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Modelling and Controlling Hydropower Plants

Springer

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Series Editors' Foreword

The series *Advances in Industrial Control* aims to report and encourage technology transfer in control engineering. The rapid development of control technology has an impact on all areas of the control discipline. New theory, new controllers, actuators, sensors, new industrial processes, computer methods, new applications, new philosophies . . . , new challenges. Much of this development work resides in industrial reports, feasibility study papers and the reports of advanced collaborative projects. The series offers an opportunity for researchers to present an extended exposition of such new work in all aspects of industrial control for wider and rapid dissemination.

Hydroelectric power has an important contribution to make to the supply of electricity in many countries. In the developed nations, those countries that have suitable topological features and plentiful rainfall have long exploited their hydroelectric potential. Norway, for example, derives 98% of its electric supply from hydroelectric power resources. In the so-called BRIC countries (Brazil, Russia, India and China) and the developing nations, some very large hydroelectric power plants have been constructed, are being constructed or being planned, thus there is a significant growth in hydroelectric power resources worldwide.

Hydroelectric power stations have many advantages in the context of climate change and the desired global reduction in CO_2 emissions. Yet, the focus of attention in the renewable energy field is often on solar power, wind energy and biomass, while hydroelectric resources are often overlooked. Nevertheless, the exploitation of hydropower is a long-standing, well-proven, reliable technology.

Pumped-storage hydroelectric facilities are one particular configuration within the field of hydroelectric power station technologies. Unlike many renewable energy technologies, hydroelectric power is not a recent development; schemes have been operating from the beginning of the last century. Pumped storage is a recirculant hydroelectric system that is able to use cheaper nighttime electricity tariffs to store energy (the pumped storage) ready for use in daytime electricity generation. However in modern times, the fast response times of hydroelectric power stations have been put to strategic use in the "peak-lopping" and network frequency control roles within large-scale electrical power networks. All this and more can be found in this *Advances in Industrial Control* monograph by German A. Munoz-Hernandez, Sa'ad P. Mansoor and Dewi I. Jones.

The book pursues three main themes for hydroelectric power plants, and pumped storage in particular:

1. Hydropower stations per se, comprising presentations on historical perspectives, a survey of the technology and its classification, industrial standards and the outlook for the future development and installation of hydroelectric power technology.
2. Control for pumped-storage facilities, comprising full presentations on plant models, model identification, control mechanisms, simulations (software and "hardware-in-the-loop"), culminating in detailed design and assessment material on classical controllers (PID) and model predictive control for these systems.
3. Case study material on Dinorwig Hydroelectric Power Station. This is a pumped-storage facility in North Wales, UK. Modelling activities showed this plant to contain non-minimum phase process behaviour, and the identification experiments for the plant controller revealed signal conditioning components in the PID controller.

The monograph shows how all the skills of the control discipline are used in a real-world control engineering study. As such, the volume is a very appropriate addition to the *Advances in Industrial Control* series. Two chapters in the monograph examine the potential benefits that are obtained by using methods from the model predictive control paradigm in place of PID control. For the reader interested in learning more about model predictive control, the *Advances in Industrial Control* series contains the monographs:

Predictive Functional Control, Jacques Richalet and Donal O'Donovan, ISBN 978-1-84882-492-8, 2009
Model Predictive Control System Design and Implementation with MATLAB®, Liuping Wang, ISBN 978-1-84882-330-3, 2009

Moreover, from the *Advanced Textbooks in Control and Signal Processing* series there is the now classic textbook:

Model Predictive Control (Second Edition), Eduardo F. Camacho and Carlos Bordons, ISBN 978-1-85233-694-3, 2004.

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Preface

Hydraulic turbines have been used as prime movers from the earliest days of electricity generation. Drawing its fuel from natural processes, hydroelectricity is widely regarded as a sustainable technology that makes a substantial contribution to low-carbon energy production. Because of its maturity, hydropower is sometimes associated with sluggish, even moribund, technology development. The truth is very different because, as for any competitive business, survival has required the hydropower industry to take full advantage of advances in science and engineering. There exists today a very active niche area of hydro oriented research, encompassing a whole range of topics – from dams and water management to turbines and power electronics – and one of these topics is control engineering. This monograph describes some of the techniques used for controlling hydro-electric plant, with particular emphasis on pumped storage schemes, whose modes of operation give rise to the most demanding set of control problems.

Effective control of hydroelectric plant is important because small improvements in generating efficiency and reduced operating costs can make the difference between profit and loss in a de-regulated trading environment that is very different to that of just 20 years ago. However, this desire for performance has to be tempered with the absolute need for safety and reliability, at the generating station itself and in a wider sense for the power system as a whole on which society is so dependent. The role of pumped storage schemes in particular is changing as variable energy sources, such as wind and solar, are progressively introduced onto power networks. The need to counteract the poor predictability of these sources and regulate the supply has changed the role of pumped storage schemes from traditional load-shifting to more active intervention on a shorter time scale. This trend is set to continue and advanced control methods will play a vital part in achieving future performance goals.

For many years, the authors have been privileged to work alongside one of Europe's largest pumped storage schemes, located at Dinorwig in north-west Wales. Dinorwig power station has six 330 MW rated hydro-turbines which, when operating in 'spinning in air' mode, can ramp from zero to full load in 12–15 s. It is a vital component of control for the United Kingdom power network. Much of this monograph draws on our experience with this plant in the form of an extended case study. However, the material is mostly generic in nature and applies equally well to many other stations around the world which are presently being refurbished, extended or built as new.

We have attempted to collect together in one place the essential material on modelling, simulation and control of hydroelectric plant and to place it in its proper industrial context, its history, current status and potential future role. In that respect, the first two parts of the book will hopefully be attractive to practising control engineers in the hydropower industry, both as an introduction to the topic and as a reference. Further, it is hoped that the final part of the book, which demonstrates the promise of advanced control methods, will stimulate the industry to move them forward from the realm of theory and simulation to being implemented on real plant – the ultimate test! We also believe that the mixture of classical and modern control, discussed in the book in terms of a specific and real application, will be useful reading for graduate students. Much of the material should also be accessible to final year undergraduate students studying control systems.

The book is divided into three parts:

- The first part includes a brief historical introduction to hydropower and how it developed to its present state. This is followed by a review of different types of hydroelectric schemes with a particular focus on the role played by pumped storage schemes in regulating grid supply. Finally, an overview of control methods is given, from early mechanical governors to today's electronic implementation. This part ends by outlining the primary industrial standards which apply to controlling hydroelectric plant.
- The second part deals with system modelling, covering all the major components required to set up a computer simulation of a hydroelectric plant connected synchronously to a power network. A typical hydroelectric station has a single tunnel drawing water from an upper reservoir into a manifold, which splits the main flow into several penstocks, each supplying a pump/turbine that drives a motor/generator on a common shaft. The power is modulated by means of a guide vane that regulates the flow of water, normally under feedback control of an electronic governor. In frequency control mode, the reference input to the power loop is the frequency deviation of the power network from its set point. The book reviews linear and nonlinear models of hydroelectric power stations, with both single-input, single-output (SISO) and multivariable characteristics. The dynamics of all the main subsystems are discussed, including conduit hydraulics, turbine, generator, guide vanes and the power network. A chapter that explains the benefits of hardware-in-the-loop simulation is included.
- The final part of the book focuses on methods of control. Starting with the classical approach that is prevalent in the industry at present, it progresses to the use of feed-forward as a means of achieving closer tracking to demanded power. The possibilities offered by using more advanced techniques such as model predictive control (MPC) and mixed logical dynamical generalised predictive control (MLD-GPC) are then considered. Simulation shows that MPC offers significantly better performance than a conventional governor, across the plant's

operating range. Constrained GPC produces a faster response when the station is operating with a single unit while preserving stability as the operating conditions change when multiple units are on-line. MLD-GPC control is faster and less sensitive than constrained GPC.

The book ends by briefly reviewing the status of hydroelectricity in the current global market, concluding that ample opportunities remain for large-scale base load development. For the moment, pumped storage schemes remain the only industry-tested and economically viable means of rapidly storing and releasing energy in bulk. However, steady improvements in other methods of energy storage, such as flywheels and chemical batteries, may soon pose a realistic challenge to this hitherto unique capability. These technologies may well meet and clash in competition for the role of maintaining power system stability and quality of supply. To compete effectively, pumped storage must seek to improve in three key areas:

- Accuracy of power delivery
- Speed of response
- Flexibility of operation

It is our hope that this book will help in this aspiration.

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This book, and the research programme from which it largely derives, would not have been possible without the assistance of Capel Aris (Consultant) and Glyn Jones, Arwel Jones and Toni Jones (all at the Control & Instrumentation Group, First Hydro Company). We also wish to thank all our colleagues who have been part of the research effort, especially David Bradley and David King (both of Abertay University) and Carlos Arturo Gracios-Marin (at Instituto Tecnologico de Puebla). Our thanks go to the series editors and the staff at Springer for their assistance. Finally, the authors would like to thank their families for all their support and consideration during the writing of the book.

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