Flexible Power Hardware-In-The-Loop Testing of DC Circuit Breakers

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Introduction
Motivation

- **Background**
  - Multi-Terminal HVDC technology (MT-HVDC)
    - Loss reduction
    - Cost reduction
    - Reliable operation
  - VSC-based MT-HVDC
    - Vulnerable in DC-faults
    - Short breaking times
  - HVDC circuit breakers: Key for reliable and cost-efficient MT-HVDC operation

- **Research Questions**
  - Component Sizing
    - Expected fault currents
    - Energy dissipation requirements
    - Blocking voltage requirements
  - Maximum breaking times
  - Optimization of HVDC breakers
  - Cost-efficient development of HVDC breakers
Introduction

Motivation

Need for High Current Source

1. Simulation of the MT-HVDC grid
   - Identification of requirements
2. Simulation of a hybrid circuit breaker
   - Optimization of the arc chamber

Power-HiL Simulations

Switchgear characterization

1. Identification of arc parameters
   - Validation of black-box modeling
   - Circuit breaker optimization
Introduction

Motivation

Current Injection Circuits

- Well-established method for test current generation
- Weil-Dobke circuit
- Sinusoidal waveform (Quasi-DC)
- Challenging decoupling of arc parameters

- New method for switchgear characterization
- Buck-converter based
- Complex waveform generation with limited dynamic
- Facilitates decoupling of arc parameters

- Advanced topology: Dynamic and precise
- Interleaved buck-type high frequency converter
- Arbitrary waveform
- “Optimal” decoupling of arc parameters
Outline

Introduction
  o  Motivation

Power Hardware-in-the-Loop
  o  Definitions
  o  Role in HVDC

Characterization of HVDC Switchgear
  o  Motivation
  o  A new approach
  o  First results

Flexible Arbitrary Current Source
  o  Applications
  o  Specifications
  o  Topology and Concept
  o  Current Source 1.0
  o  Advanced Control
  o  Current Source 2.0

Outlook
Power Hardware-in-the-Loop
Power Hardware-in-the-Loop

Definition

- **Schematic**

  - User interface
  - Real Time Simulator (FPGA)
  - ADC
  - DAC
  - Measurement
  - Power amplifier
  - Hardware under test
  - Digital signal
  - Analog signal
  - Power part
  - High power source
  - (Linear amplifier or modulator)

- **Power-HiL**
  - Cost-effective testing
  - Model validation
  - Testing under critical conditions
  - Need for high power amplifier

- **Amplifier requirements**
  - High power
  - High bandwidth
  - Low ripple – High accuracy
  - Flexibility - Modularity
Power Hardware-in-the-Loop
Role in HVDC

Example of HVDC Breaker Test Bed

Real Time Simulator

Hardware Test Bed

Interrupter [DUT]

High power current source
Characterization of HVDC Switchgear
Characterization of HVDC Switchgear

Motivation

▼ Background

- HVDC breaker
  - Challenging interruption
  - >50A/μs gradients
  - High energy dissipation

- Arc/Plasma formation
  - Electrical discharge through a previously insulating medium

- Arc understanding key to breaker optimization

▼ Passive Resonant Circuit Breaker

- Mechanical switch
- Main path
- Passive resonant path
- Energy absorption path

▼ Modelling Challenges

- Electrical, thermal and fluid dynamic dependency
  - Stochastic variations
  - Complex multi-physics simulations needed

- Black-box modeling
  - Sufficient accuracy
  - Extraction of parameters requires complex current waveforms
Characterization of HVDC Switchgear
A new approach

▼ A Novel Method

- Optimal current waveforms
  Decoupling of parameters

- Stationary currents
  Extraction of arc steady state cooling power $P$

- Steep current gradients
  Extraction of arc thermal inertia $\tau$

- High dynamic current

- Precision/low ripple

▼ Current Waveforms

- $I_{\text{max}} > 10 \text{ kA}$
  $\Delta I < 0.01 I_{\text{max}}$
  $\frac{di}{dt} > 100 \text{ A/\mu s}$

- $\frac{di}{dt} > 100 \text{ A/\mu s}$
Characterization of HVDC Switchgear
Results at HVL

▶ Dynamic characterization

- Key learning: \( \tau \) dependence on pressure

▶ Steady state characterization

- Key learning: arc voltage dependence on pressure

▶ Current Source at HVL v1.0

▶ Limitations

- Limited current to 3kA
- Limited voltage to 3kV
- Limited current waveforms
- Unipolar output voltage
Flexible Arbitrary Current Source
Flexible Arbitrary Current Source

Applications

- **Specifications**
  - Emulation of fault currents in DC grids
  - Arbitrary current source
  - 30 kA output current at 10kV
  - >200 A/μs current gradient
  
- **Current Waveforms**

  ![Current Waveforms](image)

- **Other Applications**
  - Accelerator magnets
  - Medical applications
  - Plasma sources

- **Prototype System v.1**
  ![Prototype System v.1](image)
Flexible Arbitrary Current Source
Specifications

Single Stack Topology

Single Stack Prototype

- Output voltage: ±10 kV
- Output current: 1.5 kA
- Current gradient: >10 A/μs
- Current ripple: <0.1 %
- DC current: 1 kA

Full Scale Source

- Output voltage: ±10 kV
- Output current: 30 kA
- Current gradient: >200 A/μs
- Current ripple: <0.1 %
- DC current: 20 kA
Flexible Arbitrary Current Source

Concept

- **System Concept**
  - Current shaping converter
    - 6-phase interleaved buck-type converter
  - Step voltage generator
    - Modular Multilevel Marx-Type Converter

- **Single Stack Topology**

![Diagram of Modular Multilevel Marx Type Converter (M3TC)]

- **Operation Principle**
  - Graph showing voltage levels:
    - $V_{out}$
    - 1650V
    - 1100V
    - 550V
    - 0V
    - $V_c$
    - 550V
    - 0V
    - $V_{M3TC}$
    - 1650V
    - 1100V
    - 550V
    - 0V
    - $V_{1,M3TC}$
    - 550V
    - 0V
    - $V_{2,M3TC}$
    - 1100V
    - 0V

**Diagram Components**
- Unidirectional Unipolar 1.2kV (5kW)
- Unidirectional Unipolar 1kV (10kW)
- $V_r = 0...550V$
- 6x Interleaved Current Shaping Converter
Flexible Arbitrary Current Source
Current Source 1.0

Specifications

- Output voltage: 5.5 kV
- Output current: 1.4 kA
- Current gradient: 2 A/μs
- Pulse length: 20 ms

Experimental Results with Resistive Load

Prototype System v.1
Flexible Arbitrary Current Source
Control Challenges

▼ Controlling Arcs
- Extreme load fluctuations
- Chaotic/Unpredictable behavior
- Highly dynamic control is required

▼ Free Burning Arc

![Plot showing current and voltage over time and frequency spectrum of arc voltage]
Flexible Arbitrary Current Source
Advanced Control Concept

Performance Characteristics

- Transients: Adaptive hysteresis controller
  - Near-optimal transient response
  - Excellent disturbance rejection

- Steady State: PI Controller + Phase Shifting
  - Good steady state performance
  - Constant switching frequency
  - Optimal interleaving
  - Design simplicity

Advanced Hybrid Controller

- Adaptive Hysteresis Control
- Average Current Control
- Phase Shifting Control
Flexible Arbitrary Current Source
Simulation Results

Arc Simulation

- Behavioral arc model
- Measurement-based model
- Stochastic changes
  - >400% change in R-value
  - >250 V/μs
- Resulting current: ±10%

Simulation Results: Arc load

![Graph showing current and voltage over time](image-url)
Flexible Arbitrary Current Source
Current Source 2.0

Current Shaping Converter Module

Single Stack Source: CAD model

M3TC Module
Outlook

- MT-HVDC grid investigations requirements
- Power HiL/Characterization of HVDC breakers
  - Tremendous upside on the development procedure
- High dynamic and arbitrary current
- Low ripple, precision and modularity fit various other applications
- Current source v.2 is under development
- Promising simulation results with arc loads

List of Publications

L. Bort, T. Schultz and C. Franck “Determining the time constant of arcs at arbitrary current levels”, Plasma Physics and Technology, 2019


G. Tsolaridis and J. Biela “Adaptive Hybrid Control Concept for Multiphase DC-DC Converters”, IEEE ECCE, Cincinnati, Ohio, USA 2017

Single Stack Source: CAD model
Thank you for your attention

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