Stochastic Dynamics of Power System

JU Ping

Hohai University

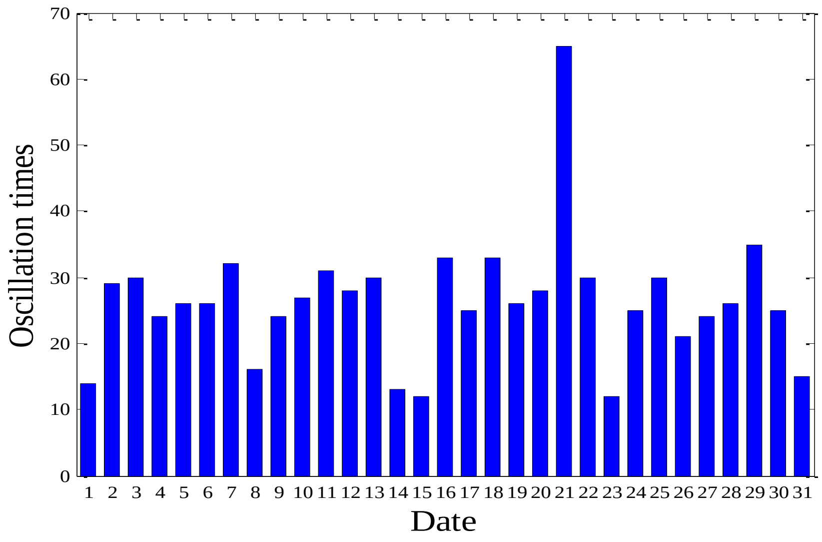
Oct. 2017● Wuhan, CHINA

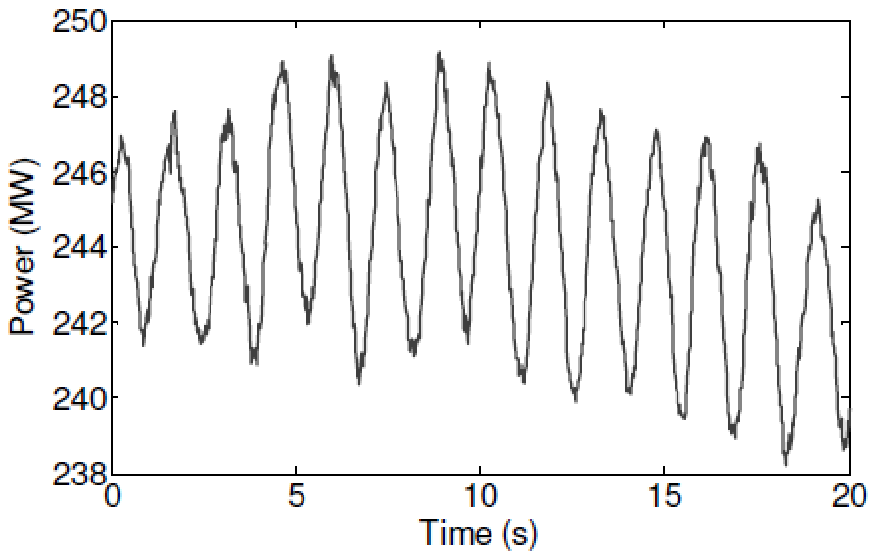
Content

1.1 Background

■ Oscillations in Power Systems

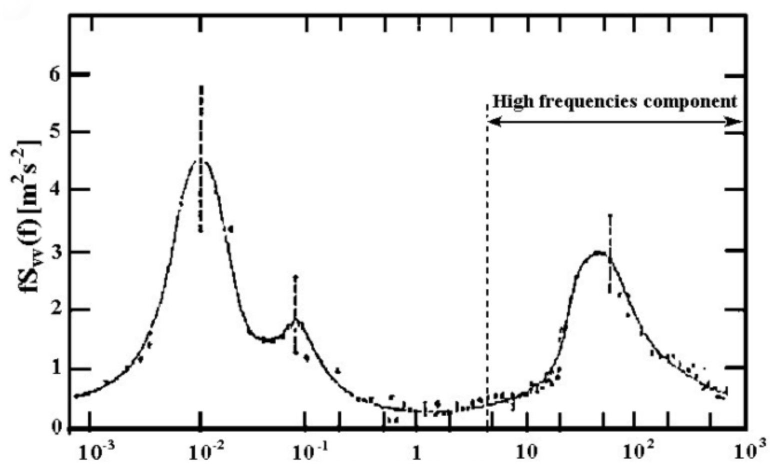
- **Occurred frequently**
- **Unclear mechanism**





1.1 Background

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



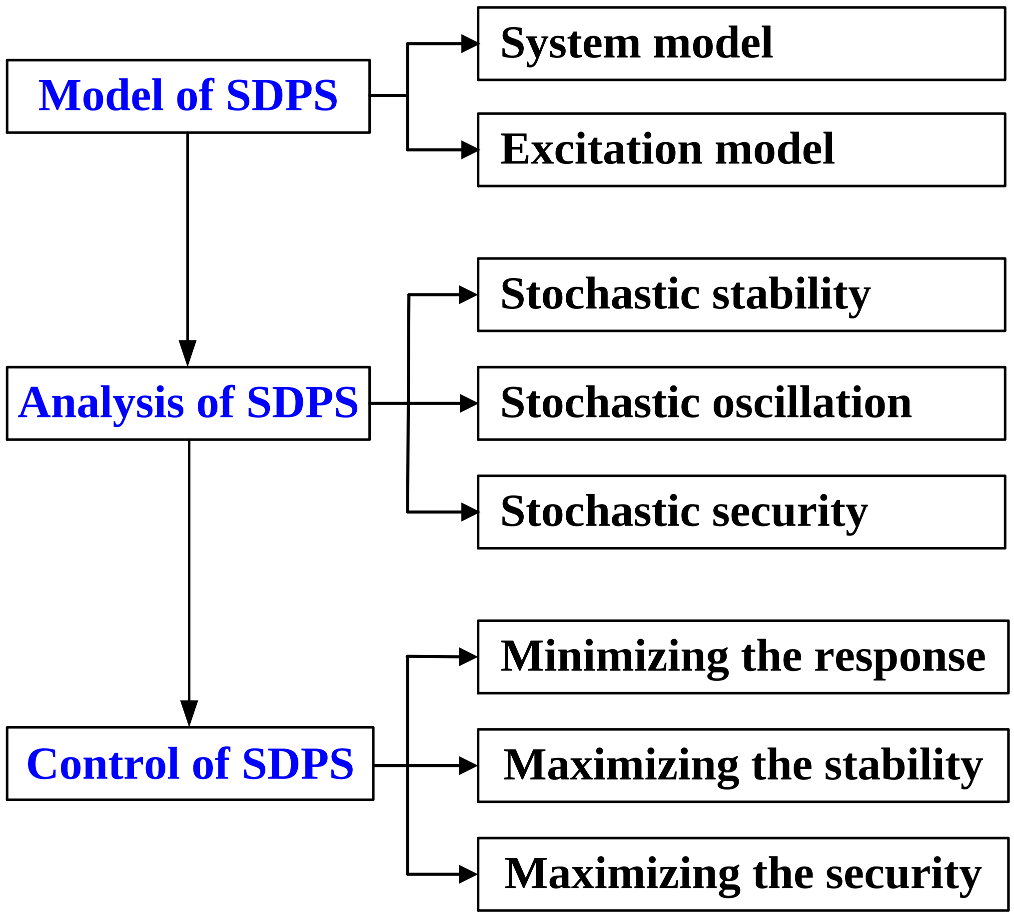
- **Is there any relation?**

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 or 0]** ⟹ $P\{\bullet\} \in [1, 0]$

1.3 Research Framework

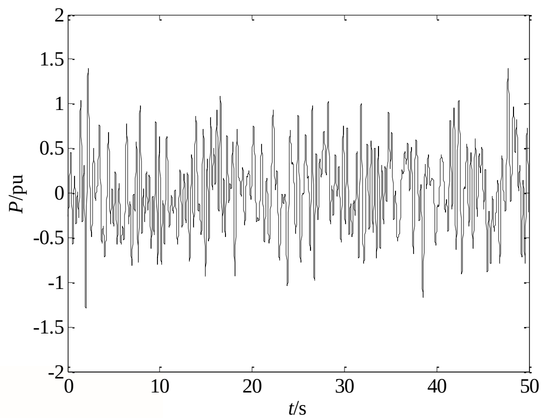
Stochastic Dynamics of Power Systems

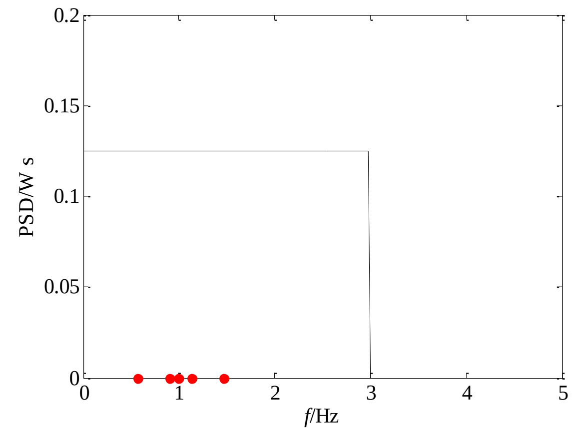


Content

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

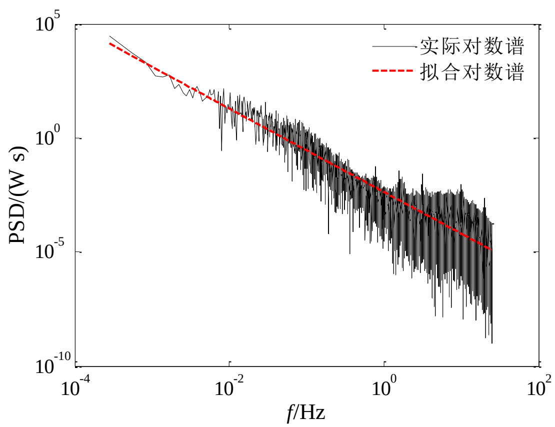
- **System Model --- Quasi Hamiltonian**
  - **Analysis method: Stochastic averaging method**
  - **Quasi Hamiltonian System: Stochastic noises excited and dissipated Hamiltonian system**

$$\begin{cases} \dfrac{dQ_i}{dt} = \dfrac{\partial H}{\partial P_i} \\ \dfrac{dP_i}{dt} = -\dfrac{\partial H}{\partial Q_i} - c_{ij}(\boldsymbol{Q}, \boldsymbol{P})\dfrac{\partial H}{\partial P_j} + f_{ik}(\boldsymbol{Q}, \boldsymbol{P})\xi_k(t) + u_i(\boldsymbol{Q}, \boldsymbol{P}) \\ i, j = 1, 2, \cdots n;\ k = 1, 2, \cdots, m \end{cases}$$

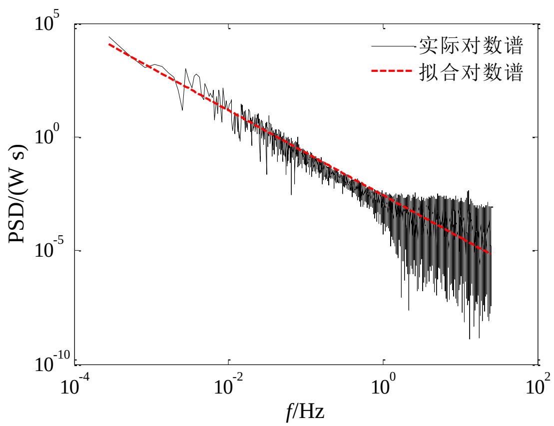
2.3 Stochastic Model of Disturbance

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

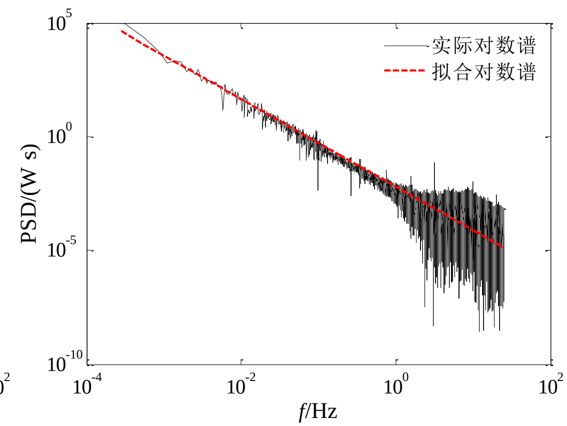
High Generation Level



Medium Generation Level



Low Generation Level



Content

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

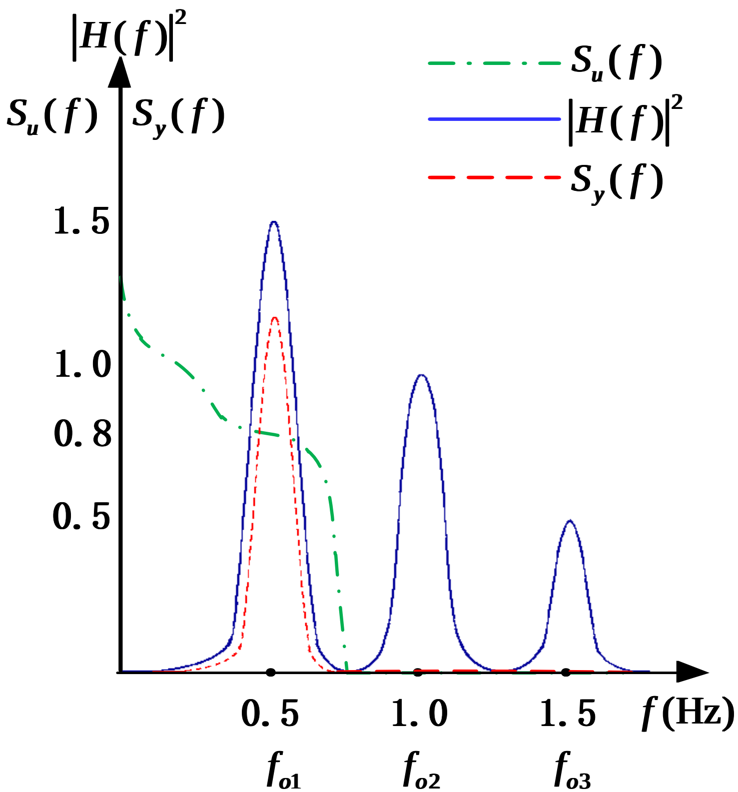
- **Input**
  - **Model:** **linearized system model**
  - **Source:** **stochastic, not a sine function**
  - **Frequency characteristics:** **narrow-band, not single-valued**
- **Output**

$$S_u(f) \rightarrow \boxed{H(f)} \rightarrow S_y(f) = |H(f)|^2 S_u(f)$$

  - **larger:** $S_u(f)$ **and** $|H(f)|^2$ $\uparrow$
  - **0 :** $S_u(f)$ **or** $|H(f)|^2$ **=0**
  - **smaller :** $S_u(f)$ **or** $|H(f)|^2$ $\downarrow$

3.3 General Forced Oscillation

■ Mechanism



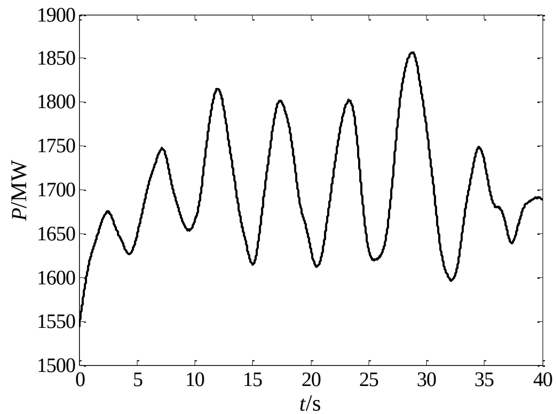
- **Condition**: **frequency coverage, not the frequency equivalence**
- **Possibility**: **GFO occurs much more frequently than classic forced oscillation**

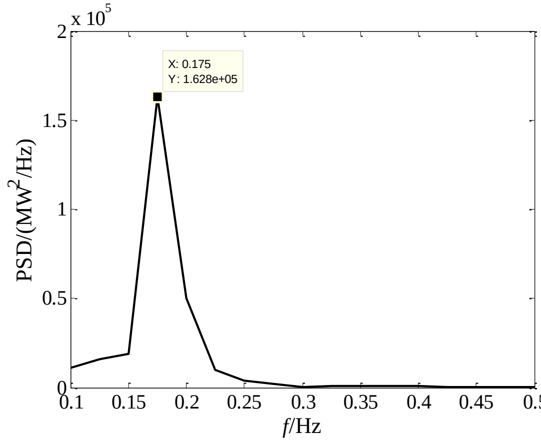
3.3 General Forced Oscillation

■ GFO in Henan Power Grid

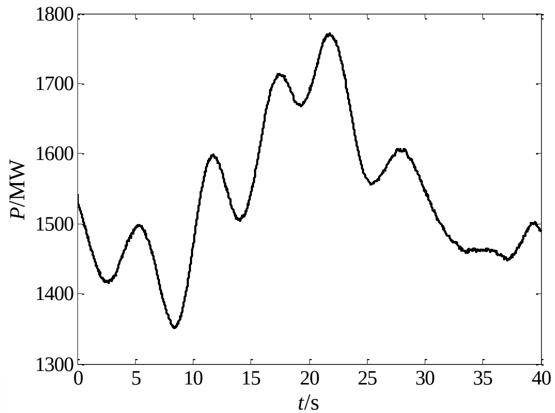
➢ Active power of the inter-area UHV tie line

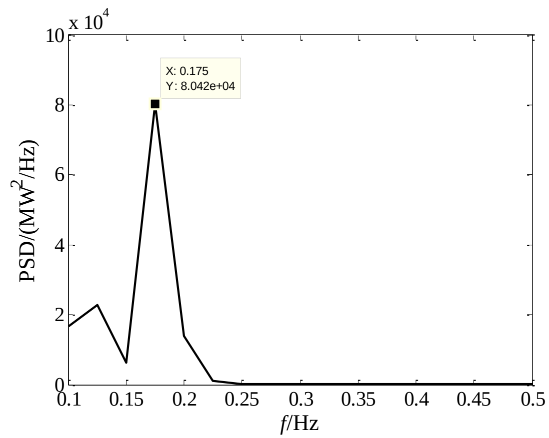
Measured





Simulated





The Institution of Engineering and Technology

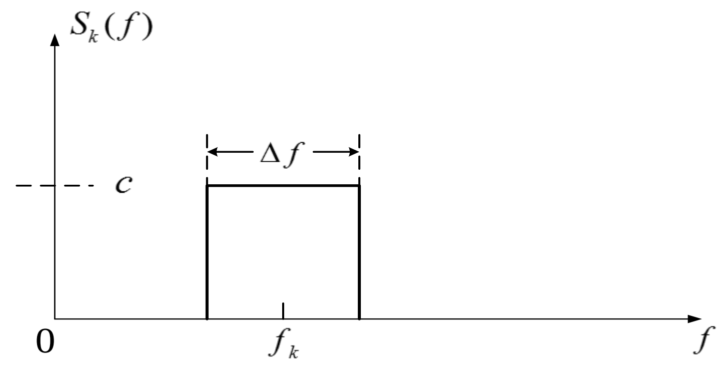
3.4 General Internal Resonance under Large Stochastic Disturbance

- **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

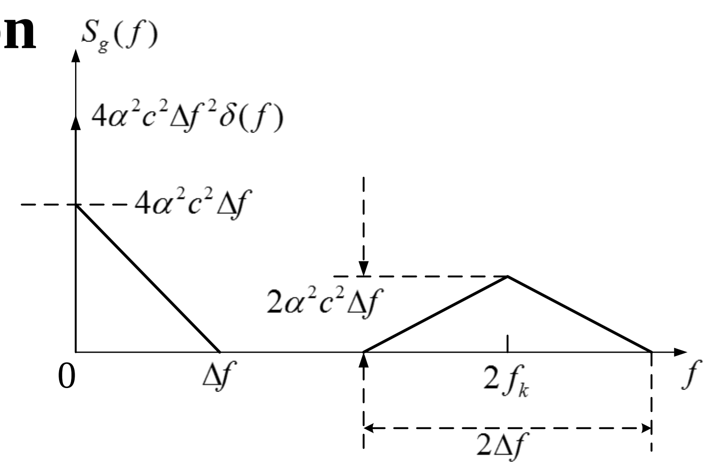
■ Mechanism

- ➢ **The mode 1 is excited at first, which frequency characteristic is supposed to be narrow-band**



- ➢ **The input to mode 2 with interaction**

$$g(z_1) = c_{11}^2 z_1^2$$



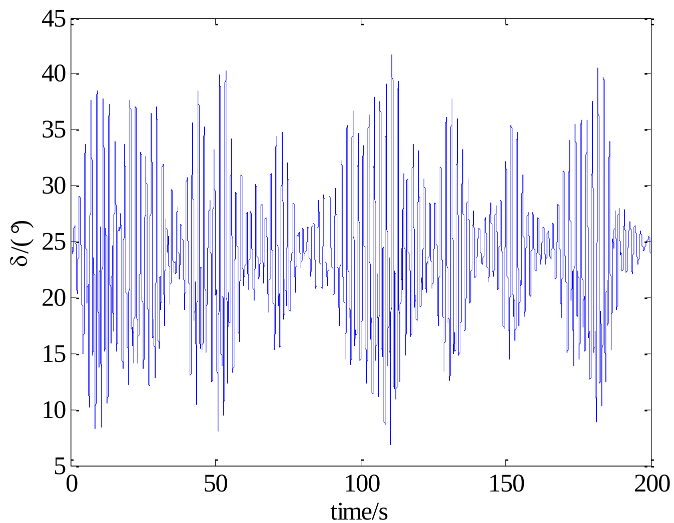
- ➢ **Criterion**

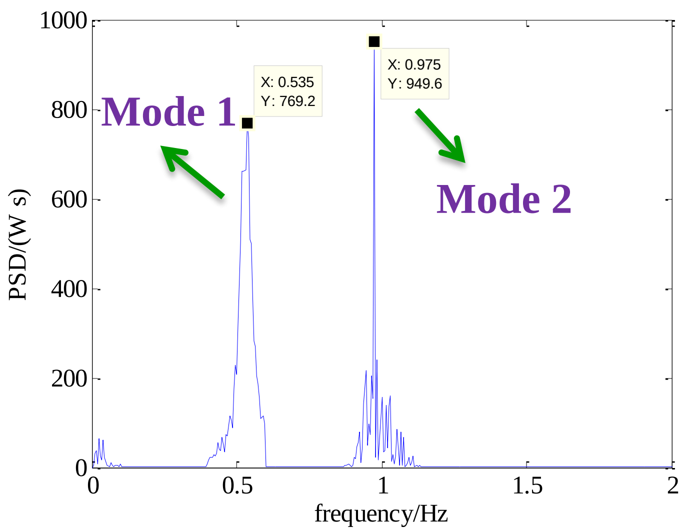
$$f_2 \in \left[0, \Delta f\right) \cup \left(2f_1 - \Delta f, 2f_1 + \Delta f\right)$$

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**

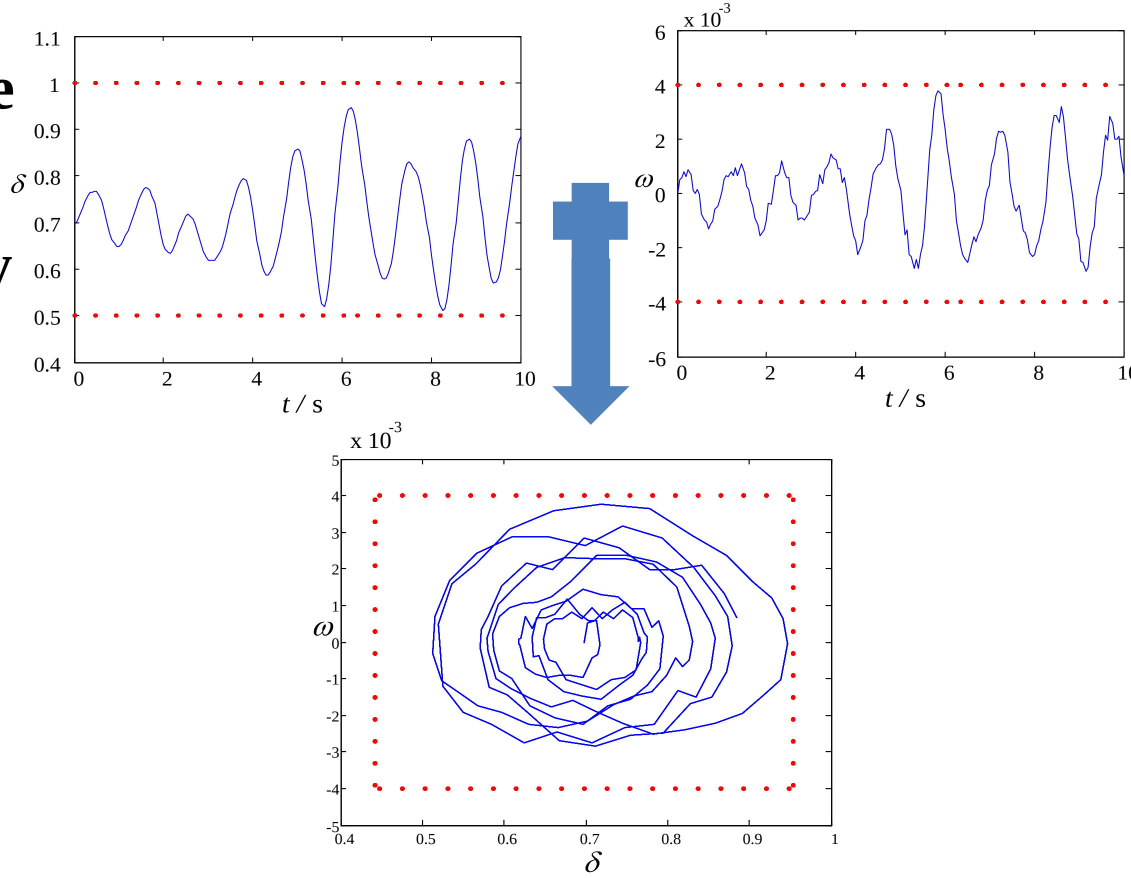




- **Internal resonance occurs when the frequency ratio is around 1:2**

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

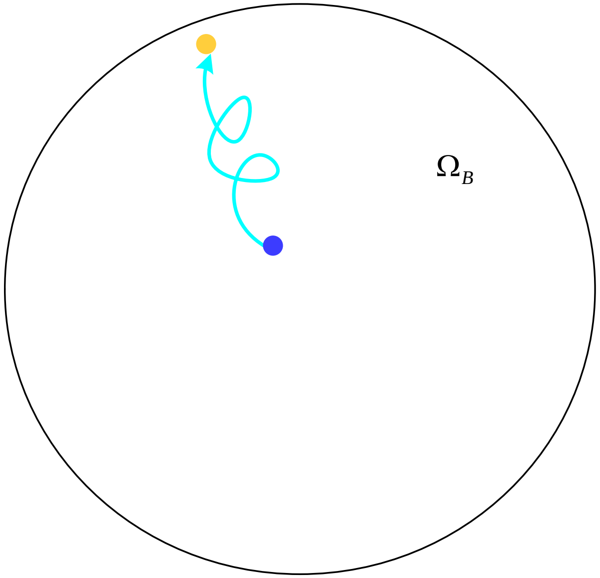
- **The intra-region probability of BFR-O – very high dimension**

$$R\left(t \mid \boldsymbol{Y}_0\right) = P\left\{\boldsymbol{Y}\left(\tau\right) \in \Omega_B, \tau \in (0,t] \mid \boldsymbol{Y}(0) = \boldsymbol{Y}_0 \in \Omega_B\right\}$$

- **The intra-region probability of BFR-E – one dimension**

$$R\left(t \mid H_0\right) = P\left\{H\left(\tau\right) < \Omega_E, \tau \in (0,t] \mid H(0) = H_0 < \Omega_E\right\}$$

Probability=?



System state

Initial state

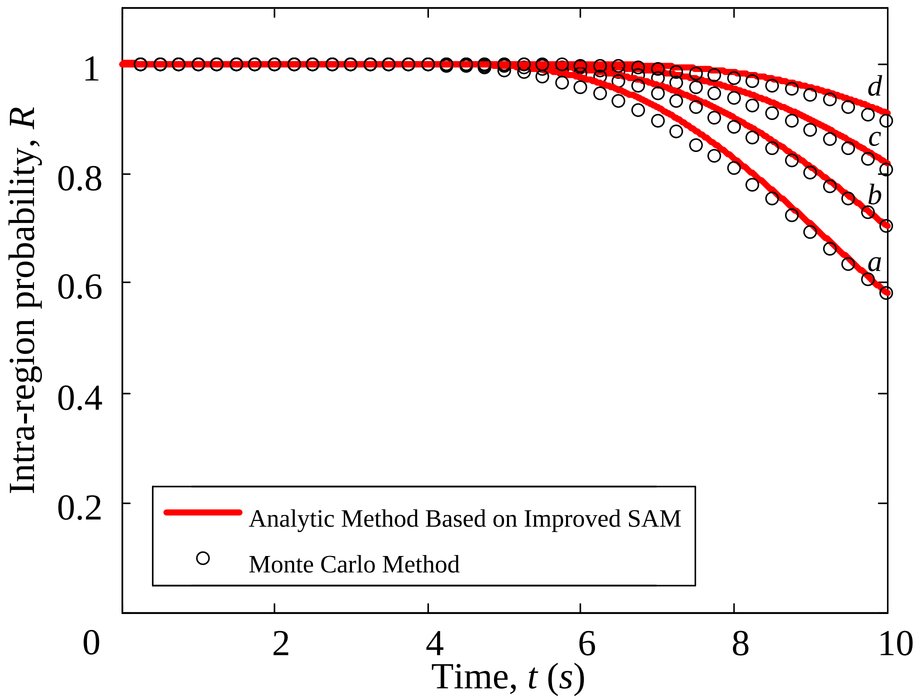
BFR Ω_B

A analytic equation is developed for solving the IRP

3.5 Stochastic Security

Case study

Almost the same value



intensity of excitations: *a* > *b* > *c* > *d*

Much less consumed time

Number of generators (*n*)	Consumed Time (*t*), s	
	Monte Carlo simulation	Analytic method based on the SAM
4	3.6	0.1
10	22.8	0.1
20	107.8	0.1
30	255.4	0.1
40	439.3	0.1
50	681.3	0.1
100	2833.4	0.1

Content

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**

$$\begin{cases} d\delta_i = \omega_N \omega_i dt \\ d\omega_i = \dfrac{1}{M_i}\left[P_{mi} - D_i\omega_i - G_{ii}E_{qi}^{'2} - E_{qi}^{'} \sum_{j=1, j\neq i}^{n} E_{qj}^{'} B_{ij} \sin\delta_{ij} \right] dt + \dfrac{\sigma_i}{M_i} dB_i(t) \\ dE_{qi}^{'} = \dfrac{1}{T_{d0i}^{'}}\left[-b_i E_{qi}^{'} + c_i \sum_{j=1, j\neq i}^{n} E_{qj}^{'} B_{ij} \cos\delta_{ij} + E_{fdsi} + u_{fi} \right] dt \end{cases}$$

$$i = 1, 2, \ldots, n$$

4.2 Maximizing the Security

- **Dynamic programming approach**

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

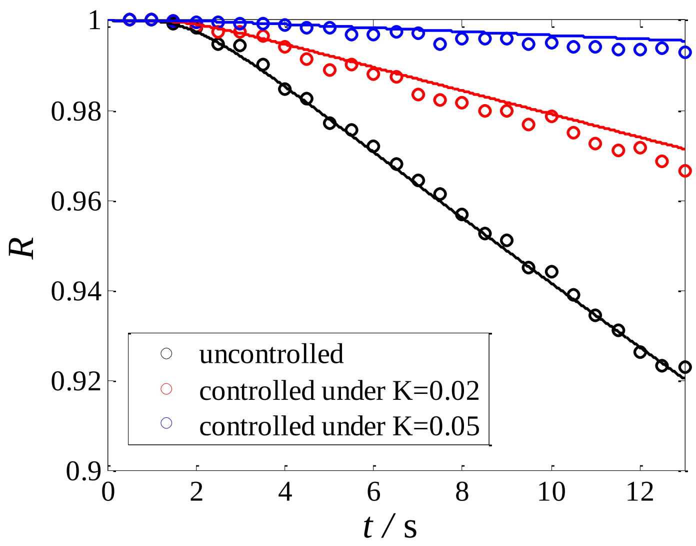
- **Control constraints:** $\left| \frac{u_{fi}}{T_{d0i}^{'}} \right| \le K_i$

- **Optimal control law**

$$u_{fi} = K_i T_{d0i}^{'} \operatorname{sgn}\left(\frac{\partial H}{\partial E_{qi}^{'}} \frac{\partial V}{\partial H} + \frac{\partial C_i}{\partial E_{qi}^{'}} \frac{\partial V}{\partial C_i} \right)$$

4.2 Maximizing the Security

- **Case Study**
  - **Results**
    - **Security increases**



Content

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

Prof. Xiaoxin Zhou

IEEE Fellow

Academician of CAS

Indexed by

ESCI INSPEC

CSAD(Chinese Science Abstract Database)

About the Journal

Quarterly Journal

Jointly Published by

CSEE/IEEE/CEPRI

Open Access

Free To Download on

IEEE Digital Library

MORE INFORMATION CAN BE SCANNED !

The Institution of Engineering and Technology

Working to engineer a better world


Thank you !