

REVIEW

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# Circuit breakers in HVDC systems: state-of-the-art review and future trends

Erfan Taherzadeh<sup>1</sup>, Hamid Radmanesh<sup>1\*</sup> , Shahram Javadi<sup>1</sup> and G. B. Gharehpetian<sup>2</sup>

## Abstract

High voltage direct current (HVDC) systems are efficient solutions for the integration of large-scale renewable energy sources with the main power grids. The rapid development of the HVDC grid has resulted in a growing interest in DC circuit breakers (DCCBs). A fast and reliable circuit breaker is a necessary requirement in the development of large scale HVDC grids. This paper provides a comprehensive review and survey of the HVDC CBs and discusses potential research directions. Operational principles and the main features of various DCCBs are described and their merits and shortcomings are also highlighted.

**Keywords** DC circuit breakers (DCCBs), High voltage direct current (HVDC) system, Multi-terminal HVDC (MT-HVDC), Fault current isolation, Renewable energies, Voltage clamping

## 1 Introduction

HVDC technology is an attractive solution for transmitting large amounts of power via long-distance and asynchronous network interconnections. The demand for HVDC grids is continuously increasing because of large installations of renewable energy such as large-scale offshore wind farms and solar power [1–5]. In recent years, the number of HVDC projects in operation or under construction has seen significant growth and HVDC grids have been built in China [6, 7]. A basic point-to-point HVDC system comprises a converter station at each end, while a multi-terminal HVDC (MT-HVDC) system (HVDC grid) is formed when more than two substations are connected to the DC network. This can offer many benefits, e.g., loss and cost reduction, reliability and redundancy enhancement, etc. [5, 8].

HVDC systems are based on two distinct technologies, i.e., a line-commutated converter (LCC) using thyristors,

and a self-commutated voltage source converter (VSC) using insulated gate bipolar transistors (IGBTs) [9, 10]. LCC-based HVDC systems consume a large amount of reactive power, which must be compensated by filters on the AC side. Moreover, the power reversal requires voltage polarity reversal of the system, which is problematic for an HVDC grid. However, this technology is mature, has low losses, and has high voltage and power ratings. VSC-based HVDC systems only produce high-frequency harmonics because of the use of the pulse wide modulation (PWM) technique, or even near sinusoidal output because of the use of advanced converter topology, and thus, only small AC filters (or even no filter) are required. VSC-HVDC systems provide independent control of active and reactive power that can be generated or consumed by the converters [11]. For power reversal, the voltage polarity will not be changed. However, it has higher losses than those of LCC technology. Table 1 lists the general characteristics of the LCC and VSC-based HVDC systems. Because of the VSC characteristics, VSC technology is suggested for using in MT-HVDC.

In contrast to the LCC, which is vulnerable to AC side faults but has a natural ability to withstand short circuits on the DC side, VSC is vulnerable to DC side faults, which can result in fast DC line voltage collapse and fault

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# Hvdc Circuit Breakers A Review Identifying Future Research Needs

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## **Hvdc Circuit Breakers A Review Identifying Future Research Needs:**

*Direct Current Fault Protection* Isik C. Kizilyalli,Z. John Shen,Daniel W. Cunningham,2023-05-23 The lack of effective DC fault protection technology remains a major barrier for the DC paradigm shift In addressing the key challenges Direct Current Fault Protection Basic Concepts and Technology Advances starts with an introduction to the advantages of DC power systems before moving on to an in depth review of DC fault protection technologies including mechanical circuit breaker MCB solid state circuit breaker SSCB hybrid circuit breaker HCB converter based breakerless protection and fault current limiter FCL Coverage includes a comprehensive comparison of various DC fault interruption technologies and their suitable applications state of the art DC fault protection concepts and advances in research identification of fundamental challenges and future directions in the field and commercialization aspects This book will be a valuable reference for practicing engineers researchers and graduate students in the field of power electronics and DC power systems **Hvdc**

**Transmission +1: Vsc Hvdc Based Mmc Topology In Power Systems** Chan-ki Kim,Seung-il Moon,Kyeon Hur,Jang-mok Kim,Gilsoo Jang,2021-04-09 HVDC grids and super grids have sparked so much interest these days that researchers and engineers across the globe are talking about them studying them supporting them or questioning them This book provides valuable information for researchers industry and policy makers It explains 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 This book is a result of collaboration between industry and academia It provides theoretical insights into the design and control of MMC technology and investigates practical aspects of the project planning design manufacture implementation and commissioning of MMC HVDC and multi terminal HVDC transmission technologies filling the knowledge gap between the technology specialists and VSC HVDC project developers and key personnel involved in those projects **HVDC/FACTS for Grid Services in Electric Power**

**Systems** José M. Maza-Ortega,Antonio Gómez-Expósito,2020-11-23 Electric power systems are headed for a true changing of the guard due to the urgent need for achieving sustainable energy delivery Fortunately the development of new technologies is driving the transition of power systems toward a carbon free paradigm while maintaining the current standards of quality efficiency and resilience The introduction of HVDC and FACTS in the 20th century taking advantage of dramatic improvements in power electronics and control gave rise to unprecedented levels of flexibility and speed of response in comparison with traditional electromechanical devices This flexibility is nowadays required more than ever in order to solve a puzzle with pieces that do not always fit perfectly This Special Issue aims to address the role that FACTS and HVDC systems can play in helping electric power systems face the challenges of the near future **HVDC for Grid Services in Electric Power Systems** Gilsoo Jang,2019-11-18 The modern electric power system has evolved into a huge nonlinear complex

system due to the interconnection of thousands of generation and transmission systems The unparalleled growth of renewable energy resources RESs has caused significant concern regarding grid stability and power quality and it is essential to find ways to control such a massive system for effective operation The controllability of HVDC and FACTS devices allows for improvement of the dynamic behavior of grids and their flexibility Research is being carried out at both the system and component levels of modelling control and stability This Special Issue aims to present novel HVDC topologies and operation strategies to prevent abnormal grid conditions

**HVDC Grids** Dirk Van Hertem, Oriol Gomis-Bellmunt, Jun Liang, 2016-02-23 This book discusses HVDC grids based on multi terminal voltage source converters VSC which is suitable for the connection of offshore wind farms and a possible solution for a continent wide overlay grid HVDC Grids For Offshore and Supergrid of the Future begins by introducing and analyzing the motivations and energy policy drives for developing offshore grids and the European Supergrid HVDC transmission technology and offshore equipment are described in the second part of the book The third part of the book discusses how HVDC grids can be developed and integrated in the existing power system The fourth part of the book focuses on HVDC grid integration in studies for different time domains of electric power systems The book concludes by discussing developments of advanced control methods and control devices for enabling DC grids Presents the technology of the future offshore and HVDC grid Explains how offshore and HVDC grids can be integrated in the existing power system Provides the required models to analyse the different time domains of power system studies from steady state to electromagnetic transients This book is intended for power system engineers and academics with an interest in HVDC or power systems and policy makers The book also provides a solid background for researchers working with VSC HVDC technologies power electronic devices offshore wind farm integration and DC grid protection

**DC Microgrids** Nikita Gupta, Mahajan Sagar Bhaskar, Sanjeevikumar Padmanaban, Dhafer Almakhlles, 2022-06-21 DC MICROGRIDS Written and edited by a team of well known and respected experts in the field this new volume on DC microgrids presents the state of the art developments and challenges in the field of microgrids for sustainability and scalability for engineers researchers academicians industry professionals consultants and designers The electric grid is on the threshold of a paradigm shift In the past few years the picture of the grid has changed dramatically due to the introduction of renewable energy sources advancements in power electronics digitalization and other factors All these megatrends are pointing toward a new electrical system based on Direct Current DC DC power systems have inherent advantages of no harmonics no reactive power high efficiency over the conventional AC power systems Hence DC power systems have become an emerging and promising alternative in various emerging applications which include distributed energy sources like wind solar and Energy Storage System ESS distribution networks smart buildings remote telecom systems and transport electrification like electric vehicles EVs All these applications are designed at different voltages to meet their specific requirements individually because of the lack of standardization Thus the factors influencing the DC

voltages and system operation needed to be surveyed and analyzed which include voltage standards architecture for existing and emerging applications topologies and control strategies of power electronic interfaces fault diagnosis and design of the protection system optimal economical operation and system reliability      *Fundamentals of Smart Grid Systems* Muhammad Kamran,2022-12-01 *Fundamentals of Smart Grid Systems* offers an expansive introduction to the operationalization integration and management of smart grids the distributed renewable responsive and highly efficient power grid on the verge of radically transforming our energy system The book reviews the design of smart grid systems their associated technologies and operations helping users develop a modern foundational understanding of smart grid systems and many of their advanced implementations where sophisticated technologies are employed The work serves as a guidebook and primer for early career researchers with a rich integration of current science modern applications and future implementations Presents critical enabling technologies of smart grid systems alongside relevant aspects of their design modeling control and operations accompanied by numerical examples Discusses how to approach the integration and management of renewable energy sources in smart grid environments Features didactic pedagogical elements including end of chapter problems supplemental slideshows and figurative elements to clarify and explain complex concepts Focuses on modern applications and current implementations in industry such as power electronics for smart grids AI and machine learning driven modeling advanced control strategies and electric vehicles      **Medium-Voltage Direct Current Grid** M. M. Eissa,2019-05-03 *Medium Voltage Direct Current Grid* is the first comprehensive reference to provide advanced methods and best practices with case studies to Medium Voltage Direct Current Grid MVDC for Resilience Operation Protection and Control It also provides technical details to tackle emerging challenges and discuss knowledge and best practices about Modeling and Operation Energy management of MVDC grid MVDC Grid Protection Power quality management of MVDC grid Power quality analysis and control methods AC DC DC DC modular power converter Renewable energy applications and Energy storage technologies In addition includes support to end users to integrate their systems to smart grid Covers advanced methods and global case studies for reference Provides technical details and best practices for the individual modeling and operation of MVDC systems Includes guidance to tackle emerging challenges and support users in integrating their systems to smart grids      **Offshore Wind Energy Generation** Olimpo Anaya-Lara,David Campos-Gaona,Edgar Moreno-Goytia,Grain Adam,2014-06-03 The offshore wind sector s trend towards larger turbines bigger wind farm projects and greater distance to shore has a critical impact on grid connection requirements for offshore wind power plants This important reference sets out the fundamentals and latest innovations in electrical systems and control strategies deployed in offshore electricity grids for wind power integration Includes All current and emerging technologies for offshore wind integration and trends in energy storage systems fault limiters superconducting cables and gas insulated transformers Protection of offshore wind farms illustrating numerous system integration and protection challenges through case studies Modelling of doubly fed induction

generators DFIG and full converter wind turbines structures together with an explanation of the smart grid concept in the context of wind farms Comprehensive material on power electronic equipment employed in wind turbines with emphasis on enabling technologies HVDC STATCOM to facilitate the connection and compensation of large scale onshore and offshore wind farms Worked examples and case studies to help understand the dynamic interaction between HVDC links and offshore wind generation Concise description of the voltage source converter topologies control and operation for offshore wind farm applications Companion website containing simulation models of the cases discussed throughout Equipping electrical engineers for the engineering challenges in utility scale offshore wind farms this is an essential resource for power system and connection code designers and practitioners dealing with integration of wind generation and the modelling and control of wind turbines It will also provide high level support to academic researchers and advanced students in power and renewable energy as well as technical and research staff in transmission and distribution system operators and in wind turbine and electrical equipment manufacturers

Electromagnetic Time Reversal Farhad Rachidi, Marcos Rubinstein, Mario Paolone, 2017-04-17 The aim of this book is to familiarize the reader with the concept of electromagnetic time reversal and introduce up to date applications of the concept found in the areas of electromagnetic compatibility and power systems It is original in its approach to describing propagation and transient issues in power networks and power line communication and is the result of the three main editors pioneering research in the area

**Nanoelectronics** Robert Puers, Livio Baldi, Marcel Van de Voorde, Sebastiaan E. van Nooten, 2017-04-11 Offering first hand insights by top scientists and industry experts at the forefront of R D into nanoelectronics this book neatly links the underlying technological principles with present and future applications A brief introduction is followed by an overview of present and emerging logic devices memories and power technologies Specific chapters are dedicated to the enabling factors such as new materials characterization techniques smart manufacturing and advanced circuit design The second part of the book provides detailed coverage of the current state and showcases real future applications in a wide range of fields safety transport medicine environment manufacturing and social life including an analysis of emerging trends in the internet of things and cyber physical systems A survey of main economic factors and trends concludes the book Highlighting the importance of nanoelectronics in the core fields of communication and information technology this is essential reading for materials scientists electronics and electrical engineers as well as those working in the semiconductor and sensor industries

Recent advances in Power Systems Om Hari Gupta, S. N. Singh, Om P. Malik, 2023-01-01 This book presents select proceedings of the 3rd Electric Power and Renewable Energy Conference 2022 EPREC 2022 This book provides rigorous discussions case studies and recent developments in the emerging areas of the power systems especially renewable energy conversion systems distributed generations microgrids smart grids HVDC FACTS power system protection etc The readers would be benefited in terms of enhancing their knowledge and skills in the domain areas The book will be a valuable reference for beginners researchers and professionals

interested in developments in the power system      *The Power Grid* Brian D'Andrade, 2017-03-03 The Power Grid Smart Secure Green and Reliable offers a diverse look at the traditional engineering and physics aspects of power systems also examining the issues affecting clean power generation power distribution and the new security issues that could potentially affect the availability and reliability of the grid The book looks at growth in new loads that are consuming over 1% of all the electrical power produced and how combining those load issues of getting power to the regions experiencing growth in energy demand can be addressed In addition it considers the policy issues surrounding transmission line approval by regulators With truly multidisciplinary content including failure analysis of various systems photovoltaic wind power quality issues with clean power high voltage DC transmission electromagnetic radiation electromagnetic interference privacy concerns and data security this reference is relevant to anyone interested in the broad area of power grid stability Discusses state of the art trends and issues in power grid reliability Offers guidance on purchasing or investing in new technologies Includes a technical document relevant to public policy that can help all stakeholders understand the technical issues facing a green secure power grid      **The Proceedings of the 11th Frontier Academic Forum of Electrical Engineering (FAFEE2024)** Qingxin Yang, Jian Li, 2024-12-04 This book contains the original and refereed research papers presented at the 11th Frontier Academic Forum of Electrical Engineering FAFEE 2024 held in Chongqing China Topics covered include Power System and New Energy Motors and Systems Power Electronics and Electrical Drives High Voltage and Discharge Electrical Energy Storage and Application New Electrical Materials Advanced Electromagnetic Technology The papers share the latest findings in the field of electrical engineering making the book a valuable asset for researchers engineers and university students etc      **Switching in Electrical Transmission and Distribution Systems** René Smeets, Lou van der Sluis, Mirsad Kapetanovic, David F. Peelo, Anton Janssen, 2015-01-05 Switching in Electrical Transmission and Distribution Systems presents the issues and technological solutions associated with switching in power systems from medium to ultra high voltage The book systematically discusses the electrical aspects of switching details the way load and fault currents are interrupted the impact of fault currents and compares switching equipment in particular circuit breakers The authors also explain all examples of practical switching phenomena by examining real measurements from switching tests Other highlights include up to date commentary on new developments in transmission and distribution technology such as ultra high voltage systems vacuum switchgear for high voltage generator circuit breakers distributed generation DC interruption aspects of cable systems disconnecting switching very fast transients and circuit breaker reliability studies Key features Summarises the issues and technological solutions associated with the switching of currents in transmission and distribution systems Introduces and explains recent developments such as vacuum switchgear for transmission systems SF6 environmental consequences and alternatives and circuit breaker testing Provides practical guidance on how to deal with unacceptable switching transients Details the worldwide IEC International Electrotechnical Commission standards on

switching equipment illustrating current circuit breaker applications Features many figures and tables originating from full power tests and established training courses or from measurements in real networks Focuses on practical and application issues relevant to practicing engineers Essential reading for electrical engineers utility engineers power system application engineers consultants and power systems asset managers postgraduates and final year power system undergraduates

Selected Papers from 2018 IEEE International Conference on High Voltage Engineering (ICHVE 2018) Issouf

Fofana, Ioannis F. Gonos, 2021-03-04 The 2018 IEEE International Conference on High Voltage Engineering ICHVE 2018 was held on 10-13 September 2018 in Athens Greece organized by the National Technical University of Athens Greece and endorsed by the IEEE Dielectrics and Electrical Insulation Society This conference has attracted a great deal of attention from international researchers in the field of high voltage engineering This conference provided not only an excellent platform to share knowledge and experiences on high voltage engineering but also the opportunity to present the latest achievements and different emerging challenges in power engineering including topics related to ultra high voltage smart grids and new insulation materials and their dielectric properties **Advanced Solutions in Power Systems** Mircea

Eremia, Chen-Ching Liu, Abdel-Aty Edris, 2016-09-27 Provides insight on both classical means and new trends in the application of power electronic and artificial intelligence techniques in power system operation and control This book presents advanced solutions for power system controllability improvement transmission capability enhancement and operation planning The book is organized into three parts The first part describes the CSC HVDC and VSC HVDC technologies the second part presents the FACTS devices and the third part refers to the artificial intelligence techniques All technologies and tools approached in this book are essential for power system development to comply with the smart grid requirements Discusses detailed operating principles and diagrams theory of modeling control strategies and physical installations around the world of HVDC and FACTS systems Covers a wide range of Artificial Intelligence techniques that are successfully applied for many power system problems from planning and monitoring to operation and control Each chapter is carefully edited with drawings and illustrations that helps the reader to easily understand the principles of operation or application **Advanced Solutions in Power Systems HVDC FACTS and Artificial Intelligence** is written for graduate students researchers in transmission and distribution networks and power system operation This book also serves as a reference for professional software developers and practicing engineers Green Energy and Networking João L. Afonso, Vítor

Monteiro, José Gabriel Pinto, 2019-02-05 This book constitutes the refereed post conference proceedings of the 5th EAI International Conference on Green Energy and Networking GreeNets 2018 held in Guimarães Portugal in November 2018 The 15 full papers were selected from 26 submissions and cover a wide spectrum of ideas to reduce the impact of the climate change while maintaining social prosperity In this context growing global concern leads to the adoption of the new technological paradigms especially for the operation of future smart cities **Grid Connected Converters** Hassan



Bevrani, Toshiji Kato, Toshifumi Ise, Kaoru Inoue, 2022-08-11 **Grid Connected Converters Modeling Stability and Control** discusses the foundations and core applications of this diverse field from structure modeling and dynamic equivalencing through power and microgrids dynamics and stability before moving on to controller synthesis methodologies for a powerful range of applications The work opens with physical constraints and engineering aspects of advanced control schemes Robust and adaptive control strategies are evaluated using real time simulation and experimental studies Once foundations have been established the work goes on to address new technical challenges such as virtual synchronous generators and synergic inertia emulation in response to low inertia challenges in modern power grids The book also addresses advanced systematic control synthesis methodologies to enhance system stability and dynamic performance in the presence of uncertainties practical constraints and cyberattacks Addresses new approaches for modeling stability analysis and control design of GCCs Proposes robust and flexible GCC control frameworks for supporting grid regulation Emphasizes the application of GCCs in inertia emulation oscillation damping control and dynamic shaping Addresses systematic control synthesis methodologies for system security and dynamic performance

**Multi-terminal Direct-Current Grids** Nilanjan Chaudhuri, Balarko Chaudhuri, Rajat Majumder, Amirnaser Yazdani, 2014-09-09 A generic DC grid model that is compatible with the standard AC system stability model is presented and used to analyse the interaction between the DC grid and the host AC systems A multi terminal DC MTDC grid interconnecting multiple AC systems and offshore energy sources e g wind farms across the nations and continents would allow effective sharing of intermittent renewable resources and open market operation for secure and cost effective supply of electricity However such DC grids are unprecedented with no operational experience Despite lots of discussions and specific visions for setting up such MTDC grids particularly in Europe none has yet been realized in practice due to two major technical barriers Lack of proper understanding about the interaction between a MTDC grid and the surrounding AC systems Commercial unavailability of efficient DC side fault current interruption technology for conventional voltage sourced converter systems This book addresses the first issue in details by presenting a comprehensive modeling analysis and control design framework Possible methodologies for autonomous power sharing and exchange of frequency support across a MTDC grid and their impact on overall stability is covered An overview of the state of the art challenges and on going research and development initiatives for DC side fault current interruption is also presented

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