Koopman operator techniques applied to data analytics in transmission systems

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Outline of Presentation

Koopman operator techniques applied to data analytics in transmission systems

$$\boldsymbol{y}(t) = \sum_{j=1}^{\infty} \exp(\nu_j t)\boldsymbol{V}_j, \quad t \geq 0$$

- Motivation
- Synchrophasor measurement in Japan: A NEDO project
- Koopman mode decomposition
- Inertia estimation of Japan's power systems via ambient synchrophasor data
- Wrap-up

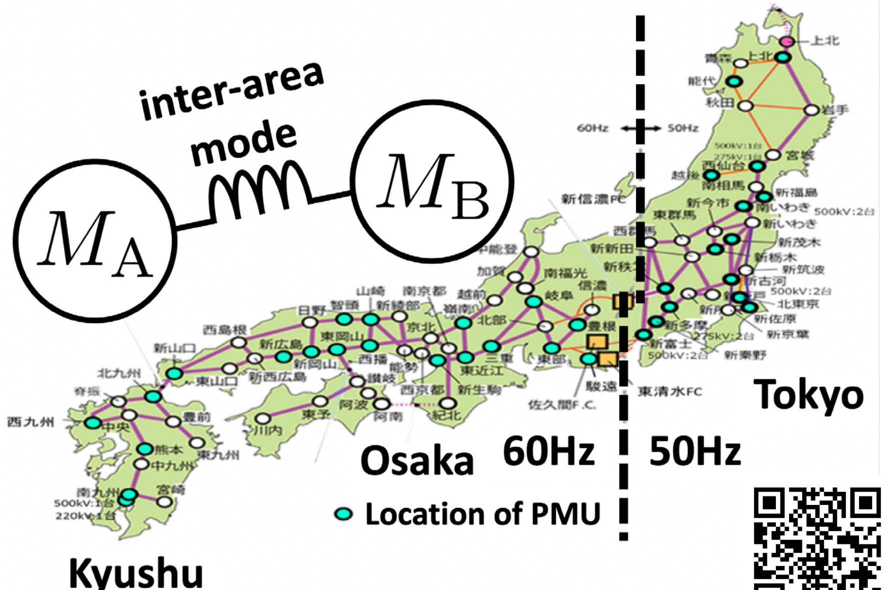
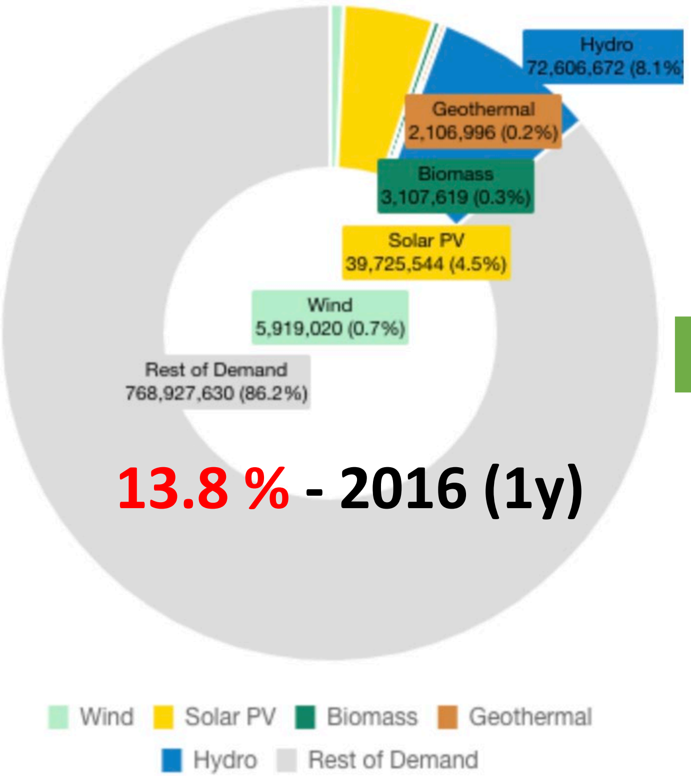


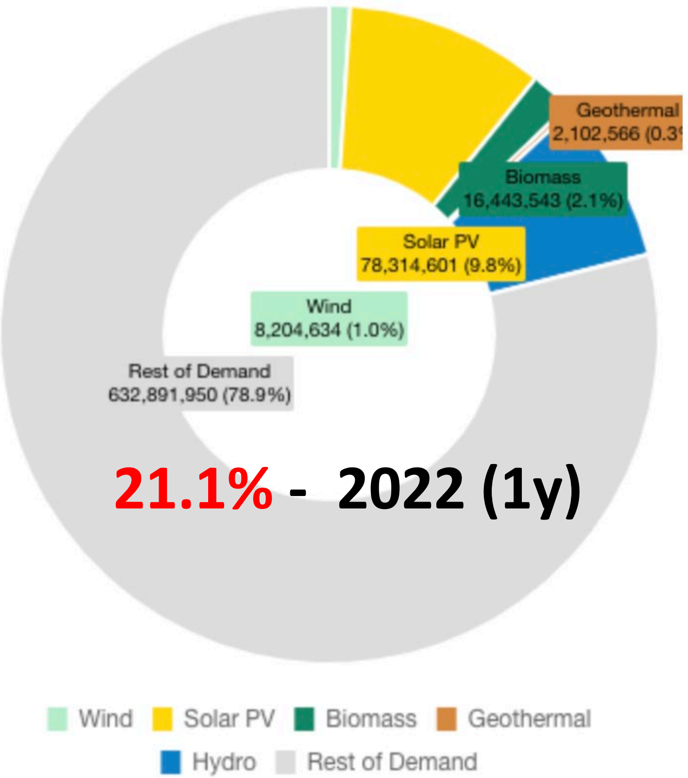
図 3-128　PMU 配置図

Motivation from Japan’s systems

Penetration of renewables



13.8 % - 2016 (1y)



21.1% - 2022 (1y)

- Expected to increase to 36-38 % in the 2030s
  - Solar PV: increase by 50 billion kWh
  - Offshore wind: increase by + 1 billion kWh
- Inevitable reduction of inertia provided by thermal plants

from https://isep-energychart.com/en/

NEDO project (2019-2021)

Synchrophasor measurement

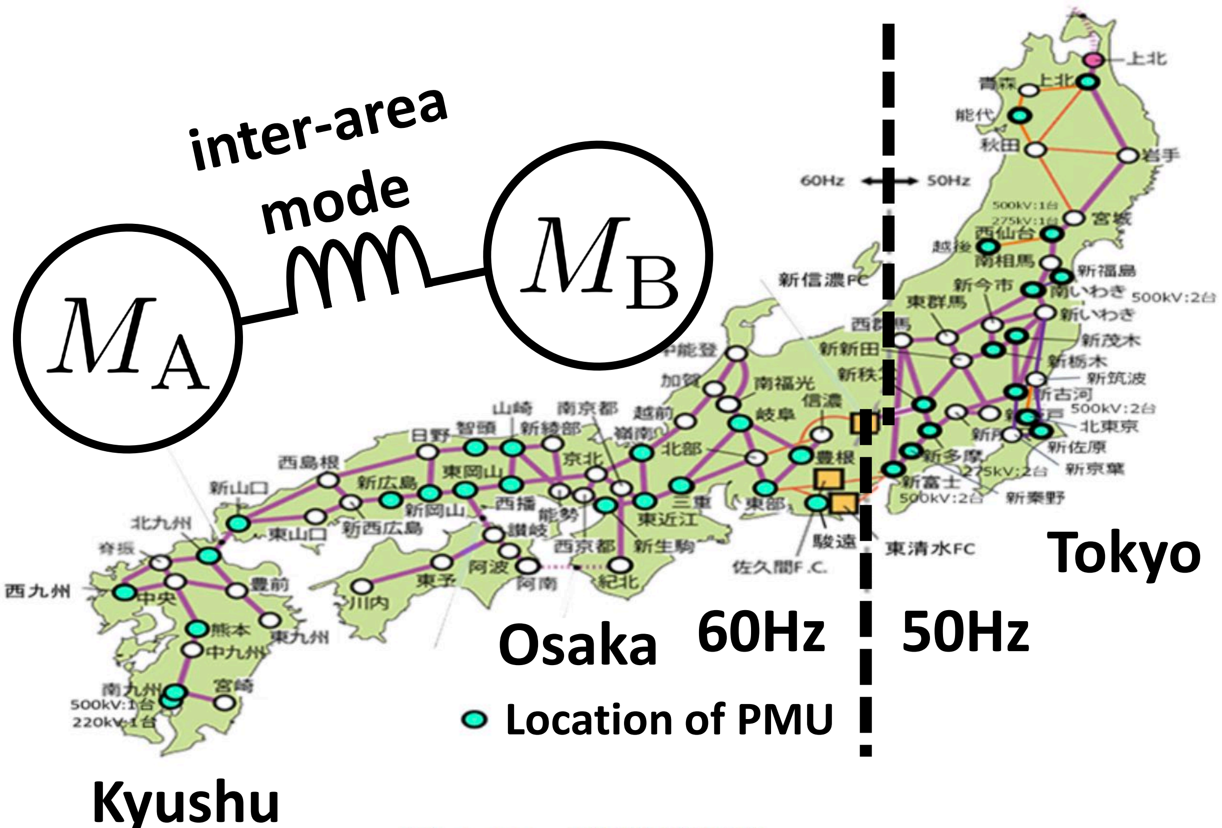


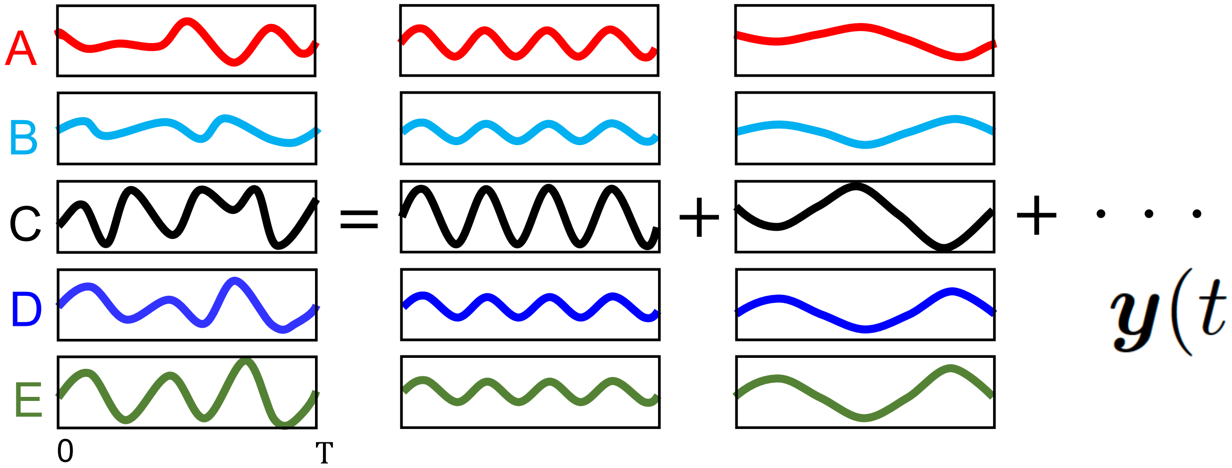
図 3-128　PMU 配置図

from the official report (in Japanese)

- Mainly led by Tokyo Electric Power Company Holdings, Inc., and Kyushu Institute of Technology
- Development of basic technology to address the problem of reduced system inertia
- Totally 40 PMUs installed at 500kV or 275kV substations

Koopman mode decomposition

(Refs.) Mezic (2005)
Rowley *et al*. (2009)

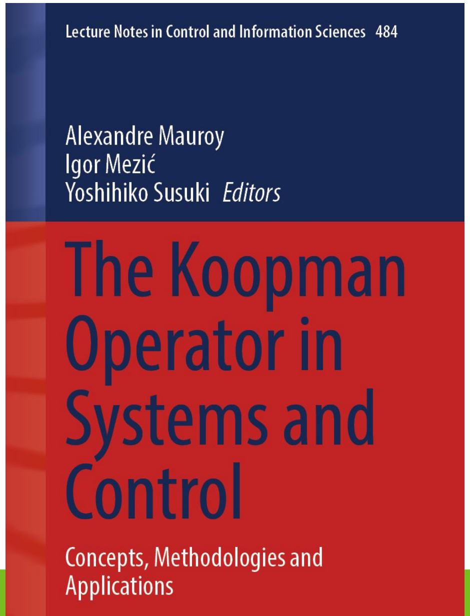


multivariate time series

oscillatory mode (single-frequency)

$$\boldsymbol{y}(t) = \sum_{j=1}^{\infty} \exp(\nu_j t) \boldsymbol{V}_j, \quad t \geq 0$$

- Guided by the Koopman operators for nonlinear systems
- Dynamic Mode Decomposition as a standard algorithm
- Utilized in power system performance assessment
  - Susuki & Mezic (2011); Barocio et al. (2015); and many

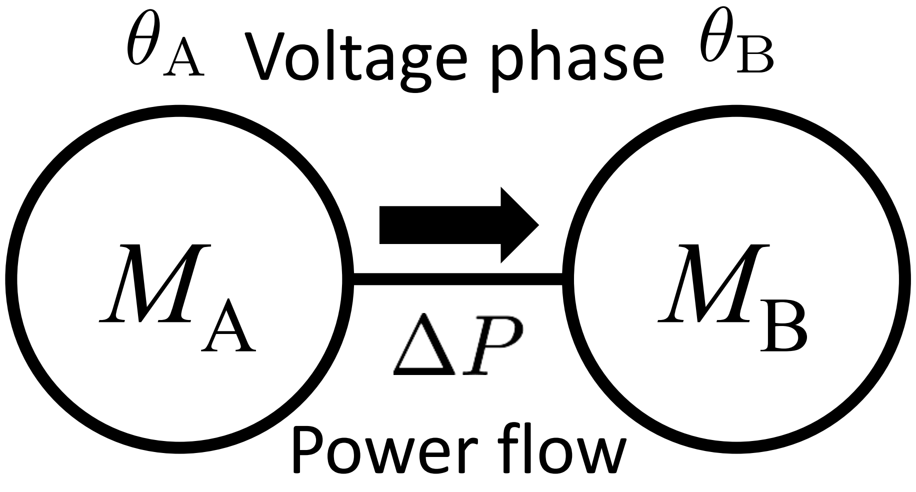


Inertia estimation 1/4

Underlying model

- Standard swing equations assumed
- Two time-series utilized for the estimation:

1. Frequency deviations (COI)
2. Exchanged power flow



Area A

Area B

$$M_{\mathrm{A}} \frac{\mathrm{d}^2}{\mathrm{d}t^2} \theta_{\mathrm{A}} = \Delta P$$

$$M_{\mathrm{B}} \frac{\mathrm{d}^2}{\mathrm{d}t^2} \theta_{\mathrm{B}} = -\Delta P$$

$$M_{\mathrm{A}} \frac{\mathrm{d}}{\mathrm{d}t} \omega_{\mathrm{A}} = \Delta P$$

$$M_{\mathrm{B}} \frac{\mathrm{d}}{\mathrm{d}t} \omega_{\mathrm{B}} = -\Delta P$$

Inertia estimation 2/4

Two steps

1. Compute Koopman modes and eigenvalues by applying a DMD to time-series data on frequency deviations and exchanged power flow

$$\begin{bmatrix} \Delta\omega_{\mathrm{A}}(t) \\ \Delta\omega_{\mathrm{B}}(t) \\ \Delta P(t) \end{bmatrix} = \sum_{j=1}^{\infty} \exp(\nu_j t) \begin{bmatrix} V_j^{\Delta\omega_{\mathrm{A}}} \\ V_j^{\Delta\omega_{\mathrm{B}}} \\ V_j^{\Delta P} \end{bmatrix}$$

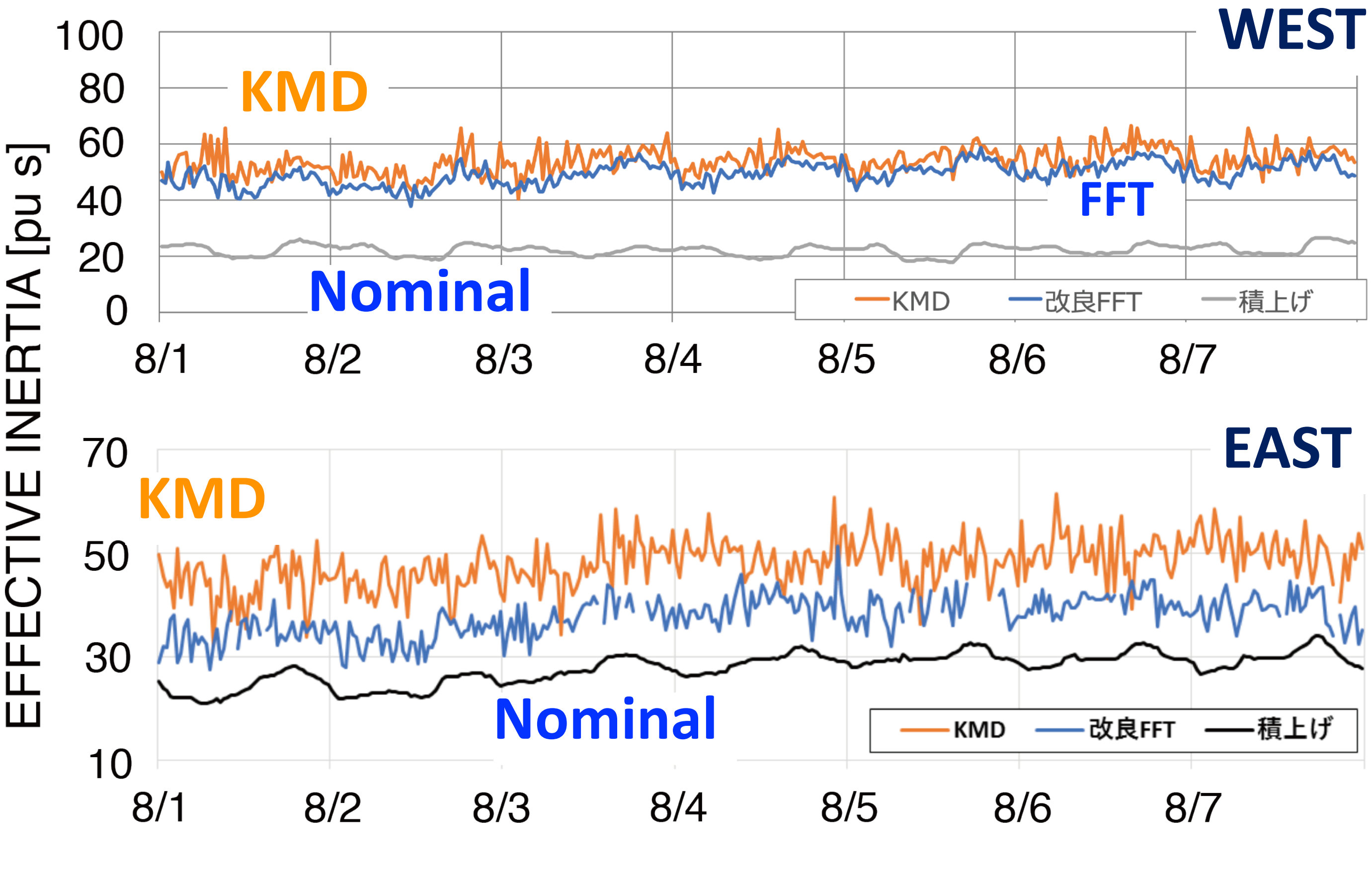
2. Estimate the inertia constants from:

$$M_{\mathrm{A}}^j := \frac{\left|V_j^{\Delta P}\right|}{\left|\nu_j V_j^{\Delta\omega_{\mathrm{A}}}\right|}, \quad M_{\mathrm{B}}^j := \frac{\left|V_j^{\Delta P}\right|}{\left|\nu_j V_j^{\Delta\omega_{\mathrm{B}}}\right|}$$

- Note: it depends on the choice of modes, here, the inter-area mode.

Inertia estimation 3/4

Result and comparison

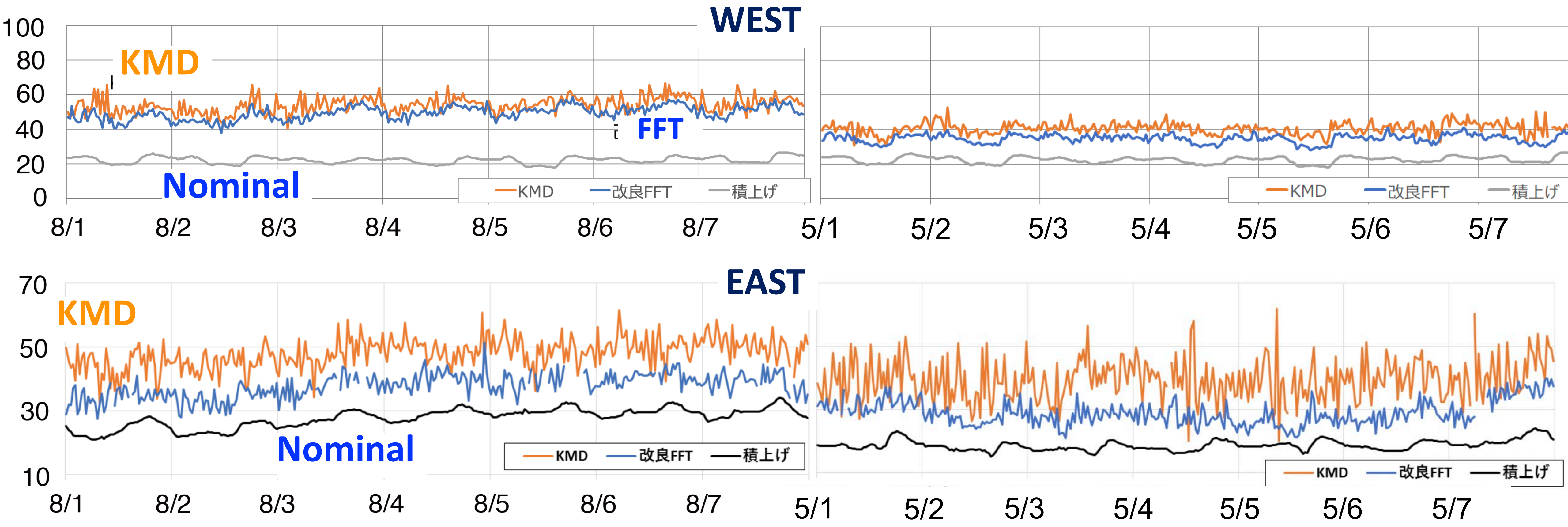


from the official report (in Japanese)

- FFT as another method of the estimation
- Nominal as the sum of inertia constants of online / offline generators
- Similarity in the estimation
- Difference caused by non-visible generators in consumer sides and control effects etc.

Inertia estimation 4/4

Dependence on loading conditions

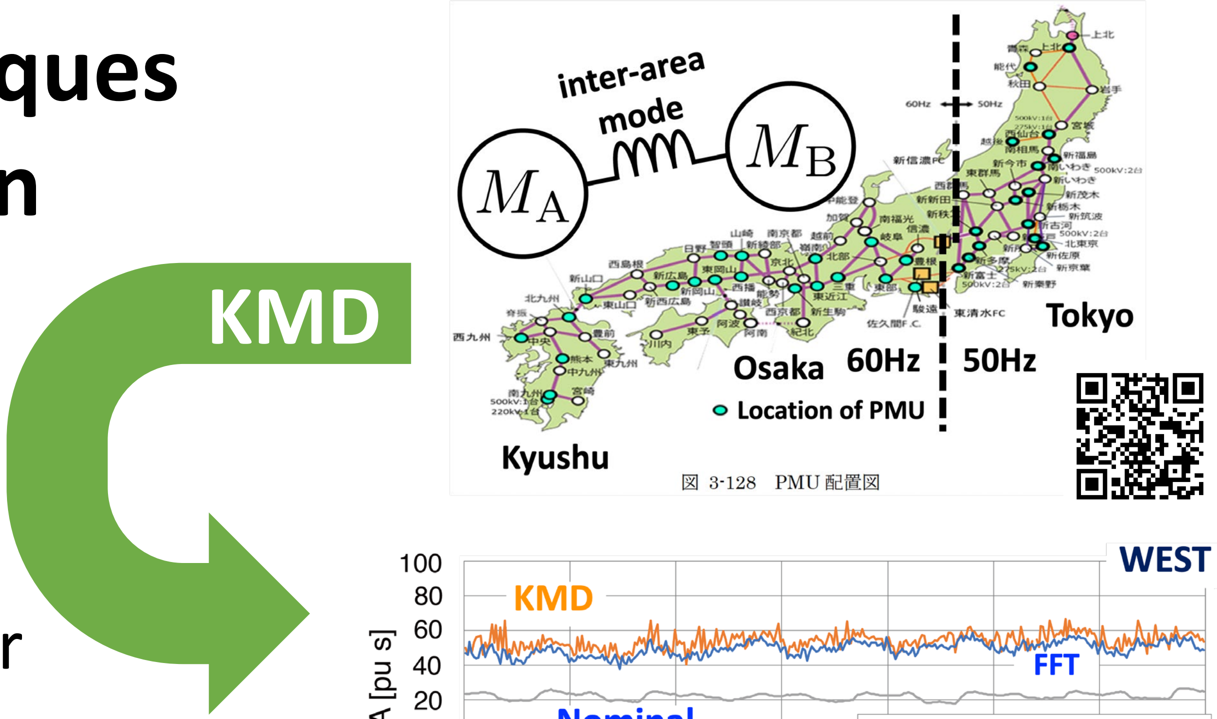


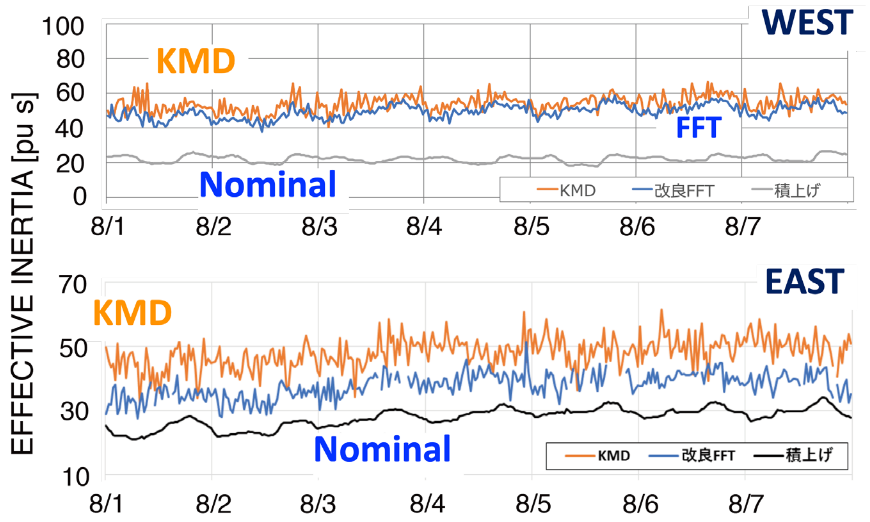
from the official report (in Japanese)

Summary - takeaways

Koopman operator techniques applied to data analytics in transmission systems

- KMD provides a fully-data-driven technique of inertia estimation from synchrophasor data and power-flow data.
- Non-visible generators and control effects have a non-negligible impact.





Thank you for your attention!

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