SpringerBriefs in Applied Sciences and Technology
PoliMI SpringerBriefs

Davide del Giudice · Federico Bizzarri · Daniele Linaro · Angelo Maurizio Brambilla

Modular Multilevel Converter Modelling and Simulation for HVDC Systems

State of the Art and a Novel Approach

POLITECNICO MILANO 1863

Springer

SpringerBriefs in Applied Sciences and Technology

PoliMI SpringerBriefs

Springer, in cooperation with Politecnico di Milano, publishes the PoliMI Springer-Briefs, concise summaries of cutting-edge research and practical applications across a wide spectrum of fields. Featuring compact volumes of 50 to 125 (150 as a maximum) pages, the series covers a range of contents from professional to academic in the following research areas carried out at Politecnico:

- Aerospace Engineering
- Bioengineering
- Electrical Engineering
- Energy and Nuclear Science and Technology
- Environmental and Infrastructure Engineering
- Industrial Chemistry and Chemical Engineering
- Information Technology
- Management, Economics and Industrial Engineering
- Materials Engineering
- Mathematical Models and Methods in Engineering
- Mechanical Engineering
- Structural Seismic and Geotechnical Engineering
- Built Environment and Construction Engineering
- Physics
- Design and Technologies
- Urban Planning, Design, and Policy

Davide del Giudice · Federico Bizzarri ·
Daniele Linaro · Angelo Maurizio Brambilla

Modular Multilevel Converter Modelling and Simulation for HVDC Systems

State of the Art and a Novel Approach

POLITECNICO
MILANO 1863

Springer

Davide del Giudice
Department of Electronics, Information and Bioengineering
Politecnico di Milano
Milan, Italy

Federico Bizzarri
Department of Electronics, Information and Bioengineering
Politecnico di Milano
Milan, Italy

Daniele Linaro
Department of Electronics, Information and Bioengineering
Politecnico di Milano
Milan, Italy

Angelo Maurizio Brambilla
Department of Electronics, Information and Bioengineering
Politecnico di Milano
Milan, Italy

ISSN 2191-530X ISSN 2191-5318 (electronic)
SpringerBriefs in Applied Sciences and Technology
ISSN 2282-2577 ISSN 2282-2585 (electronic)
PoliMI SpringerBriefs
ISBN 978-3-031-12817-2 ISBN 978-3-031-12818-9 (eBook)
https://doi.org/10.1007/978-3-031-12818-9

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Modular multilevel converters (MMCs) have evolved as the technology of choice in high voltage direct current (HVDC) systems, which nowadays are increasingly adopted to connect asynchronous AC grids and efficiently transmit power over large distances. The distinctive feature of the MMC is the presence of a stack of up to several hundreds of identical submodules (SMs) in each of its arms. On the one hand, this modular structure grants the MMC reduced switching losses and scalability to high voltage and power ratings, thus making it a popular technology in HVDC systems. On the other hand, the MMC topology and its complex control scheme pose several challenges in standard power system simulators tasks.

One of these challenges, namely the electromagnetic transient (EMT) simulation of MMCs, is the core topic of this book. In essence, the multitude of cascaded SMs in each arm implies that many electrical nodes (unknowns) and semiconductor devices must be evaluated simultaneously while simulating. Thus, simulations of MMC-based HVDC systems lead to a high computational burden if conventional EMT simulation tools and MMC models are adopted. To reduce CPU times, scholars proposed several MMC models that rely on simpler SM representations and implement different trade-offs between simulation speed and accuracy. Despite successfully reducing the computational burden, these models are incompatible with thorough MMC-based AC/DC network simulations, which may require a detailed transistor-level representation of the semiconductor devices in the SMs.

In this framework, the purpose of this book is twofold. First, it provides a comprehensive review and comparison of the MMC models developed in the literature over the years. Second, it proposes a novel and efficient MMC simulation approach based on sub-circuit isomorphism. This technique, which has its roots in the field of electronics, can be profitably exploited to efficiently simulate MMCs regardless of the model used to describe its SMs, including the most accurate ones.

The book is structured as follows.

- Chapter 1 introduces the issues currently witnessed in the electricity sector due to the increasing penetration of renewable energy sources and HVDC systems and highlights the key role of electric power system simulation in this context.

- After a brief overview of different multilevel converter technologies proposed in the last decades, Chap. 2 focuses on the MMC by describing its most relevant properties and a typical control architecture. Then, the main challenges posed by MMCs from a power system simulation and analysis perspective are summarised.
- Chapter 3 presents the main models available in the literature to simulate MMCs and describes the simulation approach based on sub-circuit isomorphism. Each solution is described in terms of the degree of retained accuracy, computational burden incurred, and the most suitable types of analyses that it can carry out.
- The isomorphism-based approach is validated in Chap. 4 by exploiting a well-known HVDC benchmark system comprising two MMCs. The benchmark is simulated in a wide array of scenarios, ranging from normal operating conditions to AC and DC-side faults, to showcase the key features of the proposed approach.
- Lastly, Chap. 5 provides some closing remarks.

The book largely draws from the Ph.D. thesis in Electrical Engineering "Simulation and Analysis of Modular Multilevel Converters Based on Isomorphism and Periodic Small-signal Analysis" by Davide del Giudice; supervisors: Federico Bizzarri, tutors: Daniele Linaro and Angelo Maurizio Brambilla, Politecnico di Milano, 2022. In particular, some of the results presented in the book appeared in the following publication: D. del Giudice, A. Brambilla, D. Linaro, and F. Bizzarri, Isomorphic Circuit Clustering for Fast and Accurate Electromagnetic Transient Simulations of MMCs, *IEEE Transactions on Energy Conversion*, 2022.

Due to its educational content, this book constitutes a useful guide for Ph.D. students and researchers interested in the topic of MMCs and their simulation. It also serves as a starting platform for junior electrical engineers who work in the field of power electronic converters for HVDC systems.

Milan, Italy
January 2023

Davide del Giudice
Federico Bizzarri
Daniele Linaro
Angelo Maurizio Brambilla

Contents

1 Introduction 1
1.1 Challenges of Renewables in Electric Power Systems 3
1.1.1 Distributed Energy Resources 5
1.1.2 Concentrated Energy Resources and the Role of HVDC systems 6
1.2 Rationale of the Book 7
1.3 Notation 9
References 9

2 Modular Multilevel Converters: Key Features, Control Strategies and Main Challenges 11
2.1 Converter Technologies for High Voltage and Power Applications 11
2.1.1 Two-Level Voltage Source Converters 12
2.1.2 Diode Clamped Converters 14
2.1.3 Active Neutral Point Clamped Converters 17
2.1.4 Flying Capacitor Converters 19
2.1.5 Cascaded H-bridge Converters 20
2.2 Modular Multilevel Converters 21
2.3 The MMC Control Strategy 28
2.3.1 Park Transformation 29
2.3.2 Phase-Locked Loop PLL 32
2.3.3 Upper Level Controls 33
2.3.4 Lower Level Controls 37
2.3.5 Protections 42
2.4 Challenges 43
2.4.1 Power Flow 43
2.4.2 Initialization 44
2.4.3 Stability Analysis 45
2.4.4 Electromagnetic Transient Simulation 46
References 47

3 Modular Multilevel Converter Models and Simulation Approaches 51
3.1 Literature Review of MMC Models for Transient Simulations 52
3.1.1 Full Physics (FP) Model 54
3.1.2 Full Detailed (FD) Model 55
3.1.3 Bi-value Resistor (BVR) Model 56
3.1.4 Thévenin Equivalent Model (TEM) 57
3.1.5 Switching Function Model (SFM) 63
3.1.6 Average Value Model (AVM) 68
3.2 Isomorphism-Based Simulation Techniques 71
3.2.1 Principles of Isomorphism 73
3.2.2 Isomorphic Simulation of MMC 75
3.2.3 Main Features and Fields of Application of the Isomorphism-Based Simulation of MMCs 80
References 82

4 Validation of the Isomorphism-Based Approach 85
4.1 Simulation Setting 85
4.1.1 AC Grids and Transformers 85
4.1.2 DC Line 87
4.1.3 MMC Parameters 94
4.1.4 Details Concerning Full-Physics, Full-Detailed, and Bi-value Resistor Submodule Models 95
4.1.5 Simulated Scenarios 98
4.2 Simulation Results 99
4.2.1 Analysis of Simulation Accuracy 99
4.2.2 Analysis of Submodules Variables 105
4.2.3 Analysis of Simulation Speed 107
References 114

5 Conclusion 117

Chapter 1
Introduction

Abstract This introductory chapter presents the challenges currently posed in the electricity sector due to the increasing penetration of distributed and concentrated Renewable Energy Sources (RESs), as well as high voltage direct current (HVDC) systems. In this context, electric power system simulation is crucial, since it allows assessing the impact of these elements at different stages, such as the design phase and real-time operation. However, modern simulators are not capable of efficiently simulating the power electronics converters typically employed as grid interfaces for RESs and HVDC systems. As a result, commercial simulators need to be updated by implementing more advanced simulation and computational techniques. After summarising these issues, the chapter introduces the technology this book focuses on: the modular multilevel converter.

Nowadays, the concept of energy is at the heart of many interconnected challenges that the world is facing. The so-called *global energy challenge* indicates that two actions are essential to ensure sustainable development for all: guaranteeing universal access and use of energy, as well as enforcing proper energy resource management, which limits environmental impact and prevents conflicts and inequalities. The Agenda 2030, an action plan signed in September 2015 by the world leaders, proposed 17 Sustainable Development Goals (SDGs), showing the path to be followed towards sustainable development for the whole world. In particular, energy has a prominent role in the seventh SDG, whose mission is: "*Ensure access to affordable, reliable, sustainable and modern energy for all*". This goal comprises five targets, one of which promotes a substantial increase in the share of RESs in the global energy mix. The pursuit of this specific target implies that also the electricity sector will keep on changing in the future.

In recent years, the integration of RESs has become more and more evident worldwide. For instance, consider Fig. 1.1, which shows the percentage share of global electricity generation by energy source in 1973 and 2019 [1]. Specifically, the penetration of non-hydro RESs and waste (e.g., geothermal, solar, wind, and biofuels) has increased by 10.2 % from 1973 to 2019. Among others, this trend is given by the progressive deployment of wind and photovoltaic energy sources reported in Fig. 1.2, which is fostered by policies and support mechanisms, such as *Feed-In Tariffs* [2].

D. del Giudice et al., *Modular Multilevel Converter Modelling and Simulation for HVDC Systems*, PoliMI SpringerBriefs,
https://doi.org/10.1007/978-3-031-12818-9_1

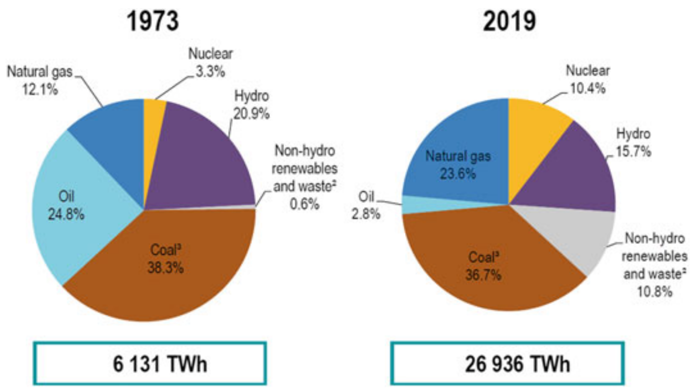

Fig. 1.1 Share of world electricity generation by source in 1973 and 2019 [1]

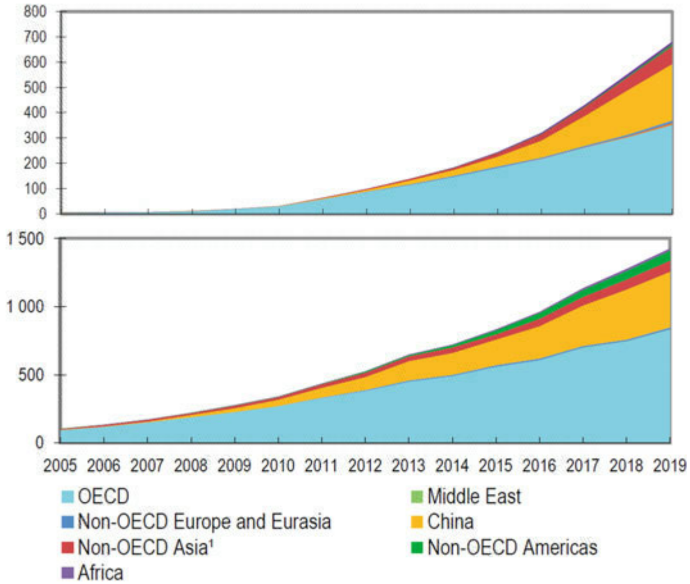

Fig. 1.2 Solar photovoltaic (upper panel) and wind (lower panel) electricity production [1]. The OECD class collects all the countries that belong to the Organisation for Economic Co-operation and Development (e.g., USA, Canada, Australia, most of the European countries). x-axis: year, y-axis: energy production (TWh)

The aim of these incentives is twofold. The first one is to reduce CO_2 emissions and allow countries to be compliant with binding international treaties, such as the well known Paris agreement. The second one is to stimulate the technical and market maturity of RES-fuelled power plants so that in the future they may become profitable even without public subsidies.

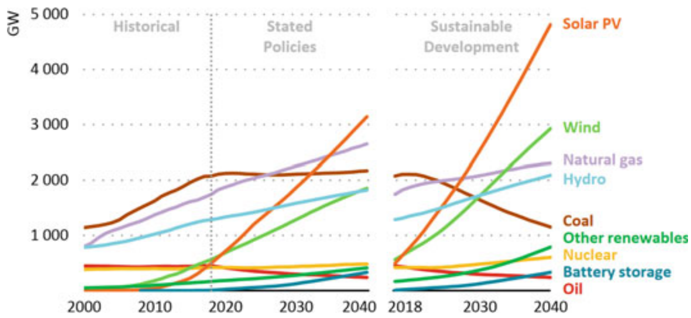

Fig. 1.3 Global yearly installed power generation capacity by scenario [3]

Although remarkable, the current rate of penetration of RESs is still insufficient for the years to come. Indeed, compare for instance the projections of the so-called "*Stated Policies Scenario*" and "*Sustainable Development Scenario*" depicted in Fig. 1.3. The former incorporates today's policy intentions and targets, whereas the latter maps out a way to meet SDGs and other treaties concerning climate change. The fulfilment of these treaties requires more investments in RESs, to the extent that plants based on wind and solar sources will eventually dominate future power systems.

On the one hand, the transition towards this scenario allows reducing the environmental impact of the electricity sector, escaping carbon lock-in, and improving energy security due to a more diversified generation mix. On the other hand, it poses several important challenges, which are pushing modern grids to a turning point.

The energy transition in the electricity sector is a very broad topic. Rather than exploring every nook and cranny of this subject—which would be out of the scope of this work—the following sections aim at reviewing some key concepts and highlighting the relevance of the research carried out in this framework and reported here.

1.1 Challenges of Renewables in Electric Power Systems

Traditional power systems were originally conceived and progressively developed based on some hypotheses. For example, it was assumed that the electric power would always flow from the transmission to the distribution networks. Indeed, most of the power consumed in the distribution grids would be produced by the synchronous generators connected to the transmission network. Other than producing power, these generators constituted (and still do to date) the backbone of power system stability due to the controls implemented within them, such as frequency and voltage regulation.

The increasing penetration of RESs clashes with this paradigm because it invalidates some hypotheses at the heart of conventional power system planning and operation. To bring the integration of clean energy sources to fruition, several barriers