Stochastic Dynamics of Power System

JU Ping
Hohai University

Oct. 2017 • Wuhan, CHINA
Content

I. Research Background of SDPS

II. Research on Model of SDPS

III. Research on Analysis of SDPS

IV. Research on Control of SDPS

V. Summary
1.1 Background

- Oscillations in Power Systems

  - Occurred frequently
  - Unclear mechanism
1.1 Background

- **Stochastic Disturbances**
  - Integration of renewable generation
  - Integration of new-type load
  - Integration of electronic devices

- Is there any relation?
1.2 Randomness in Power Systems

**Types**
- **Continuous stochastic variable**: load, renewable generation, etc.
- **Discrete stochastic event**: fault location, fault type, network operation, etc.

**Difficulties**
- Deterministic dynamics: DAE
- Stochastic dynamics: DAE + Randomness

**Problems**
- $[1 \text{ or } 0] \quad P\{\bullet\} \in [1, 0]$
1.3 Research Framework

**Stochastic Dynamics of Power Systems**

- **Model of SDPS**
  - System model
  - Excitation model
- **Analysis of SDPS**
  - Stochastic stability
  - Stochastic oscillation
  - Stochastic security
- **Control of SDPS**
  - Minimizing the response
  - Maximizing the stability
  - Maximizing the security
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2.1 Introduction to Model of SDPS

- **Topics**
  - System model
  - Disturbance model

- **Comparisons**
  - Deterministic disturbance — Stochastic process
  - Time domain model — Frequency domain model
2.2 Stochastic Model of System

- **System Model --- Quasi Hamiltonian**
  - Analysis method: Stochastic averaging method
  - Quasi Hamiltonian System: Stochastic noises excited and 
dissipated Hamiltonian system

\[
\begin{align*}
\frac{dQ_i}{dt} &= \frac{\partial H}{\partial P_i} \\
\frac{dP_i}{dt} &= -\frac{\partial H}{\partial Q_i} - c_{ij}(Q,P)\frac{\partial H}{\partial P_j} + f_{ik}(Q,P)\xi_k(t) + u_i(Q,P)
\end{align*}
\]

\(i, j = 1, 2, \cdots n; \quad k = 1, 2, \cdots, m\)
2.3 Stochastic Model of Disturbance

- **Disturbance Model --- Power Spectrum**
  - Similarity in the frequency domain
  - Logarithmic linearity

![Graphs showing similarity and logarithmic linearity across different generation levels.](image-url)
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3.1 Introduction to Analysis of SDPS

- **Topics**
  - Stochastic analysis of stability
  - Stochastic analysis of oscillation
  - Stochastic analysis of security

- **Comparisons**
  - Deterministic: stable (1) or unstable (0)
  - Stochastic: statistics of stability
3.2 Stochastic Stability

- Theorem of Stochastic Stability

- In a small-signal stable power system, if the stochastic disturbance is bounded, the system satisfies mean stability and mean square stability.

- This means that there are no new stability issues in power system under small stochastic disturbance.

? Will new oscillation issues happen or not?
3.3 General Forced Oscillation under Small Stochastic Disturbance

- **Input**
  - **Model:** linearized system model
  - **Source:** stochastic, not a sine function
  - **Frequency characteristics:** narrow-band, not single-valued

- **Output**
  
  \[ S_u(f) \rightarrow [H(f)] \rightarrow S_y(f) = |H(f)|^2 S_u(f) \]

  - larger: \( S_u(f) \) and \( |H(f)|^2 \)
  - 0: \( S_u(f) \) or \( |H(f)|^2 = 0 \)
  - smaller: \( S_u(f) \) or \( |H(f)|^2 \)
3.3 General Forced Oscillation

- **Mechanism**

![Graph showing frequency coverage and equivalence]

- **Condition**: frequency coverage, not the frequency equivalence
- **Possibility**: GFO occurs much more frequently than classic forced oscillation
3.3 General Forced Oscillation

- GFO in Henan Power Grid
  - Active power of the inter-area UHV tie line

**Measured**

**Simulated**

![Graphs showing active power and PSD for measured and simulated data.](image-url)
3.4 General Internal Resonance under Large Stochastic Disturbance

- **General Forced Oscillation**
  - Caused by *small stochastic disturbance*
  - Based on the linear system theory
  - Oscillation modes are completely decoupled

- **Nonlinear Internal Resonance**
  - The disturbance is large enough, so the system nonlinearity needs to be considered.
  - Nonlinear interaction exists among the oscillation modes
  - Classic internal resonance: *single-frequency disturbance*
  - General internal resonance: *large stochastic disturbance*
3.4 General Internal Resonance

- **Mechanism**
  
  - The mode 1 is excited at first, which frequency characteristic is supposed to be narrow-band.
  
  - The input to mode 2 with interaction:
    \[ g(z_1) = c_{11}z_1^2 \]

- **Criterion**
  
  \[ f_2 \in \left[ 0, \Delta f \right] \cup \left( 2f_1 - \Delta f, 2f_1 + \Delta f \right) \]
3.4 General Internal Resonance

- Case study
  - Stochastic disturbance with narrow-band 0.4~0.6Hz
  - Mode 1 is excited at first, according to GFO
  - Mode 2 is then excited, although it is not covered

- Internal resonance occurs when the frequency ratio is around 1:2
3.5 Stochastic Security

- Bounded fluctuation region
  - OMIB – 2 dimension
    - to keep the state fluctuation in limits
    - state space trajectory
    - rectangle
  - MMS – ? dimension

- How to simplify?
  - state space
  - energy function
3.5 Stochastic Security

- **The Intra-region Probability**
  - The intra-region probability of **BFR-O**
    - very high dimension
    \[
    R(t \mid Y_0) = P\{Y(\tau) \in \Omega_B, \tau \in (0,t) \mid Y(0) = Y_0 \in \Omega_B\}
    \]
  - The intra-region probability of **BFR-E**
    - one dimension
    \[
    R(t \mid H_0) = P\{H(\tau) < \Omega_E, \tau \in (0,t) \mid H(0) = H_0 < \Omega_E\}
    \]
  - A analytic equation is developed for solving the IRP
3.5 Stochastic Security

- **Case study**

  - Almost the same value
  - Much less consumed time

![Graph showing Intra-region probability, R vs Time, t (s) with intensity of excitations: a > b > c > d]

<table>
<thead>
<tr>
<th>Number of generators (n)</th>
<th>Consumed Time (t), s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monte Carlo simulation</td>
</tr>
<tr>
<td>4</td>
<td>3.6</td>
</tr>
<tr>
<td>10</td>
<td>22.8</td>
</tr>
<tr>
<td>20</td>
<td>107.8</td>
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<tr>
<td>30</td>
<td>255.4</td>
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<tr>
<td>40</td>
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<tr>
<td>50</td>
<td>681.3</td>
</tr>
<tr>
<td>100</td>
<td>2833.4</td>
</tr>
</tbody>
</table>

intensity of excitations: a > b > c > d
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4.1 Introduction

- **Topics**
  - If the security is not satisfied, control should be put into use
  - Maximizing the security

- **Comparisons**
  - Performance index: statistics of the objective function
  - Control law: nonlinearity
4.2 Maximizing the Security

- **Stochastic model with excitation Control**

\[
\begin{align*}
    d\delta_i &= \omega_N \omega_i dt \\
    d\omega_i &= \frac{1}{M_i} \left[ P_{mi} - D_i \omega_i - G_{ii} E_{qi}^2 - E_{qi} \sum_{j=1, j\neq i}^{n} E_{qj} B_{ij} \sin \delta_{ij} \right] dt + \frac{\sigma_i}{M_i} dB_i(t) \\
    dE_{qi}' &= \frac{1}{T_{d0i}} \left[ -b_i E_{qi}' + c_i \sum_{j=1, j\neq i}^{n} E_{qj}' B_{ij} \cos \delta_{ij} + E_{fdis} + u_{fi} \right] dt \\
    i &= 1, 2, ..., n
\end{align*}
\]
4.2 Maximizing the Security

- Dynamic programming approach

\[
\frac{\partial V}{\partial t} = -\sup_{u \in U} \left\{ \frac{1}{2} \sigma_{HH}^2(H, C_i) \frac{\partial^2 V}{\partial H^2} + \left[ m_H(H, C_i) + \left( \frac{u_{fi}}{T_{d0i}'} \frac{\partial H}{\partial E_{qi}'} \right) \right] \frac{\partial V}{\partial H} + m_C(H, C_i) + \left( \frac{u_{fi}}{T_{d0i}'} \frac{\partial C_i}{\partial E_{qi}'} \right) \right\} \frac{\partial V}{\partial C_i} \right\}
\]

- Control constraints: \[ \left| \frac{u_{fi}}{T_{d0i}'} \right| \leq K_i \]

- Optimal control law

\[ u_{fi} = K_i T_{d0i}' \text{ sgn} \left( \frac{\partial H}{\partial E_{qi}'} \frac{\partial V}{\partial H} + \frac{\partial C_i}{\partial E_{qi}'} \frac{\partial V}{\partial C_i} \right) \]

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4.2 Maximizing the Security

- Case Study
  - Results
    - Security increases

![Graph showing security over time with different control settings](image)
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V. Summary
General Forced Oscillations
- Small disturbance, linearized system
  - Condition: frequency coverage
  - Possibility: much larger

General Internal Resonant Oscillations
- Large disturbance, nonlinear system
  - Condition: frequency doubled approximately
  - Possibility: much larger
CSEE Journal of Power & Energy Systems

Editor-in-Chief
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Indexed by
ESCI  INSPEC
CSAD (Chinese Science Abstract Database)

Quarterly Journal
Jointly Published by
CSEE/IEEE/CEPRI

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