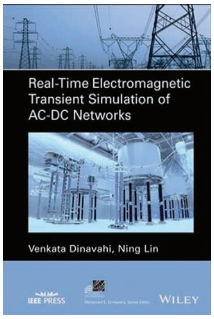
by Fernando A. Silva

Real-Time Electromagnetic Transient Simulation of AC-DC Networks



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The quest for energy sustainability requires increased penetration of renewable energy resources in electrical grids and coordinated use of distributed energy storage, together with intelligent dc grids and microgrids. High-power electronics are now suited for the integration of large-scale renewable generation and energy storage. Multiterminal transmission dc grids will increase the complexity of electrical grids/microgrids interconnections, requiring sophisticated power converters, control algorithms, machine learning, simulation, and testing to develop enhanced solutions. Power electronics is the key technology for establishment of high-power dc grids, smart grids, and microgrids and for energy storage systems capable of coping with intermittent, uncertain, low duty-cycle photovoltaics, and wave or wind renewable energy to help decarbonization. Given the complexity, costs, and risks, testing of converter or grid/microgrid control algorithms cannot take place within the real transmission power grid/microgrid environment. Today, testing must be done using digital simulators. Real-time digital power system simulators are now critical for the testing of control and protection algorithms, in hardware-in-the-loop (HIL) configurations, for high-voltage dc (HVdc) transmission systems. Modern real-time digital power system simulators for HIL can currently be based on field-programmable gate array (FPGA) hardware. FPGA HIL is also useful for education within remote laboratories and for implementing the digital twin concept, as proposed in Industry 4.0 and used in transportation, aviation, and marine industries.

HIGH-POWER ELECTRONICS ARE NOW SUITED FOR THE INTEGRATION OF LARGE-SCALE RENEWABLE GENERATION AND ENERGY STORAGE.

Research, innovation, and education must be enhanced in the field of real-time digital power system simulation using FPGAs for HIL testing of power converter control and protection algorithms to help achieve sustainability requirements.

In chapter 1, "Field Programmable Gate Arrays," the timely book *Real-Time Electromagnetic Transient Simulation of AC-DC Networks* introduces FPGA-based HIL emulation procedures, including parallel and pipelined architectures and high-level design and synthesis software tools. The book presents device-level discrete models suited for FPGA implementation using massively parallel and deeply pipelined architectures as well as numerical integration methods, convolution unit pipelines, network solvers, adaptive time-step, real-time electromagnetic transient (EMT) emulation and decomposition techniques for large power systems.

In the following chapters, the book deals with real-time EMT emulation of fundamental equipment used in ac–dc power grids, from simple, linear-passive elements, to sources, nonlinear elements, switches, transmission lines, iron-core power transformers, rotating machines, protective relays, power electronic semiconductor devices, ac–dc and dc–dc power converters, dc circuit breakers, to finish on chapter 11 with the real-time emulation of large-scale ac and dc networks.

Chapter 2, "Hardware Emulation Building Blocks for Power System Components," covers modeling and hardware emulation of simple, linear-passive elements, sources, nonlinear elements, switches, and transmission lines, dealing with digital convolution units, interpolation, frequency- and time-domain formulation, and network solvers. Case studies are used to illustrate key concepts. "Power Transformers," chapter 3, deals with a nonlinear, admittance-based, real-time transformer model; nonlinear, magnetic-equivalent, circuit-based, real-time multiwinding transformer model; and real-time, finite-element model of a power transformer, finishing with case studies.

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Chapter 4, “Rotating Machines,” derives the lumped universal machine model, a general framework for state-space electrical machine emulation, and nonlinear magnetic equivalent circuit-based induction machine model using case studies and off-line validation. In chapter 5, “Protective Relays,” digital protective relays, including hardware emulation of multifunction protection system, test setup, and real-time results, are covered.

Chapter 6, “Adaptive Time-Stepping Based Real-Time EMT Emulation,” addresses nonlinear solutions and adaptive, time-stepping schemes; adaptive, time-stepping universal line models; and universal machine models for real-time hardware emulation, presenting case studies and validation. “Power Electronic Switches,” chapter 7, presents semiconductor switching device models, including nonlinear behavioral and physics-based nonlinear models for insulated-gate bipolar transistors (IGBTs) with antiparallel diodes, nonlinear behavioral models for power diodes and physics-based nonlinear p–i–n diodes and IGBT models, multiple parallel devices, electrothermal modeling, curve-fitting models, switching transients, on state, and switching power loss, showing results with precision comparable to SaberRD that better commercial real-time simulators.

Chapter 8, “AC–DC Power Converters,” derives models for ac–dc conversion, including modular multilevel converter (MMC)-detailed, equivalent circuit, and semiconductor device-level models; power loss calculations; MMC control methods evaluating efficiency and fast Fourier transform analysis of output waveforms; HIL emulation; islanded MMC performance; and case studies. Chapter 9, “DC–DC Converters,” starts with a nonisolated, four-quadrant Buck–Boost converter, and proceeds to MMC-based solid-state transformers (SSTs), considering a three-phase saturable transformer model using proportional integral controllers and SST real-time HIL emulation to discuss power flow control and dc fault-transient results.

“DC Circuit Breakers,” chapter 10, includes the modeling of an IGBT-based hybrid HVdc breaker and an ultrafast mechatronic circuit breaker employing thyristors, using system- and device-level models for overcurrent protection and voltage-derivative protection, electrothermal modeling, and a four-terminal dc-grid test case. Chapter 11, “Large-Scale AC and DC Networks,” presents the real-time emulation of large-scale ac and dc networks, including spatial decomposition and parallelism; multi-FPGA hardware design for real-time EMT emulation; CIGRÉ dc-grid hybrid modeling methodology; real-time coemulation framework for cyber-physical systems; faster-than-real-time hybrid, dynamic-EMT emulation of ac–dc grids; and case studies.

THE BOOK PROVIDES FUNDAMENTAL METHODS AND HANDS-ON CASE STUDIES SO THAT READERS CAN BECOME FAMILIAR WITH INVALUABLE MODELING METHODOLOGIES FOR REAL-TIME EMULATION OF MODERN ELECTRICAL NETWORKS.

All the chapters are supported by simulation results and validation from sharp test cases (system parameters provided in the “Appendix”). A “Preface,” “Acknowledgments,” “List of Acronyms,” “Table of Contents,” “Index,” and “Bibliography” are also included.

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Real-Time Electromagnetic Transient Simulation of AC–DC Networks is a comprehensive book and a unique and essential practical guide on FPGA real-time modeling and HIL. It is perfect for graduate students, advanced researchers, and professional engineers willing to work on or build real-time emulation systems for power systems; complex electronic power converters and their control. The book provides fundamental methods and hands-on case studies so that readers can become familiar with invaluable modeling methodologies for real-time emulation of modern electrical networks. The book is also suited for librarians, simulation specialists, advanced modeling and simulation engineers, microgrid planning, and designing professionals and professors in related fields, providing concepts to further explore new trends in real-time modeling and HIL. The book is also essential for engineers/researchers willing to launch spinoffs in real-time modeling and HIL to take advantage of recent and future developments in FPGA technology.

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