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

Detailed list of topics and subtopics of each lecture

Part II: Instability Modes, Root Causes and Mitigation

1. Immittance Responses and Effects of Control
   - 1.1. General Considerations: What to Look for in Immittance Responses
     - 1.1.1. Sufficient Conditions for Stability
     - 1.1.2. Phase Responses and Negative Damping
     - 1.1.3. Magnitude Responses; Poles and Zeros
   - 1.2. AC Port Immittance and Effects of AC Port Control
     - 1.2.1. High-Freq. Models & Responses; Effects of AC Current Control and Delays
     - 1.2.2. Low-Freq. Models and Responses; Effects of PLL and AC Voltage Control
     - 1.2.3. Direct AC Voltage Control
   - 1.3. DC Port Control and Immittance, AC-DC Coupling, Coupling over Frequency
     - 1.3.1. DC Port Immittance; Effects of DC Bus Control and AC-DC Coupling
     - 1.3.2. Effects of DC Bus Dynamics on AC Port Immittance
     - 1.3.3. Coupling over Frequency at AC Port
2. PV Inverter and Wind Turbine Immittances
   - 2.1. PV Inverters and Type-IV Turbines
     - 2.1.1. Circuits, Control and Immittance Models; Other Applications
     - 2.1.2. Effects of Rectifier and Generator on Type-IV Turbine Immittances
     - 2.1.3. Internal DC Bus Dynamics, DC Bus Control and Stability
   - 2.2. Type-III Turbine Immittances with DC Bus Treated as Ideal Voltage Source
     - 2.2.1. DFIG Operation Principle, Converters, and Control
     - 2.2.2. Immittance of Induction Machine with Rotor-Side Converter (RSC)
     - 2.2.3. Stator-Side Converter (SSC) and Overall Turbine Immittance
   - 2.3. Type-III Turbine Immittances with Actual DC Bus Dynamics; Negative Damping
     - 2.3.1. SSC and DFIG–RSC Models with DC Bus Dynamics
     - 2.3.2. Cross Coupling Through DC Bus
     - 2.3.3. Complete Immittance Models, Effects of Coupling
3. HVDC Converter Immittances
   - 3.1. Modular Multilevel Converter Circuits, Operation and Control
     - 3.1.1. Module, String, and Converter Circuits, Principle and Operation Limits
     - 3.1.2. Averaged Models, Symmetry of Control and Operation, Modulation
     - 3.1.3. Basic Control, Circulating Current Control, Arm Voltage Control
   - 3.2. Frequency-Domain Modeling of MMC
     - 3.2.1. Steady-State Model, Phase-Sequence Relationship; Harmonics Analysis
     - 3.2.2. Small-Signal Model and Phase-Sequence Relationship; Model Reduction
     - 3.2.3. Control Modeling
   - 3.3. Immittance Models, Responses, and Use in System Analysis
     - 3.3.1. Self Admittance; Transfer Admittance; Effects of Harmonics and Control
     - 3.3.2. Frequency Scan; Voltage vs. Current Perturbation
     - 3.3.3. Immittance Responses; Use in System Stability Analysis

Detailed list of topics and subtopics of each lecture

Part II: Instability Modes, Root Causes and Mitigation

4. High-Frequency Instability – Modes and Root Causes
   - 4.1. High-Frequency Modes Involving MMC-Based HVDC Converters
     - 4.1.1. High-Frequency Models, Control Delay, and Negative Damping
     - 4.1.2. HVDC Converter Resonance with Transmission Lines and Cables
     - 4.1.3. Zero-Sequence Resonance
   - 4.2. High-Frequency Modes Involving Converter-Based Generation
     - 4.2.1. HF Impedance Characteristics of Two-Level VSC and Wind Turbines
     - 4.2.2. Resonance with the Grid, Intra-Farm and Inter-Farm Resonance
     - 4.2.3. Grid-Forming Control with Filter Capacitors
   - 4.3. Harmonic Amplification and Modes Involving Converter-Based Loads
     - 4.3.1. Steady-State Harmonics and Harmonic Amplification
     - 4.3.2. Harmonic Impedance; Effects of Harmonic Control
     - 4.3.3. Modes Involving Converter-Based Loads
5. High-Frequency Instability – Solutions
   - 5.1. Damping of High-Frequency Impedance by Converter Control
     - 5.1.1. Control Parameter Tuning and Optimization
     - 5.1.2. Broadband Damping; Feedforward & Predictive Control
     - 5.1.3. Damping under Direct AC Voltage Control
   - 5.2. Narrowband and Adaptive Damping
     - 5.2.1. Band-Pass Filters and Their Characteristics
     - 5.2.2. Narrowband Damping
     - 5.2.3. Resonance Detection; Adaptive Damping, Automatic Gain Adjustment
   - 5.3. Passive Damping, Power Loss, Hybrid Active-Passive Damping
     - 5.3.1. Low-Pass Filter and Its Damping, Power Loss and Loss Minimization
     - 5.3.2. Shunt Filters and High-Order Damping Circuits
     - 5.3.3. Hybrid Damping; Parasitic Loss of Components and Effects
6. Low-Frequency Instability – Modes and Root Causes
   - 6.1. Type-IV Wind Turbines and PV Inverters
     - 6.1.1. Impedance Characteristics, Coupled Harmonics, SSO
     - 6.1.2. Type-IV Turbines in Weak Grids; Supersynchronous Resonance (SupSR)
     - 6.1.3. PV Inverters in Weak Grids
   - 6.2. Type-III Wind Turbines
     - 6.2.1. Type-III Turbines in Weak Grids and SupSR
     - 6.2.2. Subsynchronous Impedance, Effects of DFIG and Rotor Speed
     - 6.2.3. Series Compensation; Subsynchronous Resonance (SubSR)
   - 6.3. HVDC Converters and Systems, Converter-Based Loads and Electric Machines
     - 6.3.1. HVDC Converters and Systems; Offshore Wind with HVDC Transmission
     - 6.3.2. Modes Involving Converter-Based Loads
     - 6.3.3. Machine-Related SSR/SSO; Torsional Mode, Torsional Interaction

Detailed list of topics and subtopics of each lecture

Part II: Instability Modes, Root Causes and Mitigation

7. Low-Frequency Instability – Solutions
   - 7.1. Damping of LF Resonance – Methods and General Considerations
     - 7.1.1. Control Design Optimization and Parameter Tuning
     - 7.1.2. Active Damping: Broadband Methods, Narrowband Methods
     - 7.1.3. Damping Through Passive Filters
   - 7.2. Applications and Case Studies – Converter-Based Generation and Loads
     - 7.2.1. SupSR of Type-IV Turbines in Weak Grids
     - 7.2.2. SubSR of Type-III Turbines with Series-Compensated Grid
     - 7.2.3. Data Center Power System Stability
   - 7.3. Applications and Case Studies – HVDC Converters and Systems
     - 7.3.1. HVDC Transmission for Offshore Wind
     - 7.3.2. HVDC Converters with Onshore Grid
     - 7.3.3. Damping by Adaptive Control and Passive Methods
8. Multi-Converter System Instability
   - 8.1. Frequency-Domain Stability and Modal Analysis of MIMO Systems
     - 8.1.1. GNC and Application Based on Determinant vs. Eigenvalues
     - 8.1.2. Eigenvectors and Frequency-Domain Modal Analysis
     - 8.1.3. Dealing with Variable Operation Conditions and Network Configurations
   - 8.2. Modes Related to Interactions with Network Dynamics
     - 8.2.1. Weak Grid and Supersynchronous Resonance
     - 8.2.2. Series Compensation and SubSR; Type-III & IV Turbine Interaction
     - 8.2.3. High-Frequency and Localized Modes
   - 8.3. Modes Related to Machines and Mechanical Dynamics
     - 8.3.1. SSO Classification and Analysis Methods; Impedance-Based Methods
     - 8.3.2. System Modeling with Synchronous Machines
     - 8.3.3. Torsional Mode Excitation, Torsional/Control Interaction
9. Design for System Stability; Future Development
   - 9.1. Immittance-Based Standards and Product Specifications
     - 9.1.1. Power Supply Specs for Data Center Power Systems
     - 9.1.2. Development of Standards for Renewable Energy and HVDC Systems
     - 9.1.3. Future Directions; Test and Validation Requirements
   - 9.2. System Study and Software Tools
     - 9.2.1. Current System Study Methods and Requirements
     - 9.2.2. Existing Software Functions and Applications
     - 9.2.3. Future Development; Integrated Software Tools, Models and Algorithms
   - 9.3. Closing Reflection and Discussion