PROFESSIONAL
TRAINING
COURSE

# Immittance-Based Frequency-Domain Stability Analysis and Design of Converter-Interfaced Resources and Power Systems

Taught by Prof. Jian Sun, supported by energynautics

Detailed list of topics and subtopics of each lecture

## Part I: Immittance-Based Stability Modeling and Analysis

1. Circuits and Control of Converters for Power System Application
   1.1. Converter Circuits, Switching Operation, and Harmonics
      1.1.1. Two-Level and Three-Level Voltage-Source Converters
      1.1.2. Pulse-Width Modulation and Harmonics
      1.1.3. Modular Multilevel Converters (MMC)
   1.2. Converter Control Functions and Design
      1.2.1. AC Current Control
      1.2.2. Synchronization with the Grid
      1.2.3. DC Bus and AC Terminal Voltage Control
   1.3. Converters and Power System Stability
      1.3.1. Traditional Power System Stability (Voltage, Angle), SSO/SSR/SSTI/SSCI
      1.3.2. Impacts of Converters, Examples, Behaviors & Classification
      1.3.3. EMT Simulation, Immittance-Based Frequency-Domain Methods
2. Frequency-Domain Modeling and Analysis of Converters
   2.1. Modeling of DC-DC Converters and Systems
      2.1.1. Frequency-Domain Modeling by Averaging and Linearization
      2.1.2. Impedance-Based Analysis; Nyquist Criterion and Open-Loop Stability
      2.1.3. Current vs. Voltage Source Systems; Application to AC Power Systems
   2.2. Modeling of Grid-Connected Converters
      2.2.1. Time-Domain Linearization, LTP Models, Harmonic Transfer Functions
      2.2.2. Linearization Based on Phasor Models, Harmonic Phasor Models
      2.2.3. Modeling in DQ Reference Frame, State-Space Analysis
   2.3. Harmonic Linearization and Small-Signal Sequence Immittance
      2.3.1. Modeling Based on the Principle of Measurement
      2.3.2. Form of Perturbation and Relationship to Harmonic State Space
      2.3.3. Symmetrical Components and Small-Signal Sequence Immittance
3. Modeling of Voltage-Source Converters with Constant DC Bus Voltage
   3.1. DQ-Frame Control with Ideal PLL
      3.1.1. DQ Transformation and Frequency Shift
      3.1.2. DQ-Frame AC Current Control
      3.1.3. DQ-Frame AC Voltage Control
   3.2. Angle Dynamics and Immittance Modeling with PLL
      3.2.1. Harmonic Linearization of PLL Model, Angle Perturbation
      3.2.2. Response of DQ and Inverse-DQ Transformation to Angle Perturbation
      3.2.3. Immittance Modeling with DQ-Frame Control and PLL
   3.3. Control Delay and High-Frequency Immittance, Other Control Functions
      3.3.1. Modeling of Measurement Circuits, Digital Control and PWM Delays
      3.3.2. High-Frequency Immittance Models, Additional Filter Elements
      3.3.3. Other Control Functions

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## » Part I: Immittance-Based Stability Modeling and Analysis

- 4. Modeling of Voltage-Source Converters with DC Bus Dynamics
  - 4.1. Harmonic Interaction and Two-Port Modeling
    - 4.1.1. VSC as a Two-Port Network
    - 4.1.2. Coupling over Frequency, AC-DC Coupling, Self and Transfer Immittances
    - 4.1.3. Formulation of Multi-Frequency Models; Multi-Harmonic Linearization
  - 4.2. Two-Port Characterization of Three-Phase VSC
    - 4.2.1. AC-Port Characterization with a Positive-Sequence Perturbation
    - 4.2.2. General Frequency-Sequence Relationship; Negative Sequence Models
    - 4.2.3. DC-Port Characterization
  - 4.3. AC-Port Immittance with DC Bus Dynamics
    - 4.3.1. Representation of DC Bus Dynamics, DC Bus Impedance
    - 4.3.2. AC-Port Self and Transfer Immittances Including DC Bus Dynamics
    - 4.3.3. Effects of Coupling; Model Simplification
- 5. Immittance Modeling by Frequency Scan and Measurement
  - 5.1. Frequency Response Scan Based on EMT Simulation
    - 5.1.1. Setup, Simulation Models and Considerations
    - 5.1.2. Simulation Algorithms, Integration Time Step and Calibration
    - 5.1.3. Real-Time and Control Hardware-in-the-Loop Simulation
  - 5.2. Frequency Response Scan by Physical Measurement
    - 5.2.1. Setup, Hardware and Instrumentation; Effects of Added Impedance
    - 5.2.2. Form of Injection – Parallel vs. Series, Single Sine vs. Multi Frequency
    - 5.2.3. Online Measurement, Grid Impedance Measurement and Applications
  - 5.3. Data Processing Algorithms and Considerations
    - 5.3.1. Data Acquisition, Fourier and Sequence Analysis
    - 5.3.2. Transfer Immittance and Dependency on Fundamental Voltage Angle
    - 5.3.3. Resolution, Spectral Average, Background Harmonics, Response at $k\omega_1$
- 6. Modeling of Generators, Loads, LCC and Grid-Forming Converters
  - 6.1. Load Converter Modeling
    - 6.1.1. Three-Phase Loads with PWM Rectifiers as Grid Interface
    - 6.1.2. Single-Phase Loads with PWM Rectifiers as Grid Interface
  - 6.2. Line Commutated Converters
    - 6.2.1. Definition and Application of Mapping Functions
    - 6.2.2. LCC Modeling by Impedance Mapping; Multi-Pulse Converters
    - 6.2.3. Effects of Commutation; Impedance Characteristics
  - 6.3. Electric Machines and Grid-Forming Converters
    - 6.3.1. Induction Machines and “Induction Generator” Effects
    - 6.3.2. Synchronous Machines Operating at Constant Speed and Fixed Excitation
    - 6.3.3. Effects of Excitation Control & Rotor Dynamics; Synchronous Condensers
    - 6.3.4. Modeling of Grid-Forming Converters

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## Part I: Immittance-Based Stability Modeling and Analysis

- 7. Stability at Converter-Grid Interface
  - 7.1. Stability Analysis Excluding Coupling over Frequency
    - 7.1.1. Grid Impedance and Transmission Line Modeling
    - 7.1.2. Converter-Grid System Stability, Application of Nyquist Criterion
    - 7.1.3. Instability Behavior; Frequency of Oscillation; Self Stabilization
  - 7.2. Stability Analysis Including Coupling over Frequency
    - 7.2.1. Effects of Coupling Through Grid Impedance
    - 7.2.2. Example, Simplification, Weak Grid Effects
    - 7.2.3. Effects of Coupling on Impedance Scan; Methods to Reduce Such Effects
  - 7.3. Applications
    - 7.3.1. Farm-Grid Systems, Aggregation vs. Scaling
    - 7.3.2. HVDC Converters, Offshore Wind with HVDC Transmission
    - 7.3.3. Four-Wire Systems and Zero-Sequence Stability
- 8. Stability of Power Systems with Grid-Following and Grid-Forming Converters
  - 8.1. Grid-Following Converters without Coupling over Frequency
    - 8.1.1. Nodal Analysis, Matrix Poles and Zeros, Direct Stability Analysis
    - 8.1.2. System Models in Feedback Form, Generalized Nyquist Criterion
    - 8.1.3. Network Thévenin Equivalent Circuit; Internal vs. External Stability
  - 8.2. Grid-Following Converters with Coupling over Frequency
    - 8.2.1. System Models in MIMO Feedback Form; Grid Equivalent Circuit Model
    - 8.2.2. Model Segregation and Effects of Coupling
    - 8.2.3. Special Cases
  - 8.3. Interconnection of Voltage Sources and Grid-Forming Converters
    - 8.3.1. Direct Connection
    - 8.3.2. Connection Through a Passive Network
    - 8.3.3. Example
- 9. Stability of DC and Hybrid AC-DC Grids; Other Applications
  - 9.1. DC System Stability
    - 9.1.1. DC Port Immittance Accounting for AC Grid Impedance
    - 9.1.2. DC Bus Voltage Control and Stability; AC vs. DC System Stability
    - 9.1.3. HVDC System Stability; Multi-Terminal HVDC, DC Grids
  - 9.2. Hybrid AC-DC System Stability
    - 9.2.1. Coupling between AC Nodes Through a DC Network
    - 9.2.2. Coupling between DC Nodes Through an AC Network
    - 9.2.3. Hybrid AC-DC System Modeling and Stability Analysis
  - 9.3. Miscellaneous Applications; Special Systems
    - 9.3.1. Addition, Removal and Replacement of Converters
    - 9.3.2. System with Similar or Identical Converters
    - 9.3.3. Radial Systems; Modes of Instability