Power Systems

Isik C. Kizilyalli
Z. John Shen
Daniel W. Cunningham *Editors*

Direct Current Fault Protection

Basic Concepts and Technology Advances

Springer

Power Systems

Electrical power has been the technological foundation of industrial societies for many years. Although the systems designed to provide and apply electrical energy have reached a high degree of maturity, unforeseen problems are constantly encountered, necessitating the design of more efficient and reliable systems based on novel technologies. The book series Power Systems is aimed at providing detailed, accurate and sound technical information about these new developments in electrical power engineering. It includes topics on power generation, storage and transmission as well as electrical machines. The monographs and advanced textbooks in this series address researchers, lecturers, industrial engineers and senior students in electrical engineering.

Power Systems is indexed in Scopus

Isik C. Kizilyalli • Z. John Shen •
Daniel W. Cunningham
Editors

Direct Current Fault Protection

Basic Concepts and Technology Advances

Springer

Editors
Isik C. Kizilyalli
ARPA-E
United States Department of Energy
Washington D.C., USA

Daniel W. Cunningham
ARPA-E
United States Department of Energy
Washington D.C., USA

Z. John Shen
Simon Fraser University
Surrey, BC, Canada

ISSN 1612-1287 ISSN 1860-4676 (electronic)
Power Systems
ISBN 978-3-031-26571-6 ISBN 978-3-031-26572-3 (eBook)
https://doi.org/10.1007/978-3-031-26572-3

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

Preface

Electricity, in its predominant form of alternating current (AC), is at the heart of modern civilization. However, direct current (DC) electricity is re-emerging, long after losing the *War of Currents* over a century ago. DC inherently offers higher transmission efficiency, better system stability, better match with modern electrical loads, and easier integration of renewable and storage resources than AC. DC power is gaining traction in high-voltage (HVDC) or medium-voltage (MVDC) grids, DC data centers, photovoltaic farms, electric vehicle charging infrastructures, shipboard, and aircraft power systems. However, fault protection must be provided that can simultaneously meet the efficiency, response time, lifetime, and cost requirements of the future DC grids.

The lack of effective DC fault protection technology remains a major barrier for the DC paradigm shift. Interruption of DC currents is extremely difficult due to the lack of current zero crossings which are naturally available in AC power systems. Intensive research has been conducted to address this critical need in the past 20 years. Numerous technical papers and patents have been published on the subject of solid-state and hybrid circuit breakers, including several comprehensive review or survey papers on different technical aspects of DC fault interruption techniques. However, no comprehensive book is available on this important technical topic. This book attempts to bridge this gap and cover the basic concepts and recent technology advances in the field of DC fault protection.

The book is organized in five parts with a total of 20 chapters contributed from the invited field experts around the world who are actively engaged in DC fault protection research and development. It is intended for researchers, engineers, and graduate students in the field of fault protection, DC power systems, power electronics, and power systems in general.

In *Part I—Introduction*, the readers are provided with a brief overview on DC power systems and DC fault protection technology. Chapter 1, “Introduction,” highlights the benefits of DC power over conventional AC power and the emerging markets for DC power. Chapter 2, “Overview of Direct Current Fault Protection Technology,” provides an overview of DC fault scenarios, fault detection, and fault interruption technologies. A new unified classification of various DC fault interruption methods, including simple mechanical means, solid state circuit breaker (SSCB), hybrid circuit breaker (HCB), converter-based breakerless protection, and fault current limiter (FCL), are introduced, based on the fundamental topology and operation principle. Their advantages and disadvantages for different DC applications are discussed.

In *Part II—Solid State Circuit Breakers*, we include seven chapters to showcase different approaches and considerations in designing SSCBs.

Chapter 3, "ABB's Recent Advances in Solid-State Circuit Breakers," provides an overview of ABB's recent development of SSCBs based on Si IGCTs for kA/kV ratings, and lower power SSCBs based on SiC FETs. SSCB design considerations, such as power semiconductor device, gate drive circuit, cooling system, voltage clamping circuit, and protection control are discussed.

Chapter 4, "iBreaker: WBG-Based Tri-Mode Intelligent Solid-State Circuit Breaker," introduces a new class of intelligent SSCBs using wide-bandgap (WBG) semiconductors. The iBreaker concept explores the use of WBG switching devices in low-voltage (up to 1000 V), mΩ-resistance SSCB designs and new converter-based topologies and control techniques beyond the conventional ON/OFF operation to integrate intelligent functions. Two iBreaker design examples, one rated at 380 V/20 A and based on GaN switches for data center applications and the other rated at 750 V/250 A and based on SiC switches for hybrid electric aircraft applications, are discussed to highlight the iBreaker design methodology and functionality.

Chapter 5, "T-Type Modular DC Circuit Breaker (T-Breaker)," introduces a T-Breaker concept that has a scalable modular structure with locally integrated energy storage devices. It offers a strong capability in limiting fault current, high tolerance to control signal mismatch during breaking events, and ancillary functions including power flow control, power quality improvement, and transient stability enhancement.

Chapter 6, "Soft Turn-Off Capacitively Coupled SSCBs for MVDC Applications," discusses a capacitive coupled transient current commutation technique for designing SSCBs. Applying transient current commutation in SSCBs allows soft turn-off of the main semiconductor switch during DC current interruption. Eliminating the transient stress on the semiconductor switches and mitigating the gate voltage oscillations are two significant benefits, which help to enhance the long-term reliability and lifetime of the SSCBs.

Chapter 7, "Review of Z-Source Solid-State Circuit Breakers," provides a review on a special class of SSCBs using thyristors as the main static switch, the Z-source circuit breakers. Z-source SSCBs automatically respond to a fault without requiring fault sensing circuitry. The basic principle of operation is described, followed by popular design variations in the literature. Z-source breakers with coupled inductors are then illustrated. The incorporation of the Z-source breaker into power converters is also discussed. Examples of buck and boost converters with built-in Z-source breakers are presented.

Chapter 8, "Medium Voltage High Power Density Solid-State Circuit Breaker for Aviation Applications," presents the key design challenges for medium voltage

SSCBs related to hybrid electric aviation applications. The technical approaches to address such challenges, including extremely high specific power density, high efficiency, reliability, and high-altitude insulation capability, are explained in detail with a 2 kV/1.2 kA SSCB example design.

Chapter 9, "Light-Triggered Solid-State Circuit Breaker for DC Electrical Systems," by Sandia National Labs describes the design, simulation, and characterization of a novel SSCB approach using a light-triggered commutating switch combined with a cascaded normally-on WBG transistor circuit. Simulations of the various parts of the breaker and their predicted behavior in various system designs drives a first hardware demonstration. Circuit breaker voltage and current timing diagrams illustrate the interplay between different parts of the breaker to demonstrate sensitivity of the timing. The good match between measured performance and predicted behavior allows for realizing scaled up future designs.

In *Part III—Hybrid Circuit Breakers*, we include five chapters to illustrate different HCB schemes with vastly different operating principles.

Chapter 10, "ABB's Recent Advances on Hybrid DC Circuit Breakers," introduces two types of HCBs recently developed at ABB. The first type is a hybrid fault current limiting circuit breaker (FLCB) under the term PowerFul CB which naturally commutates the fault current from a mechanical breaker to a parallel semiconductor path. A current interruption capability of more than 11 kA at a DC voltage of 5 kV with an interruption time less than 2 ms is demonstrated. The second type is a low-voltage active resonant zero-crossing HCB that demonstrates a current interruption capability of 2000 A at a DC voltage of 1650 V with an interruption time of roughly 4 ms.

Chapter 11, "Hybrid Circuit Breakers with Transient Commutation Current Injection," introduces a 6 kV/1 kA HCB based on a power electronically modulated Transient Commutation Current Injection (TCCI) concept. The TCCI circuit in the parallel electronic path remains in a standby mode with near zero power loss under normal conditions but can rapidly generate a well-regulated counter current to force the fault current in the primary mechanical path to zero or near zero, and therefore facilitate current commutation from the mechanical to the electronic path. The TCCI circuit then ensures a near-zero voltage and a small high-frequency AC ripple current condition for the main mechanical contacts to separate without forming an arc. Exhibiting ultra-low on-state resistance by virtue of having no semiconductors in the primary current path, the topology achieves minimal on-state losses and greater than 99.97% efficiency. The HCB design also employs a specially designed high-speed actuator/vacuum contactor combination enabling sub-millisecond interruption as well as a modular MVDC power electronic interrupter (PEI) design in the electronic path.

Chapter 12, "Efficient DC Interrupter with Surge Protection (EDISON)," introduces another HCB design based on counter current injection. EDISON consists of multiple submodules of IGBTs and MOVs, a fault current commutation circuit (FC3), and a fast mechanical switch (FMS) which is controlled by a piezoelectric actuator. Supercritical CO_2 is used as the switching medium to enable high dielectric strength at unprecedented short contact travel, combined with outstanding heat transfer and low viscosity. Furthermore, EDISON introduces a new topology with no semiconductors in the main current path. Commutation of the current to the fault current commutation branch is achieved by the FC3 voltage source, which substantially reduces steady-state losses.

Chapter 13, "535 kV/25 kA Hybrid Circuit Breaker Development," introduces a 535 kV/25 kA active resonant-type HCB developed by Tsinghua University for the Zhangbei flexible DC transmission project in China, one with the highest voltage and power ratings ever reported. All subsystems of the HCB are described and key technical issues are analyzed. Testing and field deployment of the HCB engineering prototype are discussed.

Chapter 14, "Ultra-Fast Resonant Hybrid DC Circuit Breaker," introduces another active resonant-type HCB for MVDC applications. The HCB uses a resonant current source made of a power electronic H-bridge in series with a resonant inductor capacitor tank to generate artificial current zero crossings in the mechanical switch.

In *Part IV—Other Fault Protection Topics*, we include four chapters to cover several important topics related to DC fault protection.

Chapter 15, "Gas Discharge Tubes for Power Grid Applications," provides an overview on the potential benefits of gas discharge tube switches and circuit breakers as an enabling technology for medium- to high-voltage direct current power systems. High-voltage, high-power gas tubes are a recent development in a long line of proven gaseous electronic devices for power conversion and transmission systems that include thyratrons and mercury-arc rectifiers and valves. In their present state of development, they are best suited for high-voltage (up to 500 kV), moderate-current (up to 1000 A) applications. Electrical opening and closing times are both fast (<5 μs) and the devices are compact and amenable to high-temperature operation. The device capabilities and critical design criteria are discussed. The key technical challenges to make gas tubes viable in various electric power system applications are also outlined.

Chapter 16, "Converter-Based Breakerless DC Fault Protection," provides a brief overview of breakerless fault protection based on different converter topologies and control techniques. A breakerless MVDC architecture for a shipboard power system is also introduced and the advantages of the breakerless approach are discussed. A comparison between the breaker-based and breakerless approaches is discussed.

Chapter 17, "DC Fault Current Limiters and Their Applications," provides a brief overview of DC fault current limiters (FCLs), including directly installed DC reactors, superconducting FCL, and power electronic FCL. The technical requirements of FCL as well as the parameter configuration methods are analyzed in detail. A classification of these FCL methods based on fundamental topology and operation principle is introduced with an extensive reference list.

Chapter 18, "Eliminating SF_6 from Switchgear," provides a brief overview of SF_6 use in medium- and high-voltage gas-insulated electrical equipment and the outsized environmental impact of SF_6 as the worst greenhouse gas for global warming that has prompted a decades-long search for alternative gases and gas mixtures.

In *Part V—Future Outlook*, we include two chapters which provide a technical and economic future outlook of DC fault protection and MVDC power systems.

Chapter 19, "Fundamental Challenges and Future Outlook," outlines the fundamental challenges in the existing SSCB and HCB solutions. Conventional SSCBs use transistors in an undesirable way—continuously dissipating power except during infrequent fault interruption throughout their service life. Conventional HCBs offer a relatively long interruption time that is limited by the finite amount of force applied to the mechanical contacts. Innovative solutions are needed to overcome these fundamental limitations for future DC grids. This chapter introduces a new series-type hybrid circuit breaker (S-HCB) concept as an example to stimulate other new fault interruption ideas. The S-HCB conducts its load current through metal wires instead of semiconductor switches and curtails its fault current to near zero throughout the entire opening process of a series mechanical switch. It offers the low on-resistance of conventional mechanical contacts for normal operation and μs-scale fault interruption speed which is even faster than the fast-acting SSCBs.

Chapter 20, "Techno-Economic Aspect and Commercialization of MVDC Power Systems," covers a study of the medium-voltage direct current (MVDC) market, including the value proposition, market and segment opportunities, channels and barriers to entry, and speed of adoption. A variety of existing and promising MVDC markets are evaluated in renewable energy generation (PV and wind), grid distribution including emerging microgrid systems, transportation domains as well as commercial and industrial sectors. A regulatory framework is introduced, with guidelines and standards that will help shape emerging MVDC markets.

This is the first book that comprehensively covers the basic concepts and recent technology advances in the field of DC fault protection. Our goal is to help the readers quickly learn the state of the art of DC fault protection, appreciate the distinct advantages and disadvantages of different technical approaches in terms of efficiency, speed, complexity, lifetime, and cost for different voltage and current ranges, and inspire new innovations. We believe that this book will provide useful information to researchers in both academia and industry.

Finally, we would like to express our gratitude to all the chapter contributors. This book would not be possible without their devoted efforts. This book was inspired by the exemplary work performed by researchers supported through ARPA-E's CIRCUITS Program and later the BREAKERS Program, the latter focusing exclusively on novel MVDC circuit breaker technologies. We would also like to thank the staff at Springer, in particular Michael McCabe and Olivia Ramya Chitranjan, for their help and support.

Washington, DC, USA Isik C. Kizilyalli
Surrey, BC, Canada Z. John Shen
Washington, DC, USA Daniel W. Cunningham

Contents

About the Editors

Isik C. Kizilyalli currently serves as the Associate Director for Technology at the Advanced Research Projects Agency—Energy (ARPA-E), U.S. Department of Energy. In this role, Dr. Kizilyalli supports the oversight of all technology issues relating to ARPA-E's programs as well as assisting with program development, and coordinating project management across the Agency. Kizilyalli's focus at ARPA-E includes novel power electronics, wide-bandgap semiconductors, electronic systems for hostile environments, electrification of transport (aviation, ships, automotive), subsurface instrumentation, novel drilling concepts, medium-voltage DC distribution grids, and grid resiliency against EMP and space weather threats. Prior to joining ARPA-E, Kizilyalli served as founder, Chief Executive Officer, and Chief Technical Officer of Avogy Inc., a venture-backed start-up focused on bulk GaN-based vertical power semiconductor technologies and power electronics. Previously, he was with Bell Laboratories, followed by Nitronex Corporation, and solar PV start-up Alta Devices where his team holds the world record for single junction solar cell conversion efficiency. Kizilyalli was elected a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) in 2007 for his contributions to "Integrated Circuit Technology." He also received the Bell Laboratories' Distinguished Member of Technical Staff award and the Best Paper Award at the International Symposium on Power Semiconductors and Integrated Circuits in 2013. Kizilyalli holds his B.S. in Electrical Engineering, M.S. in Metallurgy, and Ph.D. in Electrical Engineering all from the University of Illinois Urbana-Champaign. He has published more than 100 papers and holds 126 issued US patents.

Z. John Shen is currently a Professor and Director of School of Mechatronic Systems Engineering at Simon Fraser University in British Columbia, Canada. He has more than 30 years of industrial, academic, and entrepreneurial experience in power electronics and power semiconductor devices. He has over 300 publications and 18 issued US patents in these areas. He has been involved in DC circuit breaker research since 2013. He was Grainger Chair Professor of Electrical and Power Engineering at the Illinois Institute of Technology, Chicago, between 2013 and 2021. He has served the IEEE Power Electronics Society (PELS) in various capacities including Vice President of Products, AdCom member, Chair of Distinguished Lecturers Program, Deputy Editor-in-Chief of *IEEE Power Electronics Magazine*, Guest Editor-in-Chief of the *IEEE Transaction on Power Electronics* and the *IEEE Journal of Emerging and Selected Topics in Power Electronics*. He has been on the organizing or technical program committee of over 30 international conferences in the field, and served as the General Chair of the 2016 Energy Conversion Congress and Exposition (ECCE2016) and the 2018 International Symposium on Power Semiconductor Devices and ICs (ISPSD2018). He is a Fellow of IEEE and the US National Academy of Inventors. He also serves on the Board of Directors of Vicor Corporation (NASDAQ: VICR). He received his B.S. from Tsinghua University in China and M.S. and Ph.D. from Rensselaer Polytechnic Institute in the United States, all in Electrical Engineering.

Daniel W. Cunningham is Acting Associate Director of Technology-to-Market at the Advanced Research Projects Agency—Energy (ARPA-E), U.S. Department of Energy, where he helps prepare innovative energy technologies for transition from the lab to the market. Cunningham most recently worked at BP Group Technology in the Chief Scientist's Office evaluating emerging energy technologies such as energy storage and alternative fuels pathways and assessing their impact on future business. Prior to this role, Cunningham spent much of his career at BP Solar Inc., serving in multiple capacities, including Director of Product Development leading a multidisciplinary team to develop new technologies for BP Solar's product line. Here, he was responsible for bringing technologies to market, using innovative materials and manufacturing processes to enhance performance and reduce cost. He also took on the role of Director of Technology where he led an R&D engineering team developing and manufacturing electrochemically deposited thin film CdTe devices for use in photovoltaic applications in collaboration with NREL and the Institute of Energy Conversion (UoD). He received a Research Partnership Award in 2001 from the U.S. Department of Energy for work in this area. Cunningham has extensive experience in semiconductor crystal growth and processing including PV module packaging and product reliability. Cunningham has authored over 70 publications and 12 patent publications. He earned a Ph.D. in Chemistry specializing in electrochemistry and in situ reflectance spectroscopy, and a B.Sc. (Hons) in Chemistry at the University of Southampton, UK. He is also a Senior Member of the IEEE and a Fellow of the Royal Society of Chemistry.

About the Authors

Faisal Alsaif is currently an Assistant Professor at the King Saud University. He received his Ph.D. degree from The Ohio State University in 2022.

Antonello Antoniazzi is Corporate Executive Engineer with ABB, Electrification Smart Power Division. His current research interests include DC power distribution and microgrids, and low-voltage circuit breakers. He has published 11 papers and holds 12 patents. He is active member of IEC TC121 and SC121A standardization committees, and Convenor of TC121/WG2 and SC121A/WG10 working groups. He graduated in Physics at Università degli Studi in Milano, Italy.

Robert W. Ashton is currently the President and sole proprietor of Ashton Consulting, LLC. His research interests include naval shipboard power, high-power DC-DC converters, soft-switching inverters, and phase-controlled rectifiers. He has published more than 40 papers. Bob has had a long history with the U.S. Navy. He held the position of Associate Professor in the Department of Electrical and Computer Engineering at the Naval Postgraduate School for 25 years. He served on several working groups within the Navy related to personnel selection, roadmap planning, and power system modeling. He has served as panelist, speaker, and session chair for numerous IEEE conferences as well as conferences hosted by the American Society of Naval Engineers. He received the Ph.D. degree in Electrical Engineering from Worcester Polytechnic Institute in 1991.

Enrico Bellotti is a professor in the Electrical and Computer Engineering and the Materials Science and Engineering Departments at Boston University, Boston, MA.

Steven Chen is a Chief Engineer with Eaton Corporation's Power Components Division. In his 39-year career in electrical engineering, he has worked on new products development including vacuum interrupters, MV/HV circuit breakers, and switchgear. He is a IEEE Senior Member and has participated and led multiple national and international standards development. He is a technical advisor of the United States National Committee to the IEC TC17. He received his Bachelor's degree in Electrical Engineering from Xian Jiaotong University, China.

Zhengyu Chen received the B.S. and Ph.D. degrees from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 2014 and 2019 respectively, where he is currently a Postdoctor. His current research interests include power semiconductor devices and their gate unit drivers, HVDC system and direct current circuit breaker.

Yizhou Cong is currently a Graduate Research Assistant at The Ohio State University pursing his Ph.D. degree.

Keith A. Corzine is a Professor at the University of California Santa Cruz. His current research interests include electric machinery, power conversion, power system stability, power system fault protection, semiconductor devices, and Naval shipboard power. He has published over 200 papers and holds 5 patents. Keith has worked with the U.S. Navy for over 25 years. He has conducted research on Office of Naval Research and spent several Summers at the Naval Surface Warfare Center in Philadelphia. He was the Chair of the Institute of Electrical and Electronics Engineers (IEEE) St. Louis Section in 2010 and has been involved in numerous IEEE conferences holding positions including co-chair, finance chair, and publicity chair. He received his Ph.D. in Electrical Engineering from the University of Missouri-Rolla, in 1997.

Robert M. Cuzner is an Associate Professor of Electrical Engineering with the Electrical Engineering and Computer Science Department of the University of Wisconsin-Milwaukee (UWM), USA. He is the Director of UWM's Center for Sustainable Electrical Energy Systems and the UWM site for the National Science Foundation Industry/University Cooperative Research Center, GRid-Connected Advanced Power Electronic Systems (GRAPES). His research interests include resiliency of power electronics-based distribution systems for shipboard and transportation electrification, compatible systems integration of power electronic systems into grids and packaging of power electronic systems, and has 30 years of combined industry and academic experience in these areas. He has published over 100 publications, including 3 book chapters, and holds 5 issued US patents. He received his Bachelor of Science Degree from Brigham Young University in 1988 and M.S. and Ph.D. degrees from the University of Wisconsin-Madison in 1990 and 2012, respectively.

Dong Dong is an Assistant Professor at Virginia Tech. His current research interests include wide-bandgap power semiconductor-based high-frequency power conversion, soft-switching and resonant converters, high-frequency transformers, and MV and HV power conversion system for grid, renewable, and transportation applications. He has published over 150 papers and holds 35 patents. Before joining Virginia Tech, Dong worked at GE Global Research Center at Niskayuna, NY where he participated in and led multiple technology programs including MV/HVDC power distribution and power delivery, SiC high-frequency high-power conversion systems, solid-state transformers, and energy storage systems. He received two Prize Paper Awards from the *IEEE Transactions on Power Electronics* and *IEEE Transactions on Industry Applications*, William Portnoy Prize Paper Award and

Transportation Systems Prize Paper Award from IEEE IAS. He served as the Vice Chair of IEEE Industry Application Society Schenectady Region Chapter in 2017 and General Chair of IEEE International Conference on DC Microgrids in 2021.

Jack D. Flicker is a Principal Member of Technical Staff with Sandia National Laboratories. His current research interests include power electronics, energy conversion systems, wide- and ultra-wide-bandgap devices, and power system integration of power converters. He has published 88 papers and holds 3 patents. He received a Ph.D. in Materials Science and Engineering from the Georgia Institute of Technology and Bachelor's degree in Physics and Chemistry from the Pennsylvania State University.

Zhizheng Gan received his B.S. degree in electrical engineering from Tsinghua University, Beijing, China, 2020, where he is currently working toward the Ph.D. degree in Electrical Engineering. His current research interests include mechanical switch, DC circuit breaker, and HVDC system.

Lee Gill received the B.S. degree from University of Illinois at Urbana-Champaign and the M.S. degree from Virginia Tech, both in Electrical Engineering. He is currently with Sandia National Laboratories and his interests include designing power conversion systems with wide-bandgap power semiconductor devices for various applications.

Lukas Graber received the Diploma and Doctorate degrees in Electrical Engineering from ETH Zurich, Zürich, Switzerland, in 2002 and 2009, respectively. He is currently an Associate Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA. Before he joined Georgia Tech, in 2015, he was with the Center for Advanced Power Systems, Florida State University—initially as a Postdoctoral Research Associate and later as a Research Faculty Member. His research interests include superconducting power cables and fault current limiters, cryogenic power electronics, supercritical dielectric materials, ultrafast mechanical switchgear, short-circuit forces in substations, and grounding aspects of power distribution on future all-electric ships. Prof. Graber is a member of the CIGRE, CSA, and Electrosuisse. He serves on the Board of Directors for CSA, an Editor for select issues of the *IEEE Transactions on Applied Superconductivity*, and contributes to standard committees, taskforces, as well as study committees within IEEE and CIGRE.

Harold P. Hjalmarson is a Technical Staff Member at Sandia National Laboratories in Albuquerque, NM.

Yulong Huang received the B.Eng. degree from Hunan University, Changsha, China, in 1985, and the M.Sc. degree from Tsinghua University, China, in 1991, both in Electrical Engineering. He was a Visiting Scholar at the University of Manchester (formerly UMIST) from 2000 to 2001. He is currently an Associate Professor at the Department of Electrical Engineering, Tsinghua University, working on high-voltage circuit breakers and online monitoring for high voltage equipment.

Zhiyang Jin is a Research Engineer II with the Plasma and Dielectric Lab, Georgia Institute of Technology, Atlanta, GA, USA. His research interests focus on the design of the next-generation high-voltage electric apparatus. He has published 12 papers and holds 1 patent. He received B.E. and M.S. degree from North China Electric Power University, Beijing, China, and Ph.D. degree from the University of Canterbury, Christchurch, New Zealand, in 2018.

Ahmad Kamal is currently with Eaton Corporation as a Lead Power Electronics Engineer. He received the B.S. degree from Comsats University, Pakistan; the M.S. degree from University of Engineering & Technology, Pakistan; and the Ph.D. degree from Illinois Institute of Technology, Chicago, IL, USA, all in Electrical Engineering, in 2013, 2017, and 2022, respectively. His research interests include DC circuit breakers and power converters.

Robert Kaplar is the Manager of the Semiconductor Material and Device Sciences Department at Sandia National Laboratories in Albuquerque, NM. His research has focused primarily on various aspects of wide- and ultra-wide-bandgap semiconductors, including optoelectronics, reliability physics, and power electronics. He is a co-author on over 60 journal articles and holds 5 patents. He received a B.S. degree in Physics from Case Western Reserve University and M.S. and Ph.D. degrees in Electrical Engineering from Ohio State University. He is a Senior Member of IEEE.

Reza Kheirollahi is currently working toward the Ph.D. degree in Electrical Engineering with Drexel University, Philadelphia, PA, USA. His research interests include dc circuit breakers and wireless power transfer technology. He received his M.S. degree in Electrical Engineering from Tarbiat Modares University, Tehran, Iran, in 2016.

Jane M. Lehr is a Professor of Electrical and Computer Engineering at the University of New Mexico. Her current research interests include the physics and application of high-voltage discharges and special power conditioning. She has published over 150 papers and holds 2 patents. She is a Fellow of the IEEE and the Summa Foundation and served as President of the IEEE Nuclear and Plasma Sciences Society in 2008–2009. She has been awarded the IEEE Shea Award, the IEEE Region 6 Leadership Award, the USAF Basic Research Award, and is a New Mexico Hall of Fame inductee. She received a Bachelor of Engineering degree from Stevens Institute of Technology and a Ph.D. degree from New York University.

Kathleen Lentijo is a Senior Lead Engineer with Booz Allen Hamilton and has served as a Technical Advisor at the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) since 2019. Prior to ARPA-E she spent 2 years performing power system studies at MEPPI for utility customers. Between 2009 and 2017, she worked at GE and then UEC Electronics where she was the power electronics or control lead on several projects for megawatt medium-voltage converter prototypes for solar and ship applications as well as low-power grid-forming inverters for military microgrids. Dr. Lentijo received the Ph.D. degree in Electrical Engineering from the University of South Carolina in 2009 and is a licensed Professional Engineer in the State of Pennsylvania.

Bin Li is a Professor of Tianjin University, China. He has been engaged in the research of AC and DC grid protection and control and published 3 books and 185 papers and holds 55 patents. He was an Academic Visitor of Manchester University and an Engineer in AREVA T&D, U.K. He received his Ph.D. degree in electrical engineering from Tianjin University.

Hui Helen Li is a Professor of Electrical and Computer Engineering Department, Florida State University, USA. She leads power electronics research at the Center for Advanced Power Systems (CAPS), Florida State University. Her research interests include DC-DC isolated converters, multilevel inverters, and PV inverters applying WBG devices. She has published more than 170 papers and holds 30 issued US patents. She was Co-Editor-in-Chief of *IEEE Transaction on Power Electronics* from 2019 to 2021. She received her Bachelor's and Master's Degree from Huazhong University of Science and Technology, China, in 1992 and 1995, respectively, and Ph.D. degree from the University of Tennessee, Knoxville, TN, USA, in 2000, all in Electrical Engineering. She is a Fellow of the IEEE.

Xiao Li is currently a Research Engineer at Apple. He received her Ph.D. degree from The Ohio State University in 2022.

Fei Lu is an Assistant Professor at the Department of Electrical and Computer Engineering, Drexel University, Philadelphia, PA, USA. His current research focuses on power electronics and the application of electric vehicle charging. He received the B.S. and M.S. degrees from Harbin Institute of Technology, Harbin, China, in 2010 and 2012, respectively, and the Ph.D. degree from the University of Michigan, Ann Arbor, Michigan, USA, in 2017, all in Electrical Engineering.

Jesper Magnusson currently holds a position as Senior Scientist with ABB AB, Corporate Research in Västerås, Sweden. His research interests include fast switching devices, with DC and hybrid topologies in particular. He received his MSc and PhD degrees in Electrical Engineering, both from The Royal Institute of technology (KTH), Stockholm, Sweden, in 2010 and 2017, respectively.

Jacob Mueller is a Senior Member of Technical Staff with Sandia National Laboratories. His current research interests include grid integration of energy storage and high-performance power conversion systems for utility applications. He received the B.S., M.S., and Ph.D. degrees from Missouri University of Science and Technology.

Risha Na is an Associate Professor at Anhui University in Hefei, China. He received his Ph.D. degree in Electrical Engineering from the Harbin University of Science and Technology, Harbin, China, in 2013. From 2016 to 2019, he was a Senior Research Associate with The Ohio State University, Columbus, OH, USA. From 2019 to 2021, he was a Research Assistant Professor at Illinois Institute of Technology, Chicago, IL, USA. His current research interests include power electronics, multilevel power converters, hybrid DC circuit breaker, solid state DC circuit breaker, control of renewable energy sources, machine drive, and wide-bandgap power devices.

Jason C. Neely is a Distinguished Member of Technical Staff at Sandia National Laboratories. He is currently working on the integration of power electronics for grid, electric vehicle, and national security applications. He has authored or co-authored over 70 publications, including journal, conference, and magazine articles, and 2 book chapters. Jason received his B.S. and M.S. degrees in Electrical Engineering from the University of Missouri-Rolla, Rolla, MO, in 1999 and 2001, respectively, and earned his Ph.D. degree in Electrical and Computer Engineering from Purdue University, West Lafayette, IN, in 2010.

Gregory Pickrell is a Distinguished Member of the Technical Staff with Sandia National Laboratories. His current research interests include the development and maturation of semiconductor devices and heterogeneously integrated micro-systems. He has co-authored more than 40 papers and holds 4 patents. He leads multiple product realization teams at Sandia and is a Senior Member of IEEE. He received his Ph.D. in Electrical Engineering from the University of Illinois in Urbana-Champaign.

Li Lisa Qi is Senior Principal Scientist at ABB US Research Center. Her research areas include DC distribution and protection, AC microgrid, and power electronics applications in power systems. She has published more than 75 peer-reviewed journal and conference papers and 2 book chapters, and holds 17 granted patents. She was the Co-Chair of technical committee of 2021 IEEE International Conference on DC Microgrid. She received the Ph.D. degree in Electrical Engineering from Texas A&M University.

Lu Qu received the Ph.D. degree in Electrical Engineering from the University of Chinese Academy of Sciences, Hefei, China, in 2016. He is an Associate Researcher at Tsinghua University. His research interests include DC grid and DC breaking technology. He undertakes one China Postdoctoral Science Fund. He also participated in drafting one national standard, three industrial standards, and three group standards.

Luciano Andres Garcia Rodriguez received the B.S. degree in Electronics Engineering from the Universidad Nacional del Sur (UNS), Bahia Blanca, Argentina, and the Ph.D. degree in Electrical Engineering from the University of Arkansas, Fayetteville, AR, USA. He is with Sandia National Laboratories, Albuquerque, NM, since 2019, where he is currently a Senior Member of the Technical Staff, working for the Power Electronics and Energy Conversion Systems Department. His current research interests are power electronic topologies and controls for medium-voltage grid-connected energy storage systems.

Maryam Saeedifard received her Ph.D. degree from the University of Toronto, Canada, in 2008, in Electrical Engineering. Since January 2014, she has been with the School of Electrical and Computer Engineering at Georgia Institute of

Technology, where she is currently a Professor and holds a Dean's professorship. Prior to joining Georgia Tech, she worked as an Assistant Professor at Purdue University (2010–2013) and a Researcher with the Power Electronic Systems Group, ABB Corporate Research Center, Switzerland (2007–2009). Dr. Saeedifard's research interests are power electronics, medium- and high-power energy conversion systems, power electronic systems based on wide-bandgap switching devices, high-voltage DC (HVDC) transmission systems, protection and control of multi-terminal DC grids, and cybersecurity of power electronics-based systems. She has published 2 book chapters and more than 200 refereed journal and conference papers. She is an IEEE Fellow and is serving as a Co-Editor-in-Chief of the *IEEE Transactions on Power Electronics*. She is the recipient of several prestigious awards including the Natural Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellowship in 2008, Richard M. Bass Award Outstanding Young Power Electronic Engineer Award of the IEEE Power Electronic Society in 2010, Excellence in Research Award from the Office of Vice President for Research at Purdue University in 2011 and 2012, Outstanding Young Engineer Award of the IEEE Power Engineering Society of Atlanta Chapter in 2015, J. David Irwin Early Career Award of the IEEE Industrial Electronic Society in 2018, several first prize paper awards from the *IEEE Transactions on Industrial Electronics* (2016 and 2018) and *IEEE Transactions on Power Electronics* (2021 and 2022), IEEE Region 3 Outstanding Engineer Award in 2019, Roger Webb Outstanding Mid-Career Faculty Award in the School of Electrical and Computer Engineering at Georgia Tech in 2021, the Technology, Research and Innovation Award (C3E) of the US Department of Energy in 2021, and the 8th Nagamori Awards in 2022. She was selected as an invited speaker at the National Academy of Engineering, Frontiers of Engineering Symposium in 2011 and as an invited attendee at the National Academy of Engineering, Frontiers of Engineering Education Symposium in 2012.

David Schaeffer currently holds a position as Principal Scientist with ABB AB, Corporate Research in Västerås, Sweden. His current research interests include switching devices and system protection. He received his PhD degree in Condensed Matter from Université Joseph Fourier, Grenoble, France, in 2005.

Steven Schmalz is an Engineering Senior Specialist with Eaton Corporation's Research Labs. In his 30+ years with Eaton, his principal research interests have included sensing technologies, energy management, and methods for protecting electrical systems. Steven has served as the Principal Investigator on several research projects funded by the US government, designing technology for both ground-based and aerospace power applications. He is also a member of the Institute of Electrical and Electronics Engineers, is a licensed Professional Engineer in the State of Wisconsin, and holds 35 patents and trade secrets. Mr. Schmalz earned both his Bachelor's and Master's degrees in Electrical Engineering from Marquette University.

Emily Schrock is a Technical Staff Member at Sandia National Laboratories in Albuquerque, NM.

Peter A. Schultz is a Technical Staff in the Computational Multiscale Department at Sandia National Laboratories. His current research involves developing the SeqQuest density functional theory code, and theory and modeling of defect physics in semiconductors. He has published 90 papers or book chapters. He served as Co-Editor-in-Chief of *Modelling and Simulation in Materials Science and Engineering* from 2016 to 2020.

David Smith is a Principal Scientist with General Electric Research. His research interests include the development of novel materials, devices, and processes for a diverse range of technologies in lighting, healthcare, aviation, and renewable energy. He has published 17 papers and holds 12 patents. He received both his B.Sc. and Ph.D. degrees from the Department of Physics and Applied Physics at the University of Strathclyde.

Timothy Sommerer is a Principal Scientist with General Electric Research. His research interest is the application of gaseous electronic technology in various applications such as electric power systems. He has published 40 papers and holds 38 patents. He received his Ph.D. in Physics from the University of Wisconsin.

Xiaoqing Song is an Assistant Professor at the University of Arkansas. His current research interests include power electronics packaging and solid-state circuit breakers. He has published more than 50 peer-reviewed journal and conference papers and 2 book chapters and filed 14 US and international patents. He is the recipient of 2016 Outstanding Young European Power Electronics (EPE) Association Member Award, 2020 ABB Inventor of the Year Award and 2021 ABB Publisher of the Year Award, and 2022 ITEC Best Paper Award. He received the Ph.D. degree in Electrical Engineering from North Carolina State University in 2017, and from 2017 to 2022, he was working with ABB US Corporate Research Center as a Principal Research Scientist.

Michael Mischa Steurer received the B.S. and M.S. degrees in Electrical Engineering from the Vienna Technical University in 1994 and a PhD degree in Electrical Engineering from the Swiss Federal Institute of Technology in 2001. Since 2001, Dr. Steurer is a Senior Researcher at Florida State University in the Center for Advanced Power Systems where he currently leads the Power Systems group with primary focus on hardware-in-the-loop real-time simulation and modeling of integrated power and energy systems for all-electric ships and future terrestrial power systems. Dr. Steurer has authored and co-authored more than 180 technical papers in the area of shipboard power systems, hardware-in-the-loop real-time simulation, fault protection, and superconductivity. Dr. Steurer is a Member of the International Council on Large Electric Systems (CIGRE), the American Society of Naval Engineers (ASNE), and a Senior Member of the Institute of Electrical and Electronic Engineers (IEEE), where he contributes to several working groups. He currently chairs IEEE WG P2004 which develops a recommended practice for HIL simulations. Dr. Steurer is also the recipient of the 2019 ASNE Solberg Award.

Thorsten Strassel is Global Product Manager for solid-state circuit breakers with ABB Electrification, Smart Power Division. His current research interests include solid-state circuit breakers, LVDC protection, and DC microgrids. He has published 5 papers and holds 6 patents. He received his Ph.D. degree in Physics from Ruprecht-Karls-University Heidelberg, Germany.

Maryam Tousi received the B.Sc. degree in Physics from the Sharif University of Technology, Tehran, Iran, in 2010, the M.Sc. degree in Condensed Matter/Solid-State Physics from the Amirkabir University of Technology, Tehran, Iran, in 2012, and the Ph.D. degree in Electrical Engineering from Virginia Tech, Blacksburg, VA, USA, in 2020. She is currently a Research Engineer II with the Plasma and Dielectric Lab, Georgia Institute of Technology, Atlanta, GA, USA, conducting research on the ultra-fast mechanical switchgear. Her main research interests include high-voltage technology, electrical insulation materials and systems, multiphysics modeling, and wide-bandgap power electronics packaging.

Jin Wang is a Professor at The Ohio State University. His current research interests include wide-bandgap power device-based high-voltage and high-power converters, renewable energy integration, and transportation electrification. He has over 200 journal and conference papers and 9 patents. He received the IEEE Power Electronics Emerging Technology Award in 2022 and the Nagamori Award in 2020. Dr. Wang received his Ph.D. degree from the Michigan State University in 2005.

Nathan D. Weise is an Associate Professor at Marquette University in Milwaukee, WI. He received the B.S. degree in Computer Engineering, the M.S. degree in Electrical Engineering with an emphasis on wireless, and the Ph.D. degree in Electrical Engineering with an emphasis on power from the University of Minnesota, Minneapolis, MN, USA, in 2005, 2007, and 2011, respectively. He was an Electrical Engineer with Cummins Power Generation, Minneapolis, and General Electric Global Research, Niskayuna, NY, USA. He joined Marquette University, Milwaukee, WI, USA, as an Assistant Professor, in 2014. His current research interests include power electronics, power converters, wave energy conversion, electrification of transportation, all-electric aircraft, fault tolerance, control of renewable energy sources, digital control of power electronics, and wide-bandgap devices.

Ren Xie is a Research Engineer on power electronics with GE Global Research, Niskayuna, NY, USA. His current research interests include WBG-based power electronics for aviation and fault management in the dc power distribution systems. He received the B.S. and M.S. degrees from Zhejiang University, Hangzhou, China, in 2010 and 2013, respectively, and the Ph.D. degree from Florida State University, Tallahassee, FL, USA, in 2019, all in Electrical Engineering.

Qichen Yang received the Ph.D. degree from the Georgia Institute of Technology, Atlanta, GA, USA, in 2018. He is currently a Research Faculty I at the Center for the Advanced Power System (CAPS) at the Florida State University, which he joined as a Postdoctoral scholar in 2019. His current research interests include medium-voltage power electronics converter, medium-voltage dc circuit breaker, and high-voltage insulation technology.

Xin Yan received the B.S. degree in Electrical Engineering from Tsinghua University, Beijing, China, 2019, where he is pursuing the Ph.D. degree in Electrical Engineering. His current research interests include power semiconductor devices, DC circuit breaker, and HVDC system.

Emily Yedinak was a Fellow at the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) from 2020 to 2022. While at ARPA-E, she conducted outreach calls and assisted in developing ARPA-E's exploratory topic that aimed to develop technologies enabling SF6-free electrical equipment for medium- and high-voltage applications. Dr. Yedinak earned a Ph.D. in Materials Science and Nanoengineering from Rice University in 2020.

Zhanqing Yu received the B.Sc. and Ph.D. degrees in Electrical Engineering from Tsinghua University, Beijing, China, in 2003 and 2008, respectively. After graduation, he became a Postdoctor and Lecturer at the Department of Electrical Engineering, Tsinghua University, in July 2008 and July 2010, respectively, and an Associate Professor at the same department in December 2012. He has participated in several projects sponsored by High-Tech R&D Program (863 Program), National Basic Research Program of China (973 Program), and National Natural Science Foundation of China. His research interests include DC grid, DC breaker, DC converter, and electromagnetic compatibility.

Rong Zeng received the B.Eng., M.Eng., and Ph.D. degrees from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 1995, 1997, and 1999, respectively. He was a Lecturer at the Department of Electrical Engineering, Tsinghua University in 1999, and an Associate Professor and Professor at the same department in 2002 and 2007, respectively. He is currently working in the fields of power semiconductor, DC grid and DC circuit breaker, and electric and magnetic field measurement by integrated electro-optical sensors.

David Zhang is a Senior Technical Program Manager at Mainspring Energy, managing development programs for a fuel-flexible distributed linear generator. Prior to Mainspring Energy, he worked at Energy Solutions as a Distributed Energy Consultant, deploying battery storage and microgrid programs for California utilities. In 2018, he was a Technology to Market Summer Scholar in the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E), where he supported the creation of the BREAKERS program, and from 2014 to 2017, he was at Siemens Energy, where he managed R&D development for combined cycle power plants. He earned his Bachelor's and Master's degrees in Mechanical Engineering from Columbia University and the University of California, Berkeley, respectively, and is a Clean Energy Leadership Institute (CELI) Fellow.

Di Zhang is an Associate Professor at Naval Postgraduate School. His current research interests include high-/medium-voltage transmission and distribution of electric power systems for land/marine/aviation applications. He has published 25 journal papers and holds 35 US patents. He also has 10 years industrial R&D experience in General Electric company. He received his Ph.D. degree from Virginia Tech in 2010.

Xiangyu Zhang received his B.S. and Ph.D. degrees in Electrical Engineering from Tsinghua University, Beijing, China, in 2015 and 2020, respectively. After graduation, he became a Lecturer at State Key Laboratory of Alternate Electrical Power System With Renewable Energy Sources, North China Electric Power University.

Yue Zhang is currently a Research Engineer at Tesla. Yue received his Ph.D. degree from The Ohio State University in 2022.

Yuanfeng Zhou is currently with Monolithic Power Systems as a Senior Application Engineer. He received the B.S. degree from Xi'an Jiaotong University, Xi'an, China; the M.S. degree from the Huazhong University of Science and Technology, Wuhan, China; and the Ph.D. degree from Illinois Institute of Technology, Chicago, IL, USA, all in electrical engineering, in 2009, 2012, and 2021, respectively. From 2012 to 2015, he was with Emerson Network Power, Shenzhen, China, as a Design Engineer. His research interests include DC circuit breakers and DC/DC converters.

Part I
Introduction

Chapter 1
Introduction

Isik C. Kizilyalli, Daniel W. Cunningham, and Z. John Shen

Electricity delivered by alternating current (AC) has a long and colorful history [1]. This method, which alternates the flow of electricity back and forth many times per second, has dominated the transmission and distribution system in the world for over a century. AC proliferation has been driven by the ease and lower cost of voltage conversion as compared to direct current (DC). However, DC electric power offers several benefits over AC, reducing system power losses due to improved electrical conductivity and utilizing fewer power cables with higher power carrying capacity (as shown in Table 1.1) [2, 3]. In addition, controlling of DC electric power could be easier since frequency and phase synchronization requirements are eliminated.

There are a few examples of high voltage DC transmission projects around the world, which boast lower costs and a smaller physical footprint by avoiding additional power conversion equipment while supporting higher transmission efficiency. At lower voltages (i.e., <1 kV), simpler controls and fewer conversion stages have made DC microgrids an appealing option for datacenters, industrial facilities, and office blocks [4]. This is due to the fact many of the services commonly connected to microgrids, such as energy storage, renewables, electric vehicle charging, and consumer devices, all operate on DC platforms.

There is a tremendous opportunity to extend the benefits of DC power to medium voltage (MV) markets, particularly in electric grid distribution (i.e., 3.3–100 kV) where MVDC provides several promising characteristics in the same way that HVDC does for high voltage grid transmission. DC has improved efficiency due

I. C. Kizilyalli (✉) · D. W. Cunningham
ARPA-E, U.S. Department of Energy, Washington, DC, USA
e-mail: kizilyalli@ieee.org; daniel.w.cunningham@ieee.org

Z. John Shen
Simon Fraser University, Surrey, BC, Canada
e-mail: zjshen@sfu.edu

I. C. Kizilyalli et al. (eds.), *Direct Current Fault Protection*, Power Systems,
https://doi.org/10.1007/978-3-031-26572-3_1

Table 1.1 Transmission benefits of DC versus AC

	DC	AC
Overhead line loss[a]	3.5%	6.7%
Cables required	2	3
Power capacity[b]	1.4	1

[a]Per 1000 km
[b]For the same wire size and insulation as AC

to a lack of reactive power losses, skin effects, and corona losses. DC also exhibits greater power delivery capacities compared to AC. The effective value of AC current and voltage has a root mean square (RMS) relationship, which is approximately 70% of peak. Since AC distribution cables still need to be sized for peak current, this creates an inherent benefit via greater power delivery with the same sized DC cable or line. Expansion of MVDC distribution would make connecting a growing portfolio of DC energy consumers and producers much less complex since the distribution systems are connecting to an increasingly DC world: 50% of electricity runs through DC devices today [5]. Currently DC networks are typically a collection of point-to-point interconnections, but a multi-point DC mesh network would allow for greater diversification of generation, frequency response, and energy arbitrage and would increase grid resiliency. As the MVDC market matures, meshed DC distribution and large-scale grid integration of renewables and storage are expected to grow, driven by higher efficiency and flexible system operation.

There remains, however, a significant technology gap in the safety and protection mechanisms required to mitigate potentially damaging faults in MVDC systems. Circuit breakers, current limiters, and fault detection mechanisms are essential to grid resiliency in a number of ways: sectioning the grid during a fault; preventing damage to wiring, power electronics, and other important assets; and restoring power to the grid after a fault is cleared. Since, unlike AC, DC does not exhibit natural current zero-crossings (the result of alternating the flow of electricity back and forth), novel methods for fault isolation have to be developed to safely bring the fault current to zero [6].

In addition, the fast reduction of current (di/dt) needed to mitigate the potentially damaging arc in DC circuits can eventually create a large overvoltage (V) in the system, especially when the inductance (L) of the load is large [7]. This risk is largely avoided for AC systems, since transformers and generators can handle high fault currents (20×–40× nominal current) for much longer periods of time (>100 ms), which minimizes the associated overvoltage. Three main types of circuit breakers are being used in the LVDC and HVDC markets: mechanical circuit breakers (MCBs), solid-state circuit breakers (SSCBs), and hybrid circuit breakers (HCBs). All circuit breakers feature a parallel surge arrestor, typically a metal oxide varistor (MOV), to conduct and absorb any residual energy stored in the line inductance after a fault, if needed [8, 9].

MCBs use a mechanical switch in combination with an arc interruption mechanism (e.g., vacuum, SF_6, oil) to clear faults. MCBs feature low on-state resistance and power losses (<0.01% loss), but suffer from lifetime concerns due to arcing and, at least historically, slow switching speeds. In addition, MCBs are limited up to 3 kV applications due to technical challenges in breaking high voltage arcs without a zero-crossing. Since switching speeds and arc elimination are lower risk for AC systems, MCBs are used for AC circuit breakers [8, 9]. SSCBs use semiconductor devices, including integrated gate-commutated thyristors (IGCTs) and integrated insulated-gate bipolar transistors (IGBTs), as the switching medium. SSCBs do not generate arcs and have much faster switching speeds in the range of <100 μs, leading to lower maximum fault currents [8]. This makes them ideal for applications where the circuit breakers are located in close proximity to the equipment being protected, e.g., in electric vehicle battery packs [10]. However, the high on-state conduction losses (>0.3% conduction loss, up to 30% of the losses of a voltage source converter station [11]) and capital costs are the main drawbacks for this technology. Conduction losses are due to the on-state device resistance. These losses result in a significant amount of heat generation, and a cooling system (either liquid or air) is often required to prevent overheating and ensure semiconductor stability [12]. HCBs are capable of delivering fast switching speeds (response times of <2 ms), while still keeping power losses low (<0.01% loss). HCBs typically have three parallel branches: a normal, low on-resistance operation branch which contains a load commutation switch and mechanical switch; a main breaker branch which is formed by stacking several semiconductor switches; and an energy dissipation branch which typically consists of surge arresters. When a fault occurs, the commutation switch shifts the current to the main breaker. The mechanical switch will open under zero current once the current has been completely commutated, thus avoiding arc creation. Then the main breaker will be turned off, and the remaining fault current will be dissipated by the surge arresters. Table 1.2 provides a comparison summary among all three types of DC circuit breakers based on five key performance metrics. Since there is no clear winner, it becomes a tradeoff in selections based on applications. Typically for low voltage applications, we see MCBs being used while in high voltage applications both

Table 1.2 Tradeoffs between all DC circuit breaker types

	Mechanical circuit breaker	Solid state circuit breaker	Hybrid circuit breaker	Ideal Mvdc circuit breaker
Efficiency	✓	✗	✓	✓
Response time	✗	✓	✗	✓
Scalability (voltage)	✗	✓	✓	✓
Cost	✓	✗	✗	✓
Lifetime	✗	✓	✓	✓

SSCBs and HCBs are selected. Interestingly, for MV applications, all five key metrics are critical enough that the selection of breaker types becomes even more challenging.

The challenge of leveraging HVDC or LVDC for MVDC circuit breakers is as follows. The complexity of existing HVDC circuit breakers (HCB or SSCB), driven by a large number of semiconductor devices and associated cooling infrastructure, makes it difficult to scale down to MVDC levels without substantial compromises in operational efficiency and cost. Conversely, scaling up from LVDC (conventionally MCB) to MVDC is also difficult because of arcing concerns: at higher voltage levels, arcing becomes a significant hazard. As a result, development in MVDC circuit breaker technologies (and MVDC distribution applications) has been challenging. Currently, MVDC circuit breakers are only available for lower voltage (<3 kV), low power (<3 MW) applications, and are primarily limited to the rail sector [13–16].

While circuit protection protocols in AC systems are very advanced, with IEEE standards implemented for many grid, ship, and rail systems, there is minimal commercially available products and limited documentation to define the performance requirements for MVDC circuit breakers. To bridge this gap metrics were established in the ARPA-E Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely (BREAKERS) program [17] shown in Table 1.3.

In order to enable circuit protection for MVDC applications in renewable collection, offshore oil and gas distribution, electrification of transportation, high energy physics, nuclear fusion, and other applications, the metrics in BREAKERS program targeted medium voltage circuit breakers rated between 1 and 100 kV, with instantaneous power levels between 1 and 200 MW. Circuit breaker efficiencies above 99.97%, through low conduction losses, are currently realized in HCBs at LVDC and HVDC levels, but have not yet been delivered for MVDC applications. A fast response time, where the response time is defined as the instant from when the breaker receives the trip order to the instant when the current has been lowered to approximately zero, limits the maximum fault current protecting DC power conversion and equipment, and enables fast electricity recovery. Combining low loss with aggressive circuit breaker response times would lead to advances in

Table 1.3 BREAKERS program technical metrics

ID	Category	Target
1.1	Rated voltage	1 kV DC $\geq$ V $\geq$ 100 kV DC
1.2	Rated power[a]	$\geq$1 MW
1.3	Efficiency	$\geq$99.97%
1.4	Response time	$\leq$500 μs
1.5	Lifetime	$\geq$30,000 cycles, $\geq$30 years
1.6	Nuisance trips	$\leq$0.1%
1.7	Power density[a]	$\geq$60 MW/m^3
1.8	Cooling	Passive or forced air[b]

[a] Instantaneous power
[b] Power consumed for any active cooling must be included while measuring breaker efficiency