A unified energy-domain theory of rotor-angle stabilities

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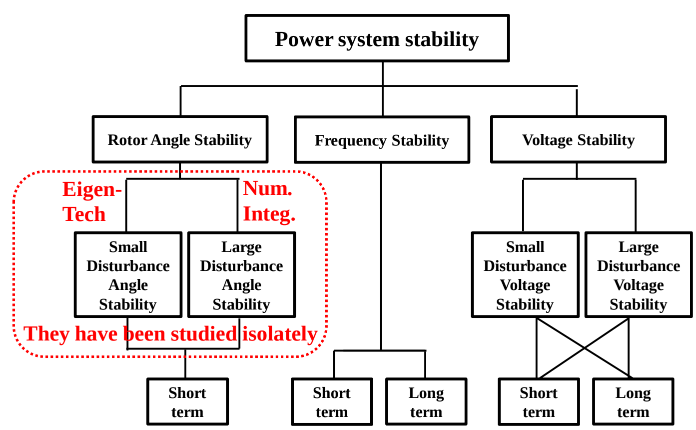
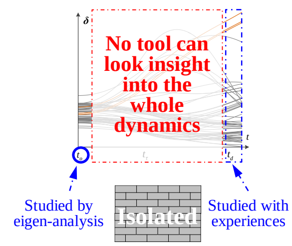
The classification of power system stability

IEEE/CIGRE, 2004



A unified method is preferred

- Besides of the drawbacks of either original eigen-tech or numerical integration, the two techs are isolated
- Factitiously breaking holistic view
- Difficult to understand mechanisms
- Difficult to link oscillation with asynchronism



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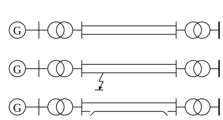
Equal-area criterion (EAC) *
for classical OMIB systems solely

- A simple analytical method for power system transient stability
- **TSA index is areas in $P(\delta)$ plane, i.e. the energy, not the angle**



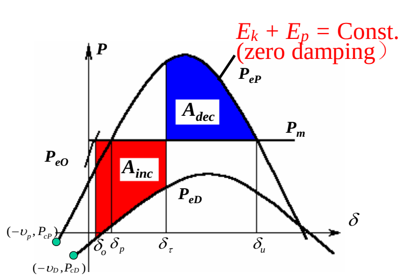
$$M\ddot{\delta} = P_m - P_{\max} \sin \delta$$

$$\eta = A_{dec} - A_{inc} = \frac{M\omega^2}{2}$$

$$= -\int_{\delta_0}^{\delta_{UEP}} (P_m - P_{max} \sin\delta) d\delta$$

$$A_{inc} = (P_m - P_{c.D})(\delta_\tau - \delta_0) + P_{\max D}[\cos(\delta_\tau - \upsilon_D) - \cos(\delta_0 - \upsilon_D)]$$

$$A_{dec} = (P_{cP} - P_m)(\pi - \delta_\tau - \delta_p + 2\upsilon_P) + P_{\max P}[\cos(\delta_\tau - \upsilon_P) + \cos(\delta_P - \upsilon_P)]$$

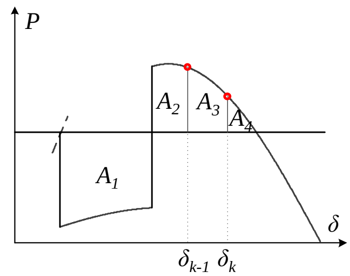


A guess of mine

Transient stability analyses and oscillation stability analyses can be unified in the energy domain

* K.Y. Kimbark, *Power System Stability . Vol.1 : Elements of Stability Calculation.* John Wiley & Sons, 1948

Energy change ratio for a classical OMIB system



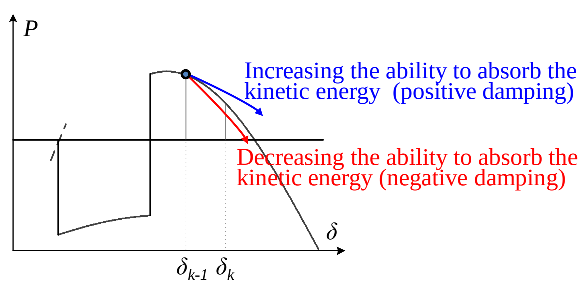
$$\eta_{\delta_{k-1}} = E_{p.\delta_{k-1}} - E_{k.\delta_{k-1}} = (A_3 + A_4) - (A_1 - A_2)$$

different different The same

$$\eta_{\delta_k} = E_{p.\delta_k} - E_{k.\delta_k} = A_4 - (A_1 - A_2 - A_3)$$

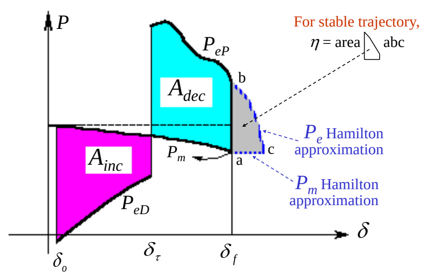
$$D_{\delta_k} = \frac{\eta_{\delta_k} - \eta_{\delta_{k-1}}}{\omega_{\delta_k}\left(\delta_k - \delta_{k-1}\right)} = 0 \qquad \text{For any } k$$

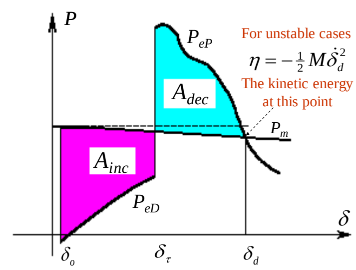
Energy change ratio for an OMIB system with damping



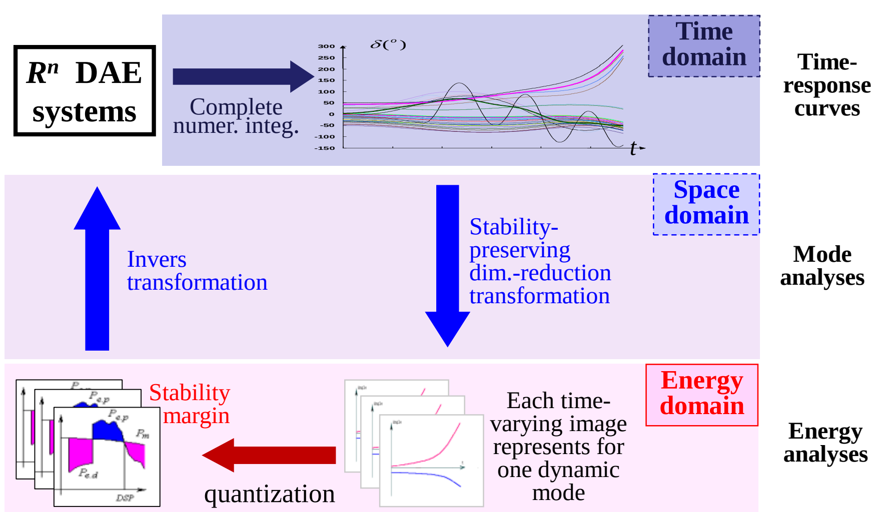
Extending to any time-varying OMIB system

$$M\ddot{\delta} = P_m(t) - P_{max}(t)\sin\delta$$
$$\eta = -\int_{\delta_0}^{\delta} (P_m(t) - P_{max}(t)\sin\delta)\, d\delta$$

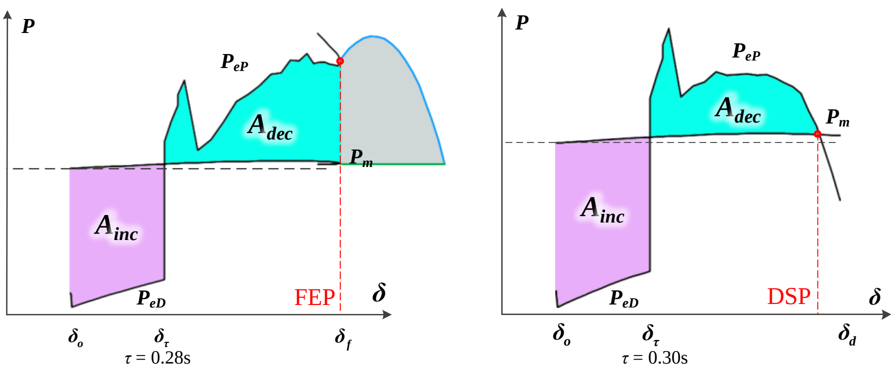




Extending the EAC to a multi-dimension system



A complex case in Xinjiang Grid



- The macro quantized knowledge for both stable and unstable swings are known
- However, the micro dynamics at every time-section are still unclear, e.g. how to describe the time-varying damping features

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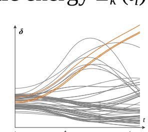
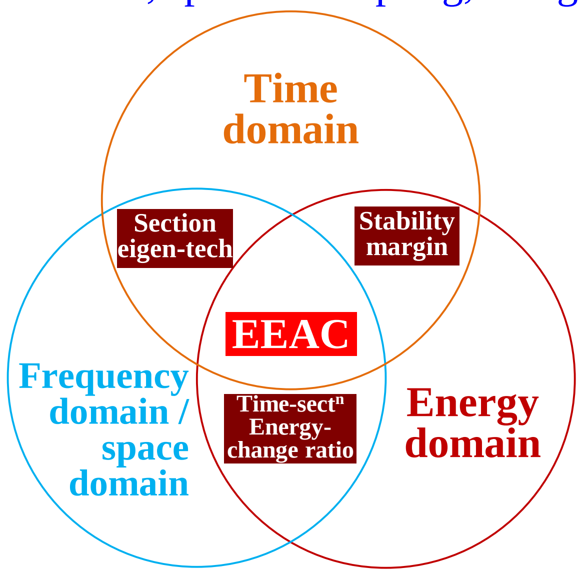
Stability margin of a swing VS stability margin of a time-section

- **Either FEP or DSP will be encountered on every swing of the image trajectory:**
  - FEP is characterized by zero kinetic energy, which marks the end of the swing. The residual capacity of it to absorb kinetic energy is defined as the stability margin, i.e. the area between FEP and VDSP, which is the residual potential energy $\eta = E_{r.p}(\delta_{FEP})$
  - DSP on the image trajectory is a point with zero potential energy, indicating the swing unstable. The kinetic energy at DSP is defined as negative margin, e.g. $\eta = - E_k(\delta_{DSP})$
- **How to define the stability margin at other time sections besides of FEP/DSP ?**
  - Suppose that (δ_i, ω_i) is the state point on an image trajectory at time t_i
  - If all non-Hamiltonian factors are frozen after time t_i, the physical meaning of the area between the time-section and VDSP is that the maximum additional kinetic energy $E_k(t_i)$ that can be absorbed without loosing the stability
  - The kinetic energy of the image at t_i, $E_k(\delta_i(t_i)) = E_k(\delta_i)$
  - General formula for stability margin at t_i : $\eta(t_i) = E_{r.p}(\delta_i) - E_k(\delta_i)$
  - The residual capacity at any moment to absorb more E_k can be assessed

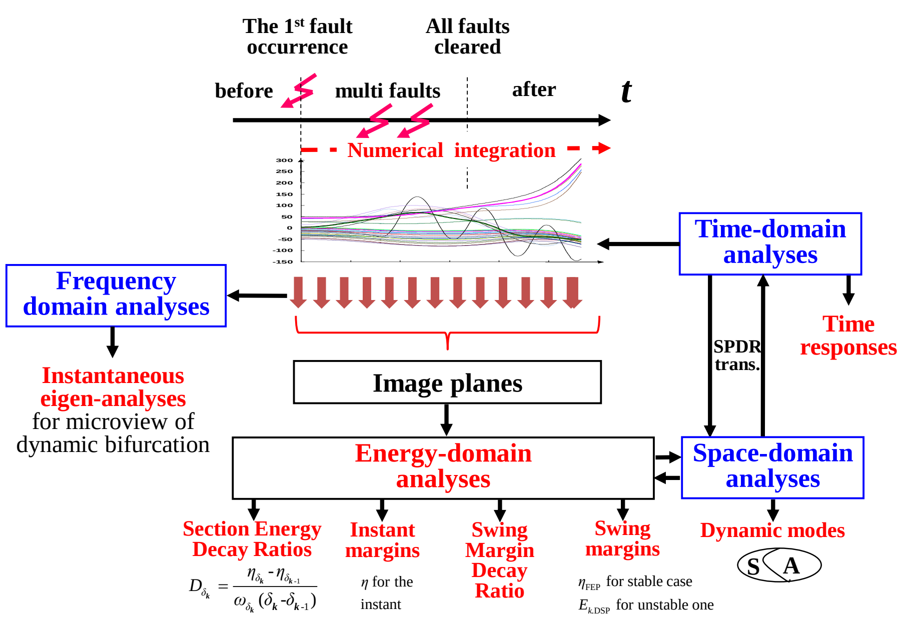


- **The stability margin at FEP or DSP is just that at the special time-section**
  - FEP and DSP are special time sections on the disturbed trajectory
  - At a special section $(\delta_{FEP}, 0)$, the η of a stable swing is: $\eta = E_{r.p}(\delta_{FEP}) - 0 = E_{r.p}(\delta_{FEP})$
  - At a special section (δ_{DSP}, ω_i), the η of an unstable swing is: $\eta = 0 - E_k(\delta_{DSP}) = - E_k(\delta_{DSP})$

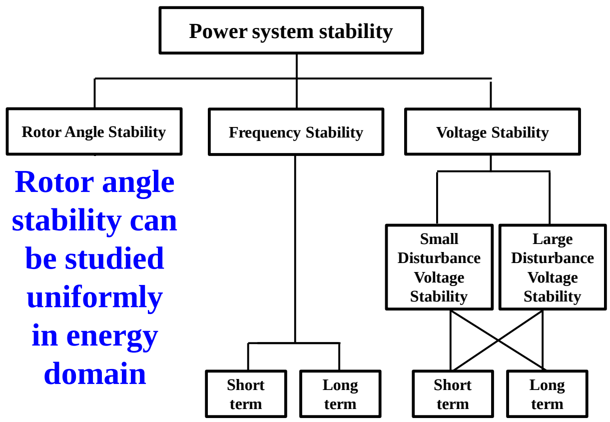
Basis of the unified stability theory: Trajectories based, space decoupling, energy indexed



Unified analyses for rotor angle stabilities



The mechanism of oscillations is dissipation/injection of energy between complementary clusters, rather than changes in amplitude



Rotor angle stability can be studied uniformly in energy domain

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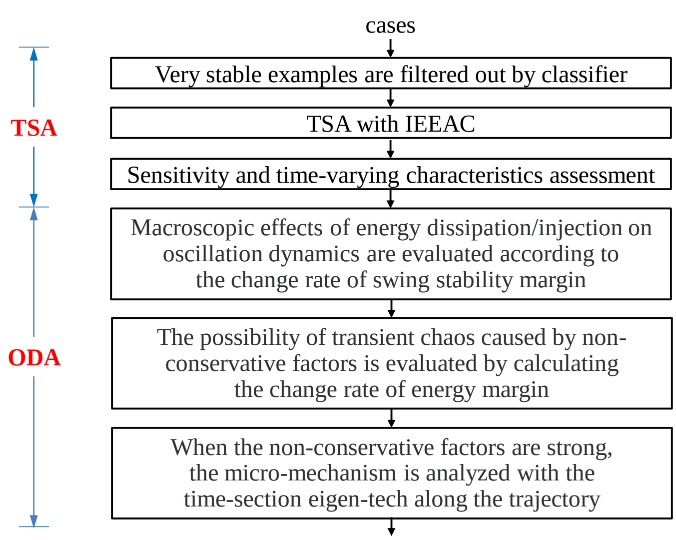
Unified analysis process for both TSA and ODA

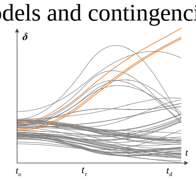


The new methodology for studying time-varying nonlinear motions

- Deep knowledge can be provided
  - Stability margins for not only each swing, but also any time-instant
  - Dynamics for interacted multi-modes
  - Instant damping factors
  - Mechanisms at bifurcation points
  - Including non-integer multiple frequencies
  - Concept of electrical-Mechanical damping

- Applications
  - Multi-time-varying-frequency oscillations
  - Including non-integer multiple frequencies
  - Decision making support for nonlinear control
  - e.g. the impact of large scale of REG on grids

The whole trajectories containing all info on models and contingencies



The proposed framework gives a global insight to TSA & TSC