HVDC Grids

For Offshore and Supergrid of the Future

Edited by
DIRK VAN HERTEM,
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AND JUN LIANG

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To Els, Elena, Sílvia, Clara,
Rita, Chunmei, Qianyun,
our wives and daughters,
for keeping us onshore
and connected to ground

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FOREWORD

Dear Reader,

The present book is one of the first and most significant studies on the concept of a European electricity Supergrid. The editors' work fills the scientific vacuum in this area. It is very much welcome!

The concept of an electricity Supergrid is now a well-routed expression in the sector, especially in Europe. However, clear definitions are still lacking, and one of the merits of this book is to tackle this. The notion of "Supergrid" has embraced various concepts. I would believe that it is correct to say that initially the Supergrid was limited to that part of the offshore grid which could—potentially—interconnect offshore wind farms located in the North and Baltic Seas. Gradually, the concept was enlarged in order to encompass all of Europe and now represents the very high voltage grid which would be needed to enable the transmission of significant volumes of renewables from where they would be produced to their consumption points. What is meant by "very high voltage" is at this very moment still not precisely defined as are the technical details of the needed technical equipment HVDC and/or others. Again, as mentioned, this work addresses many of these matters.

Today, we can affirm that (almost) nobody really opposes the need to build as soon as possible additional transmission infrastructure in Europe and that the "Supergrid" must become an essential part of that new transmission infrastructure.

The technical challenges are still numerous, but they are not the only ones. Financing the needed infrastructure is definitely another important challenge. The amounts needed to fund the infrastructure are not counted in the millions but in the hundreds of billions. Of course, transmission infrastructure is highly regarded by long-term investors, especially when the investment occurs in a regulated environment. Unfortunately, when one looks closer to the different regulatory regimes currently applicable in the 28 European countries, one will observe that, for the same kind of assets, the rate of returns approved by the respective authorities do greatly vary and could lead to forum shopping by investors, which will make the development of an Energy Union in Europe unfortunately more remote or at least more difficult. We believe it is urgent that Europe looks efficiently into the implementation of, at least, a harmonized regulatory system which will not only provide an attractive investment proposal but will also accelerate the development and construction of the infrastructure as well as foster Europe's security of supply.

Infrastructure, including high-voltage grids, can only be developed and built inasmuch as the developers have obtained the numerous environmental and other permits prior to construction. When it comes to supra-national infrastructure as is the Supergrid, the developers have to abide by the permitting laws and regulations in several countries. The rights protected by these permits as their respective procedures are more or less similar everywhere in Europe. However, the developer still needs to go country by country. Europe is certainly not (yet…) "lawyer-land" as is the United States of America, but everybody will agree that legal proceedings related to permits can and do take a lot of time (7 to 10 years is definitively not an exception, unfortunately!). This needs to be solved if one wants Europe to become less dependent on foreign energy sources.

The 2013 Electricity Infrastructure Regulation wants the Member States of the European Union to offer a "one-stop shop" body handling the various national permits. This is a strong indicator of Europe's will to try to clean up this situation without, however, limiting or reducing the individual rights of the European citizens. This initiative is mostly welcome and we hope that the Member States which today are trailing behind regarding for the implementation of this "one-stop shop" body will soon take the necessary steps to comply with this important European Regulation.

Even though permitting remains principally a national competence, we wonder if it would not make sense for Europe to think about an efficient and pragmatic way to have a "European One-Stop Shop" for essential infrastructure having a cross-border impact. A breakthrough herein would certainly significantly reduce the time but also the cost for new infrastructure in Europe.

It is now time to let you, dear Reader, dive into the important work of professors Van Hertem, Gomis-Bellmunt, and Liang and to hope that you too, once you will have been through this book, will definitely be a fan of the European electricity Supergrid!

Enjoy the read.

Pierre Bernard
Chairman of the Board of Friends of the Supergrid

PREFACE

THE FIRST electricity transmission line in the world was a DC line which was built in 1882. Since Westinghouse and Tesla won the "War of Currents" against Edison in the 1890s, AC technology has dominated the electric power transmission. However, DC transmission has enjoyed a revival since the middle of the twentieth century and, so far, more than 200 high-voltage DC (HVDC) projects have been built around the world and offer efficient transmission of large amounts of power over long distances. In the past couple of years, development of DC transmission has gained significant momentum as a result of two key drivers: firstly, the development of modern conversion technology (voltage source converter) and secondly, the need for transmission of offshore wind power. Plans for the interconnection of multiple renewable power sources, loads, and AC grids through DC technologies are leading to an exciting transmission concept: HVDC grids. HVDC grids and supergrids have sparked so much interest that researchers and engineers across the globe are talking about them, studying them, supporting them, or questioning them.

The editors of this book and their research teams have been carrying out extensive and collaborative research on HVDC grids for offshore wind power transmission and have achieved a series of outcomes. It is the editors' motivation to share their understanding and vision of HVDC grids. It is also the editors' privilege and responsibility to present a complete picture of HVDC grid technologies by collecting and summarizing recent technological advances, academic research development, and engineering applications.

The objectives of this book are to answer why HVDC is favorable over AC technologies for power transmission; what the key technologies and challenges are for developing an HVDC grid; how an HVDC grid will be designed and operated; and how future HVDC grids will evolve. The book also devotes significant attention to nontechnical aspects such as the influence of energy policy and regulatory frameworks. As such, this book is the first to discuss all relevant topics within the scope of HVDC for offshore grids and the supergrid. It provides valuable information for researchers, industry, and policy makers.

There are 5 parts in this book consisting of 22 chapters.

Part I, "HVDC Grids in the Energy Vision of the Future," discusses the reasons for and the necessity of building HVDC grids from the viewpoint of energy development and supply. There are two chapters in this part.

Chapter 1: Describes the motivations for developing new transmission infrastructure, including HVDC grids. Clean, cheap, and secure energy supply is a policy goal that drives grid development, requiring new transmission infrastructure. The development of offshore grids and of a supergrid will produce such a closely interconnected energy system.

Chapter 2: Elaborates on the basis of the transmission of electrical energy: generation and demand, and their evolution. The energy balance between supply and demand is emphasized, and its implication toward the DC grid development are investigated. Some future scenarios for the European energy mix are summarized.

Part II, "HVDC Technology and Technology for Offshore Grids," discusses two of the main technologies for future HVDC grids: HVDC and offshore wind power technologies. These are the foundations which will steer the management, operation, and control of HVDC grids. There are four chapters in this part.

Chapter 3: Gives an overview of both conventional LCC HVDC and newly emerging VSC HVDC technologies. The components of these HVDC technologies are analyzed. The benefits of VSC HVDC over LCC technology for grids are emphasized.

Chapter 4: Gives comprehensive technical and economic comparison between HVAC and HVDC transmission, indicating the advantages of HVDC over traditional HVAC.

Chapter 5: Briefly summarizes the wind turbine technology, with fixed-speed and variable-speed wind turbines.

Chapter 6: Discusses offshore wind power plants using AC or DC collection and transmission technologies.

From **Part III, "Planning and Operation of HVDC Grids,"** readers can expect to learn how an HVDC grid will be planned, designed, regulated, operated, and controlled. There are five chapters in this part.

Chapter 7: Focuses on the planning of HVDC grids. It provides answers for the four "W" questions on HVDC grid planning—that is, Where, What, When, and Who to invest HVDC grids. Design methods for HVDC grid expansion are also given in this chapter.

Chapter 8: Presents possible layouts of HVDC grids which can be designed in future. This chapter starts from HVDC substation configurations, to VSC pole and grounding configurations and extension, and to the network topologies of HVDC grids. Analyses of topologies particular suitable for offshore HVDC grids are also given.

Chapter 9: Discusses governance issues with national and transnational systems. Ownership, financing, and tariffs of such HVDC grids are described.

Chapter 10: Gives the operation and control principles for future HVDC grids, specifically looking at the interface with AC systems.

Chapter 11: Gives more specific operation and control methods for offshore wind power plants which are connected to HVDC links and HVDC grids.

Part IV, "Modeling HVDC Grids," presents models and modeling requirements of HVDC grids under various time frames for the purposes of power flow calculation, control design, protection, and system validation. There are seven chapters in this part.

Chapter 12: Defines different time frames for the modeling of HVDC grids for different applications. The objective is to highlight the need for different models within power system analysis and to indicate the specifics of HVDC grids with respect to modeling. The models themselves are introduced in greater detail in Chapters 13 to 18.

Chapter 13: Power flow calculations form the basis of all further analysis of the power system, including economics and stability. This chapter provides models and calculation methods of HVDC grids, particularly when HVDC grids are operating alongside AC grids.

Chapter 14: Deals with the theoretical and practical implementation of optimal power flow (OPF) for DC grids. Both the regular and security constrained OPF are presented as an extension to the deterministic AC optimal power flow case.

Chapter 15: Discusses the control principles of HVDC grids and covers requirements, modes, and strategies for the control of converters, DC networks, and hybrid AC/DC systems. The main focus lies on the power–voltage regulation in DC grids.

Chapter 16: Discusses state-space representation, which is a key tool for steady-state or dynamic analysis of power systems. The chapter describes a methodology to obtain a state-space model of HVDC grids. The procedure is based on combining the equations representing different parts of the transmission grid.

Chapter 17: Deals with DC grid protection, which is a major challenge for the development of an HVDC grid. The behavior of DC short-circuit faults is discussed in this chapter, as well as the special protection requirements of HVDC grids. The chapter summarizes the DC protection methods and algorithms and describes the DC relaying protection equipment.

Chapter 18: Describes the use of real-time simulation and physical experimental tests to validate the operation of HVDC grids and control systems which provide more reliable verification than the use of offline simulation. Physical experimental platforms are the most feasible representation of a real system and can be combined with real-time simulation.

Part V, "Applications," presents advanced ideas of operation and control HVDC grids. These include optimal control of VSC within HVDC grids to improve HVDC grid dynamics, flexible DC power flow control using advanced control devices, design of an offshore AC hub to remove the need for DC circuit breakers, and AC/DC grid interactions. There are four chapters in this part.

Chapter 19: Discusses the AC/DC grid interactions, focusing on the damping of AC system oscillations, low-frequency oscillation, and subsynchronous resonance (SSR) by using converter control of HVDC grids.

Chapter 20: Presents a design method to achieve optimal droop control of HVDC grid converters in order to improve the dynamic response of grid control.

Chapter 21: Summarizes advanced control devices which can be used in HVDC grids to increase control freedom and flexibility of power regulation. Device configurations, control systems, and control effectiveness are discussed and compared.

Chapter 22: Starts from the fact that, so far, HVDC circuit breakers are not yet commercially available. The chapter discusses a solution without DC circuit breakers for HVDC design, an AC hub, also referred to as the Super-node concept. This idea is particularly suitable for offshore applications. Design and control system of AC hubs is presented. Use of a variable nonstandard frequency idea is described in this chapter.

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We hope that the book proves to be useful for researchers and engineers. The comments and discussions from readers with diverse backgrounds are highly appreciated as the field of HVDC grids is an emerging one and significant research and development is still required to reach the ultimate objective of a secure, sustainable, and cost-effective energy supply with the aid of HVDC grids.