖.O.P. Malik 教授、G.S.Hope 教授、S.Maurin 研究员、G.Bornard 教授、魏守平教授、周泰经研究员,以及我的部分博士生、硕士生李朝晖教授、徐海波博士、曾瑜明博士、李维东博士、蒋日东博士、景雷博士、王

生铁博士、张永刚博士、余刃博士等是收集在本书中部分论文的合作者，在此谨向他们为本书所作出的贡献表示衷心感谢.

本书第一章对水力发电过程自动化及其发展趋势进行了综述.第二章论述了水电机组的现代控制策略，含适应控制策略、模型参考多变量最优控制策略、智能自完善变构变参控制策略、智能模糊控制策略等.由于水轮机调节系统具有非线性、时变、非最小相位等特点，而不同的水电站又各具其不同的“个性”，传统的 PID 控制策略已不令人满意.本章所研究的现代控制策略正是为解决上述问题，提高水电机组的控制性能而提出的.第三章是关于水电机组微计算机调速器的论著，其中，3-1 是笔者为《中国水力发电工程·机电卷》(该书由两院院士潘家铮教授担任主编，为迎接 2000 年在我国召开的国际大坝会议而作)编写的有关微机调速器的一章，在编辑这本书时补充了一些最新科研成果；3-2～3-6 为有关微机调速器的论文，这些论文是笔者及其课题组研究数字调速器的理论总结.第四章亦是笔者为《中国水力发电工程·机电卷》编写的有关调节保证的章节，调节保证计算是确保能量转换过程中机组和水工设施安全可靠的重要环节.第五章是有关控制系统可靠性的论文，论述了容错、避错、纠错、诊断等多种高可靠性技术.第六章对智能控制-维护-管理集成系统进行了研讨，包括其基本概念、特性、方法论与工具，以及在水电站与电力系统中的应用.

书中保留外文论文原貌的目的，既是为了便于进行国际学术交流；也是为了提高硕士生、博士生的外文阅读与写作能力.

尊师程良骏教授挑灯挥汗为本书作序，愧不敢当，在此谨表由衷的敬意和感谢.

由于笔者学识疏浅，不足之处在所难免，恳请读者批评指正.

叶鲁卿

2001 年 8 月于华中科技大学

FOREWORD

The book is edited by selecting most of my papers and works published since the early 80s' of the 20 century. On the one hand, all papers keep their original aspects including the adopted language and contents, except for a few writing modifications; on the other hand, the papers are organized and arranged by contents, and their formats are modified according to the requirements of book, by adding the introduction and a few sections and supplementing some recent research results, so that the book consists of a relative integral system. As for the distribution of published date, the papers published in the 90s' of the 20 century constitute 80% of the sum total.

From the macroscopic viewpoint, the hydropower process is a hydraulic-mechanical-electrical energy conversion process. The hydropower process control is for controlling the whole energy conversion process in order to gain high performance, high reliability and high benefits. The hydroelectric generating unit is the key-equipment during this energy conversion process, and plays an important role. Obviously, in its upper and lower streams, it is necessary to control hydraulic and electrical systems. From the microcosmic viewpoint, there are three technical domains: control, maintenance, and management (mainly technical management) in the hydropower process. Generally, the performance and quality (e.g. the quality of electrical energy) are guaranteed by control; the reliability and availability are guaranteed by maintenance; and management may obtain the economical and social benefits as well.

Investigated from history and present conditions, these three domains develop unevenly. The development of automation and information in control has had a longer history. The applications of automatic and information techniques in management, such as OA, MIS etc., have started since the 80s' of the 20 century while the computer has been extensively applied. The application of automation and information in the field of maintenance has lagged behind. There are only scheduling and curative maintenance till now. It means that the maintenance has remained in manual level. Only in the 90s' of the 20 century, the condition-based maintenance and predictive maintenance started to be developed. Moreover, these three domains have been isolated losing contact with one another. But in fact, they are mutually connected and constrained. Only since the 90s' of the 20 century, the problem of their integration has been studied.

Because the hydropower process is a complex hydraulic-mechanical-electrical one, it is not possible to involve all problems in this book. The control and maintenance for hydroelectric generating units and hydropower stations are mainly discussed, and then the Intelligent Control-Maintenance-Management integrated System (ICMMS) is proposed and discussed. I certainly believe: ICMMS will be an inevitable trend in the 21st century for hydropower plants, power systems and other enterprises.

Among the papers collected in this book, I am the author who wrote the papers alone, or I am the first author, or I am the second author and the Ph. D candidates under my guidance are the first authors. And in some papers written cooperatively, I wrote the whole manuscripts. Most of papers collected in the book have been published in the journals well known at home and abroad. The international journals include *IEEE Transactions on Energy Conversion*, *IEEE Transactions on Power Systems*, *La Houille*

Blanche, *Revue Générale de l' Electricité*, *Canadian Journal of Electrical and Computer Engineering*, *Electric Power System Research Electrical Power and Energy Systems*, IFAC Publications of Elsevier Science etc.. The national journals include *Proceedings of the CSEE*, *Automation of Electric Power System* cited by EI etc. In the end of each paper, are indicated the journal or press, the date and pages, and the citations by international famous indices (SCI—Science Citation Index; EI—Engineering Index; SA—Science Abstracts) as well. Most of papers collected in the book have been cited by the above-mentioned indices. According to the statistics for the international famous journal *IEEE Trans. On Energy Conversion* during the ten years from 1989 to 1998, in the field of control for hydroelectric generating unit, the papers written by the author and his co-authors make up one third, and both SCI and EI cited all of them. The theoretical results concerning the modern control strategies of hydroelectric generating units in this book have been conferred with The First Prize of Natural Sciences of China Universities, 2000. Prof. O. P. Malik, Prof. G. S. Hope, Dr. S. Maurin, Prof. G. Bornard, Prof. Wei Shouping, Prof. Zhou Taijing, and some of my former Ph. D. candidates and graduate students Prof. Li Zhaohui, Dr. Xu Haibo, Dr. Zeng Yuming, Dr. Li Weidong, Dr. Jiang Ridong, Dr. Jing Lei, Dr. Wang Shengtie, Dr. Zhang Yonggang, Dr. Yu Ren etc. are co-authors for some papers collected in this book. I express my heartfelt gratitude to them for their excellent contributions.

The contents of the book are organized as follows. Chapter 1 introduces the automation of hydropower process and its trend. In Chapter 2, the modern control strategies for hydroelectric generating units are discussed, including adaptive control strategy, model-reference multivariable optimal control strategy, intelligent self-improving control

strategy with variable structure and time-varying parameters etc. Because the water turbine governing systems have non-linearity, time-varying, non-minimum phase and other characteristics, and different hydropower plants have their various "individualities", the conventional PID control strategy has not been satisfactory. The modern control strategies researched in this chapter have been proposed just for solving the above-mentioned problems and for improving the control performance of hydroelectric generating units. Chapter 3 collects papers concerning the microcomputer-based governor, hereinto, 3-1 was written by the author for *Hydropower Engineering in China · Electromechanical Equipment* (This monograph was edited by Professor Pan Jiazheng, Academician of The Academy of Science and Academician of The Academy of Engineering) and supplemented with some recent research results while editing of this book, and 3-2 ~ 3-6 are papers on digital governor which are the theoretical results of the authors and his group's R&D in this field. Chapter 4 concerning the regulation guarantee is also written by the author for *Hydropower Engineering in China · Electromechanical Equipment*. The calculation of regulation guarantee is a key link for assuring the safety and reliability of units and hydraulic installations in the process of energy conversion. Chapter 5 concerns the reliability of control system. Many high reliability techniques are discussed and described, such as fault tolerance technique, fault avoidance technique, fault correction technique, fault diagnosis technique etc.. In Chapter 6, the intelligent control-maintenance-management integrated system is discussed and described, including its basic concepts, characteristics, methodologies, tools and its applications to hydropower plants and power systems.

Keeping the papers in English and French is for facilitating international academic exchanges, as well as for improving graduate

students' and Ph. D candidates' ability to read and write scientific and technical papers in English and French.

My respected teacher, Professor Cheng Liangjun wrote the preface for the book at night in very hot room temperature, which made me feel very sorry and uneasy. I really don't deserve this. I want to express my respect and gratitude to him.

Owing to the limitation of knowledge, deficiencies are unavoidable in the book and please oblige me with your valuable comments and criticism.

Ye Luqing
In Huazhong University of
Science and Technology
August 2001

目　录