Least costly probing signal design for power system mode estimation

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Outline

- Motivation
- Probing-based mode estimation
- Optimization problem formulation
- Results
- Conclusions
- Q&A

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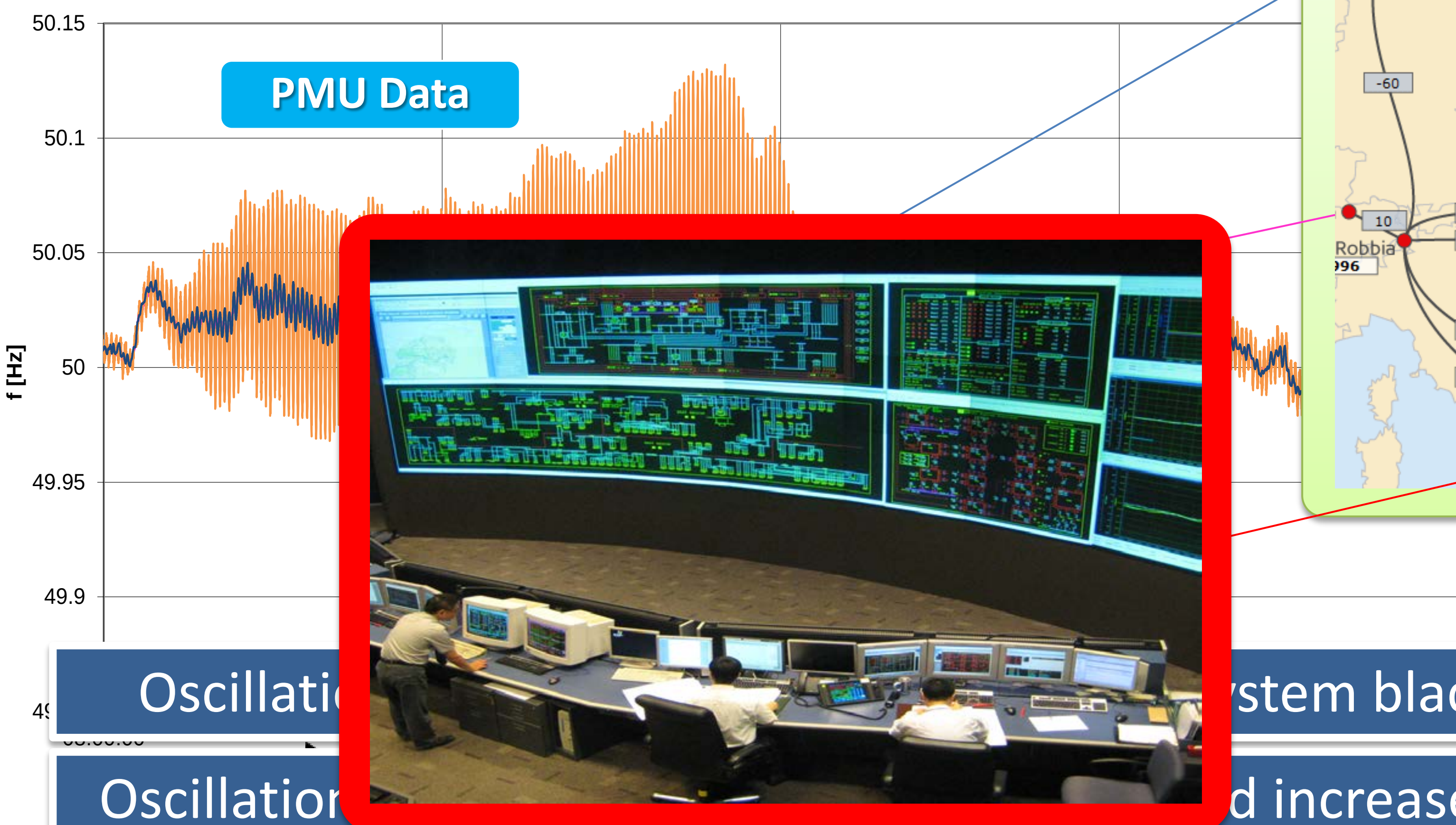
Oscillation monitoring

February 19th 2011 – North-South Inter-Area Oscillation

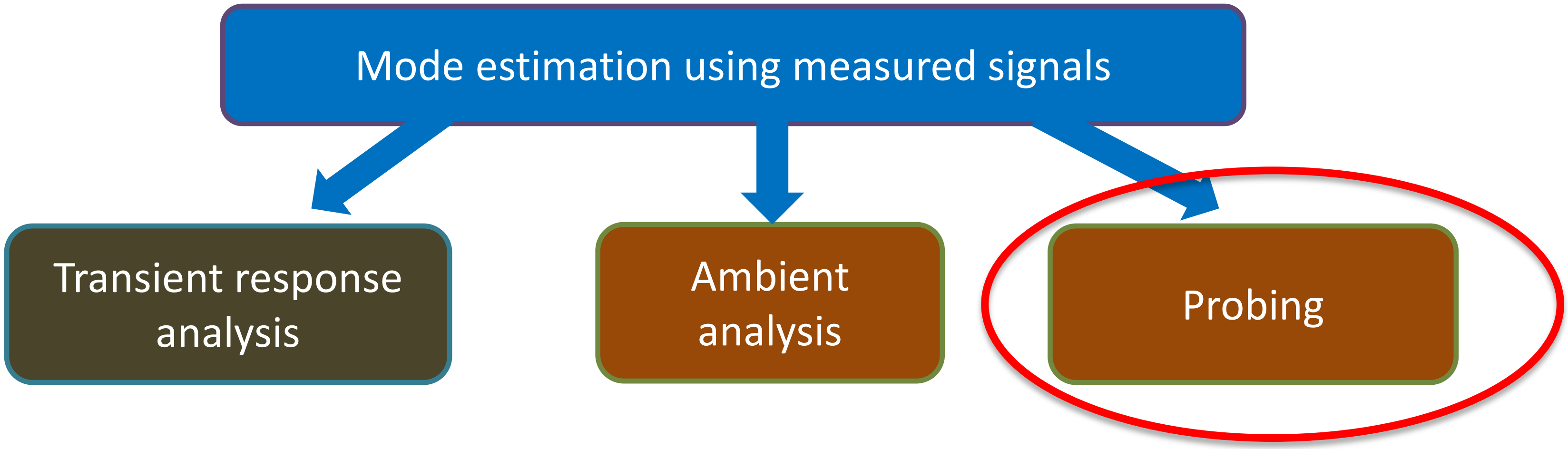


Oscillati… …ystem black-out

Oscillation… …d increase losses

Frequency and damping ratio monitoring

Algorithms for measurement based mode estimation



- Transient response:
  - Prony, ERA, Pencil Matrix
  - Well established
  - Good accuracy
  - Not suitable for real-time monitoring
- Ambient and probing :
  - SysID and signal processing algorithms
  - Suitable for real-time monitoring
  - Lower accuracy

Probing based mode estimation

Inputs

(load noise)

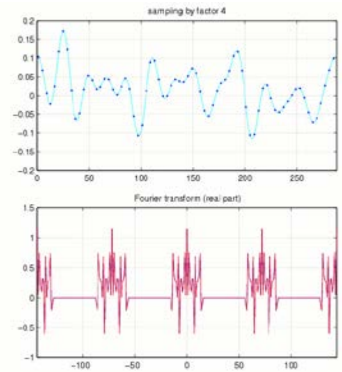
Power system

$dx/dt = Ax + Bu + Fz$

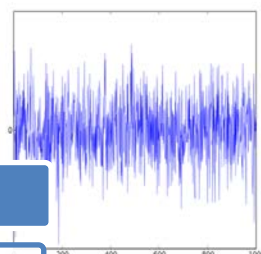
$y = Cx + Du + Gz$

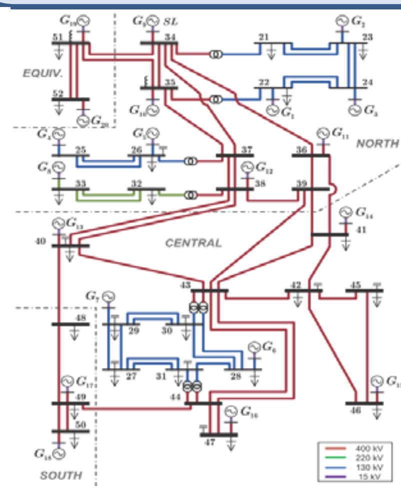
Outputs

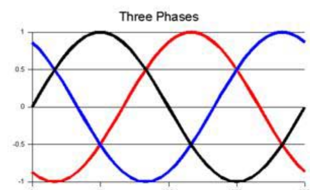
(PMUs)



Deterministic signal







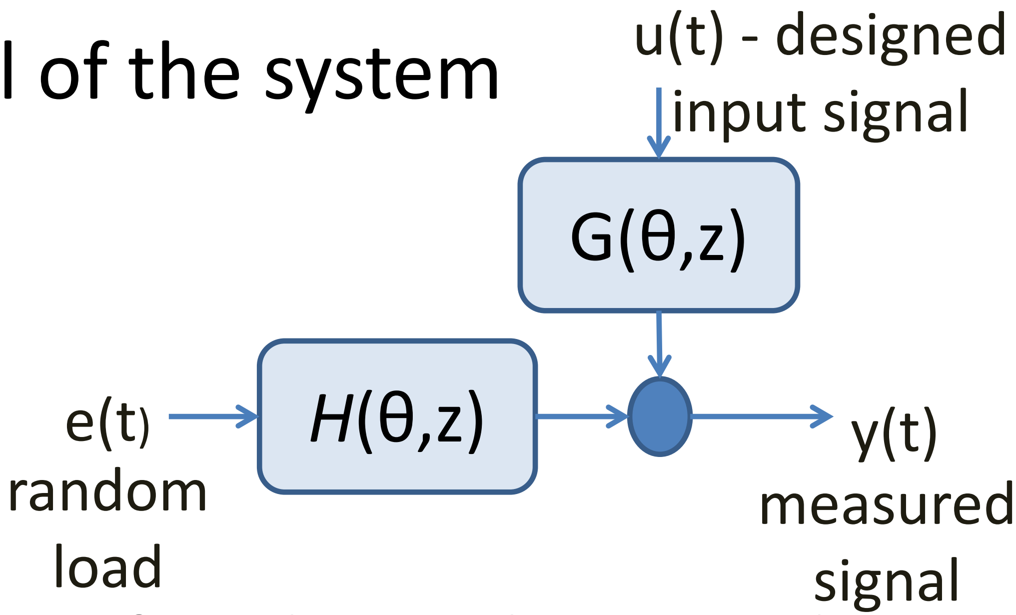
- Probing signals
  - FACTS devices
  - AVR
  - Turbine governors

Measured signals

Exactly known excitation brings new information that can be used for improved mode identification

Mathematical description of the probing-based mode estimation

- Model of the system



- In case of probing, the model is:

$$y(t) = \frac{B(z,\theta)}{A(z,\theta)} u(t) + \frac{C(z,\theta)}{D(z,\theta)} e(t)$$

✓ ARMAX

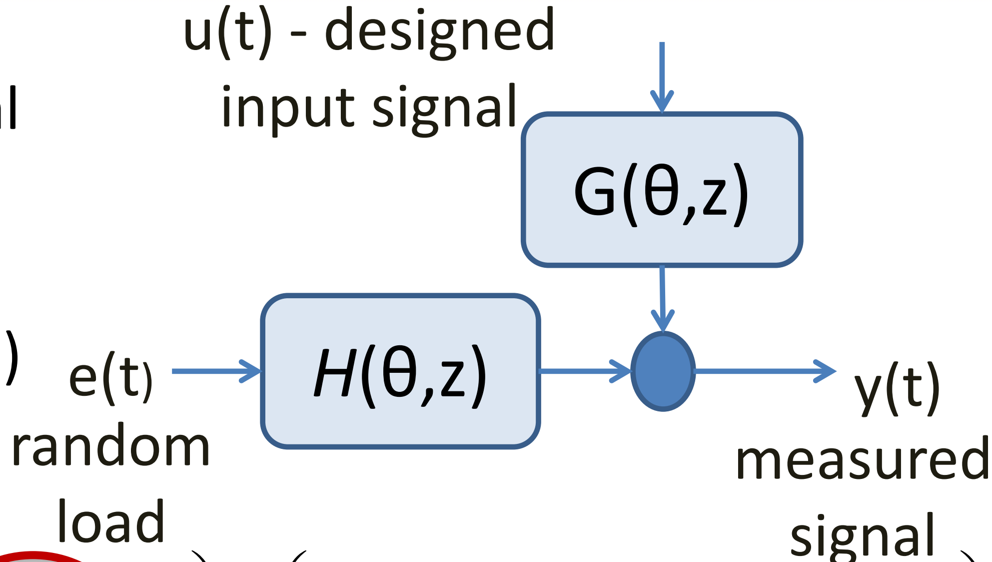
✓ Box Jenkins

- Mode estimation as an optimization problem

$$\min_{\theta} \frac{1}{N} \sum_{t=1}^{N} \varepsilon(t,\theta)^2 \qquad \varepsilon(t,\theta) = y(t) - \widehat{y}(t|t-1)$$

Parameter covariance matrix

- The goal is to identify the critical damping ratio of G(z)
- The critical damping ratio is parameter of G(z) (element of θ)



$$P_\theta^{-1} = \left(\frac{N}{\sigma^2} \frac{1}{2\pi} \int_{-\pi}^{\pi} F_u(\omega,\theta_0) F_u^*(\omega,\theta_0) \Phi_u(\omega) d\omega \right) + \left(\frac{N}{2\pi} \int_{-\pi}^{\pi} F_e(\omega,\theta_0) F_e^*(\omega,\theta_0) d\omega \right)$$

How should the probing signal look like ???

1) Length
2) Frequency spectrum
3) Time domain

Spectrum calculation

Requirements :

1) Control effort   2) System disturbance   3) Accuracy

Opt. criterion:

$$\min_{u(t)} J = \left(\frac{k_1}{2\pi} \int_{-\pi}^{\pi} \Phi_u(\omega) d\omega \right) + \left(\frac{k_2}{2\pi} \int_{-\pi}^{\pi} |G(s)|^2 \Phi_u(\omega) d\omega \right)$$

Input   *Output (frequency deviation)*

Constraint:

$$\mathrm{var}(\zeta_i) = e_i^T P_\theta e_i < r$$

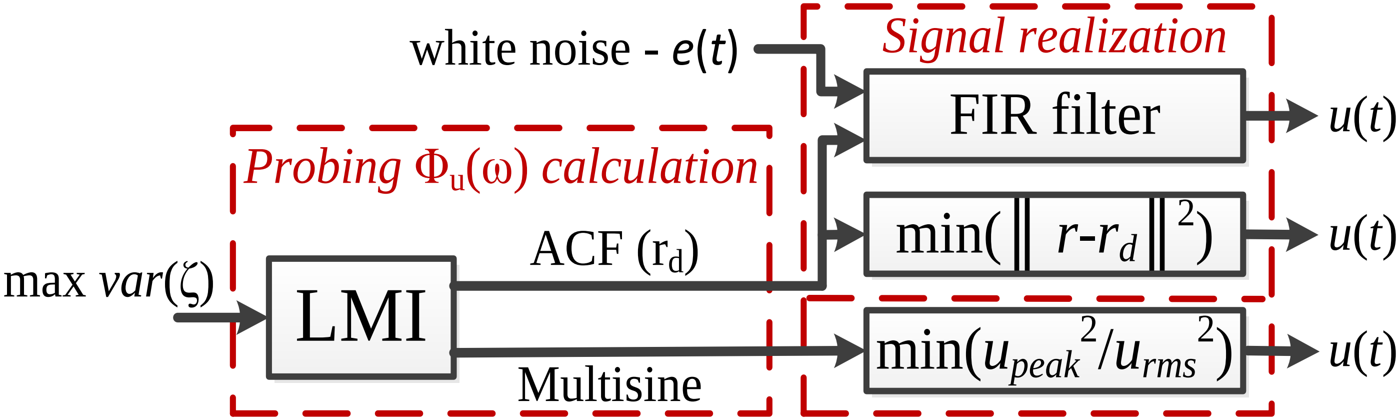
r - tolerance

Keeping in mind:

$$P_\theta^{-1} = \left(\frac{N}{\sigma^2} \frac{1}{2\pi} \int_{-\pi}^{\pi} F_u(\omega, \theta_0) F_u^*(\omega, \theta_0) \Phi_u(\omega) d\omega \right) + \left(\frac{N}{2\pi} \int_{-\pi}^{\pi} F_e(\omega, \theta_0) F_e^*(\omega, \theta_0) d\omega \right)$$

Global algorithm (two steps)

- Spectrum calculation (LMI optimization)
- Time domain signal realization
  - FIR filter
  - Sample autocorrelation optimization
  - Multi-sine input signal [1]



[1] J.W. Pierre, et al. “Probing signal design for power system identification”, *IEEE Trans. Power Syst.*, vol.25, no.2, pp.835-843, May 2010.

Signal realization with constrained magnitude

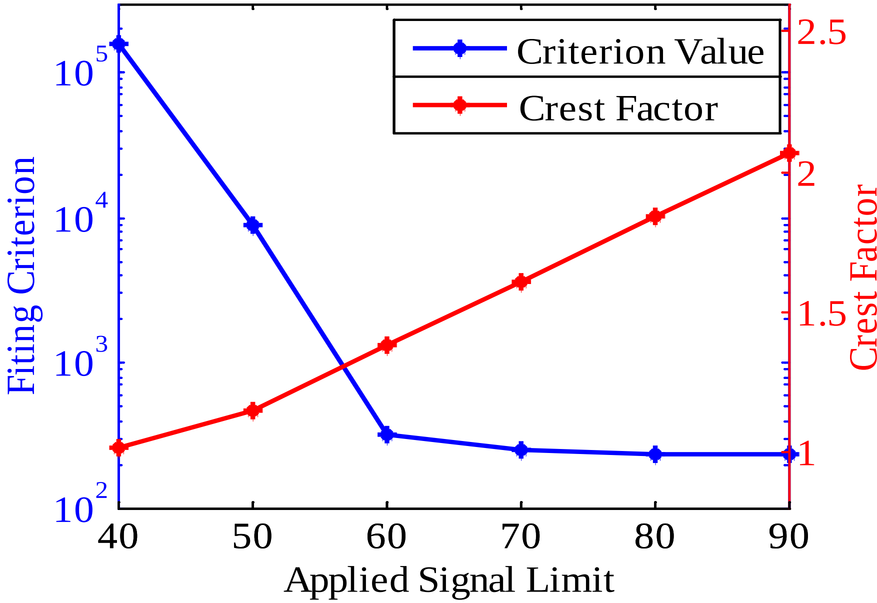
- Power spectrum $\Phi_u(\omega) = \sum_{r=-m}^{m} c_r e^{j\omega r}$
- Sample autocorrelation

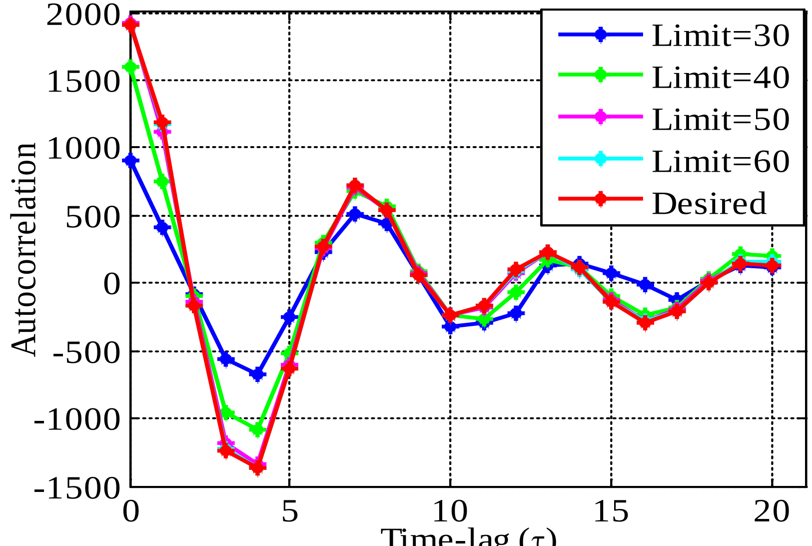
$$ACF_k(\tau) = \frac{1}{k} \sum_{i=\tau+1}^{k} u(i)u(i-\tau)$$

- Optimization

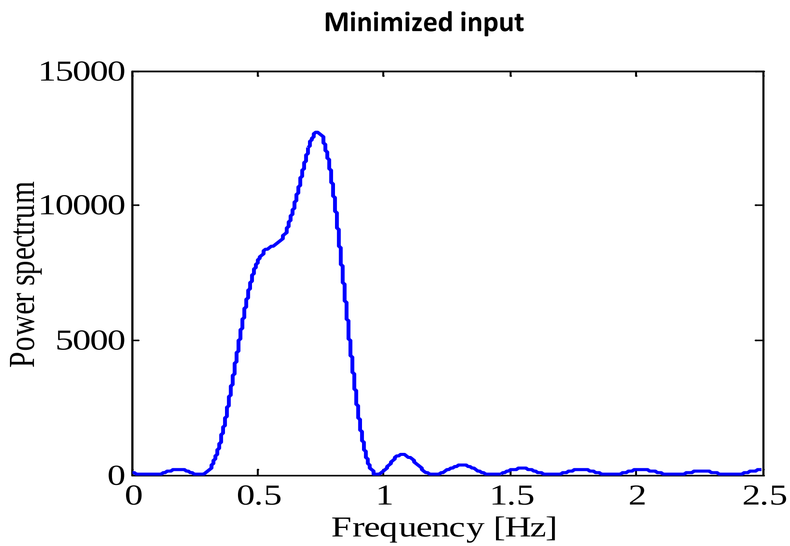
$$\min_{u(k)} \sum_{\tau=0}^{M+K} \left(ACF_k(\tau) - ACF_{des}(\tau) \right)^2$$

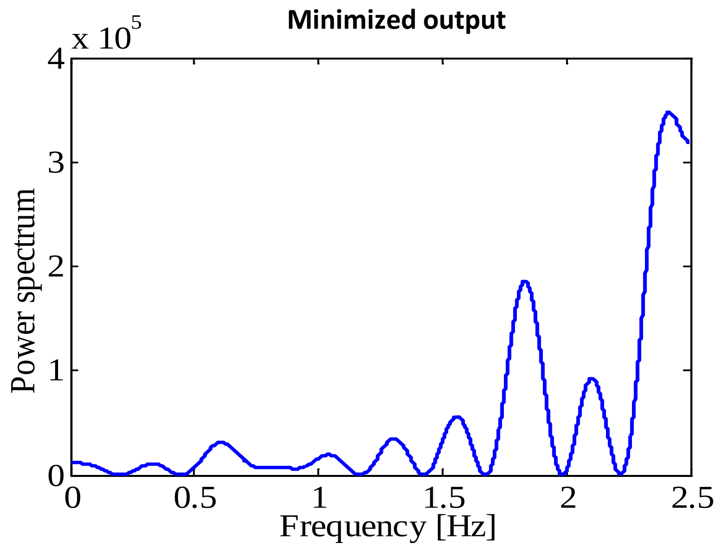
- Efficient recursive algorithm
  - Sample by sample
  - Every sample result of a simple optimization problem





Optimal probing signal design results





	Input spectrum parameterization		
	White noise	Multi-sine	FIR filter
var{u(t)}	10 410.00	1 441.58	1 933.55
var{y(t)}	1.67	1.59	1.55
var{uy(t)}	6 881.10	2 318.81	2 518.24

Optimal probing allows us to reduce probing power and/or system disturbance while maintaining desired accuracy

Conclusions

- Monitoring of electromechanical modes is important
- Staged probing tests can provide a good accuracy
- Shape of the probing signal affects estimation accuracy
- Several considerations can be taken into account during design process
- Optimal probing allows us to reduce probing power and/or system disturbance while maintaining accuracy
- The proposed method is easy to implement

Thank you!

Questions?

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