Virtual Inertia Scheduling (VIS) for IBR-penetrated Power Systems

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IBR: Inverter-based resources

About me

- 2020-2023 Ph.D. Electrical Engineering
  - University of Tennessee Knoxville
- 2022-2022 Research Internship
  - Argonne National Laboratory
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  - Pacific Northwest National Laboratory
- 2026-Now Assistant Professor
  - Kansas State University

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Argonne NATIONAL LABORATORY

Pacific Northwest NATIONAL LABORATORY

Research Group and Mission

- **I**ntelligent **P**ower (IP) **Lab** in KSU with the mission of advancing power systems through inverter-based resources (IBRs) and artificial intelligence (AI) to enable secure, resilient, and economical power supply.

This could be you !

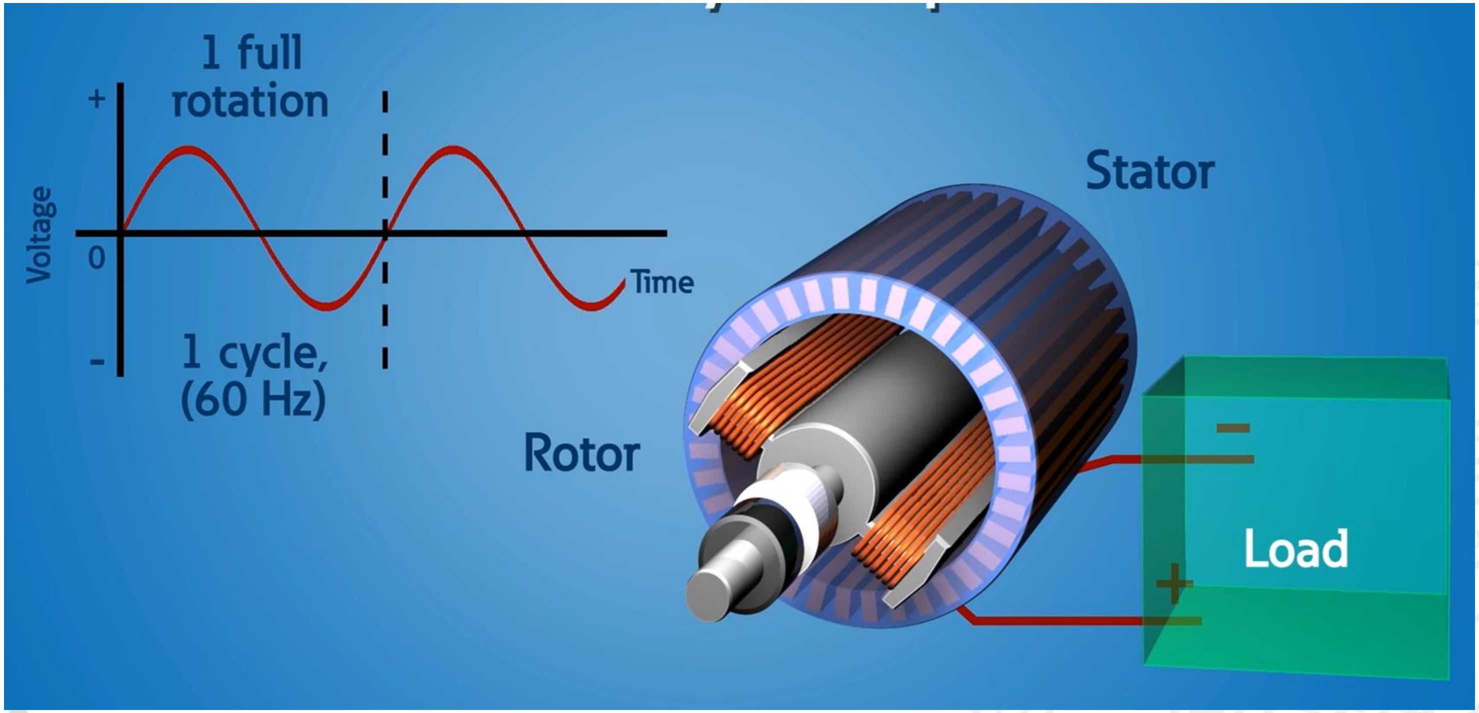
Research Area

- Modeling, control, and stability of Inverter-based Resources (IBRs)
- Dynamics-informed planning and operation of power systems
- AI-driven power system simulation, control and optimization

Power System Background

AC Power Generation

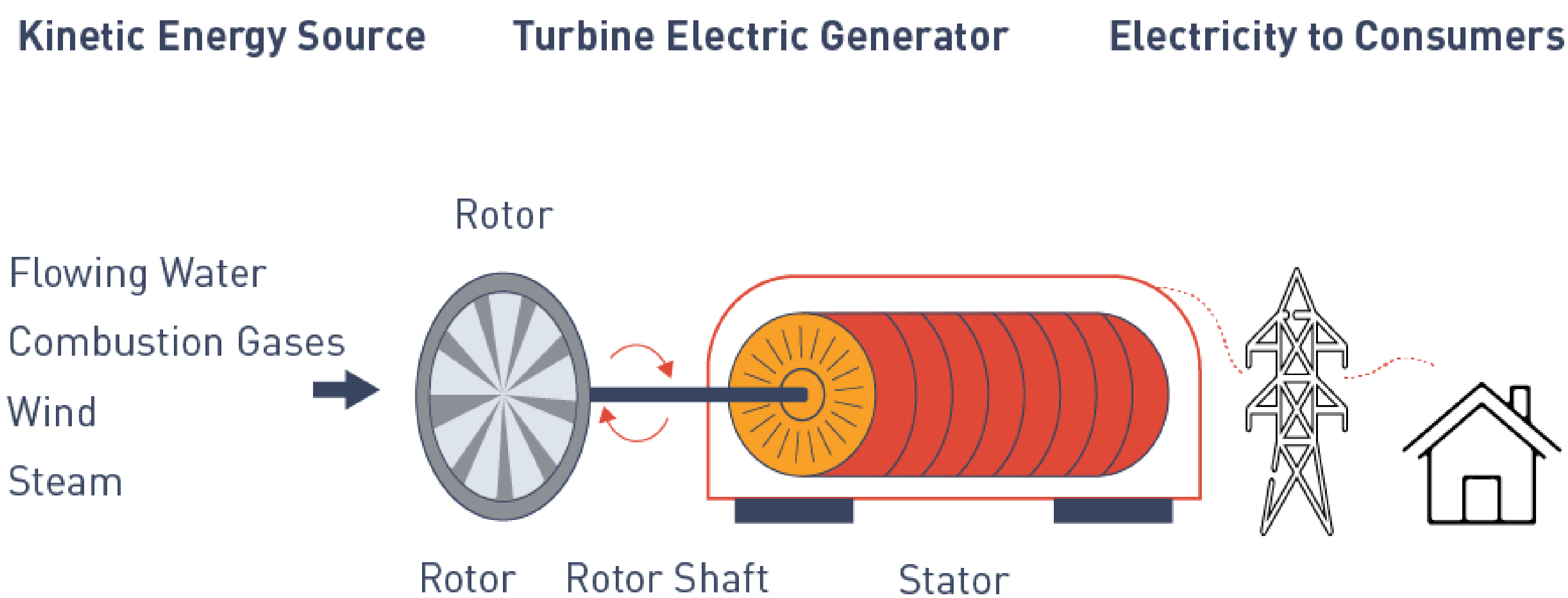
- Alternating current (AC) power generation



Source: EATON Tutorial: https://videos.eaton.com/experience/detail/videos/electric-utilities/video/6171633894001/power-generation?autoStart=true

AC Power Generation

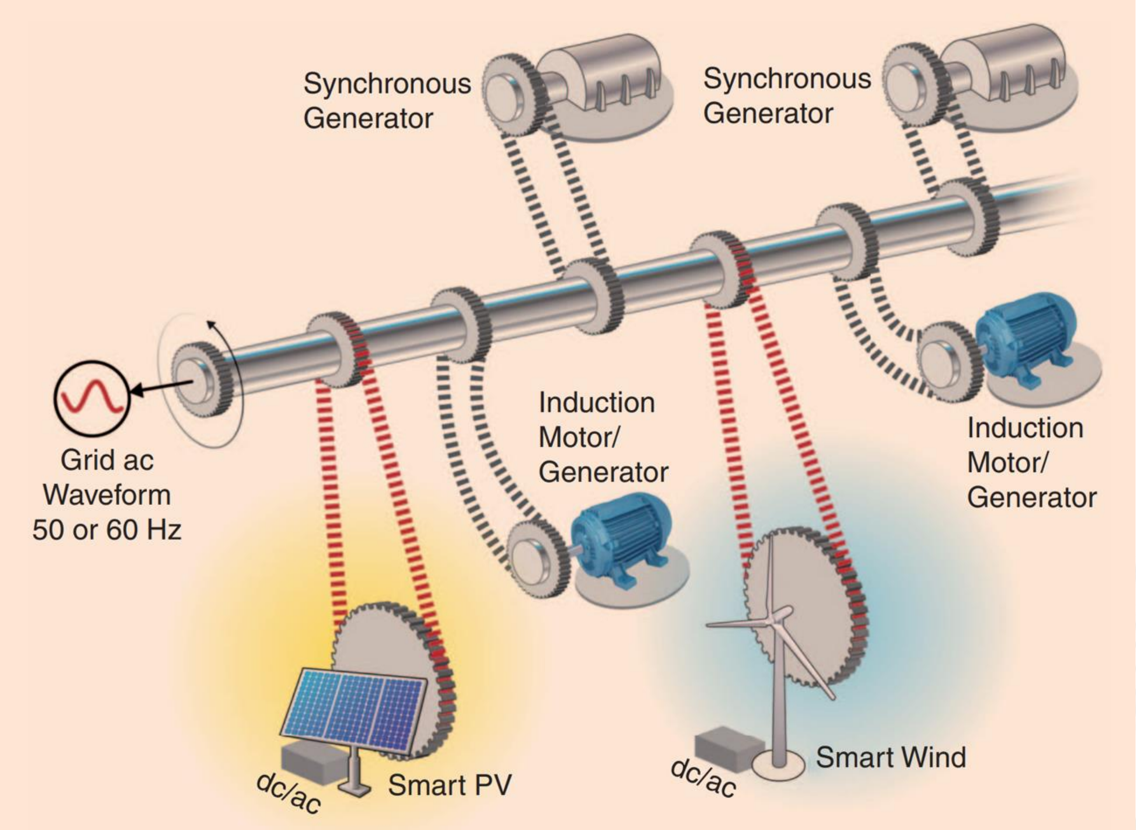
- Alternating current (AC) power generation



Source: EATON Tutorial: https://videos.eaton.com/experience/detail/videos/electric-utilities/video/6171633894001/power-generation?autoStart=true

Power System Synchronization

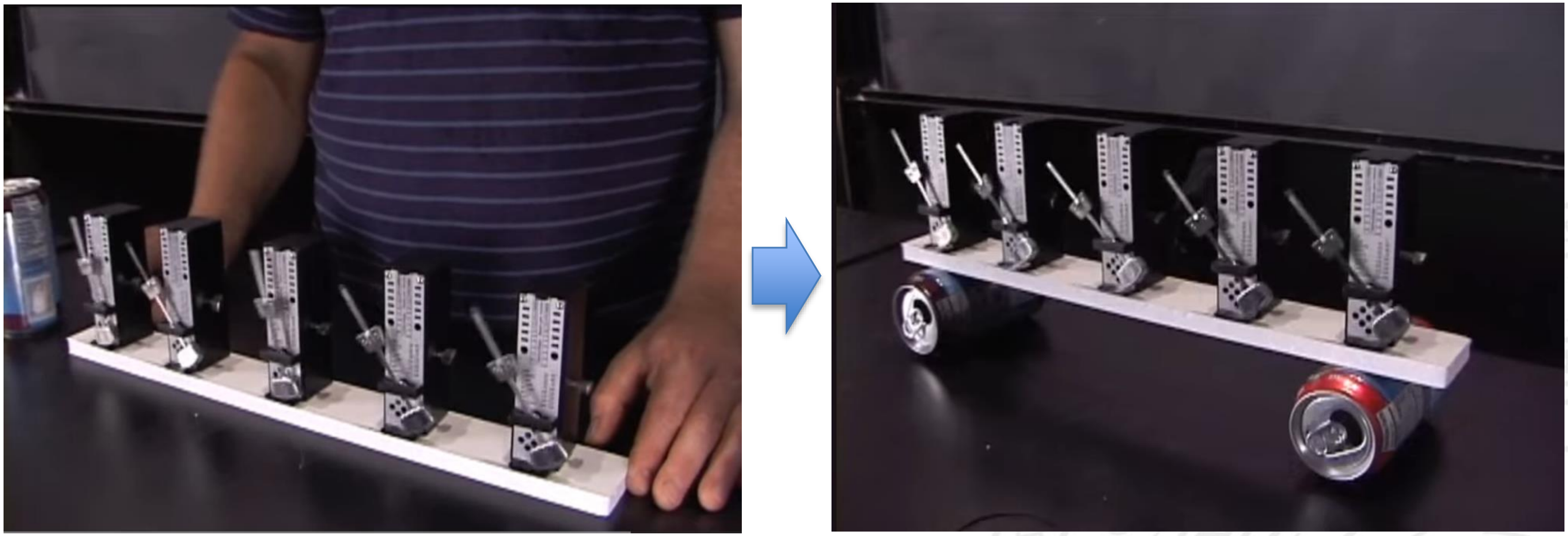
- All generators are expected to be **synchronized** at 60 Hz.



Source: B. Kroposki et al., "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," IEEE power & energy magazine.

Synchronization

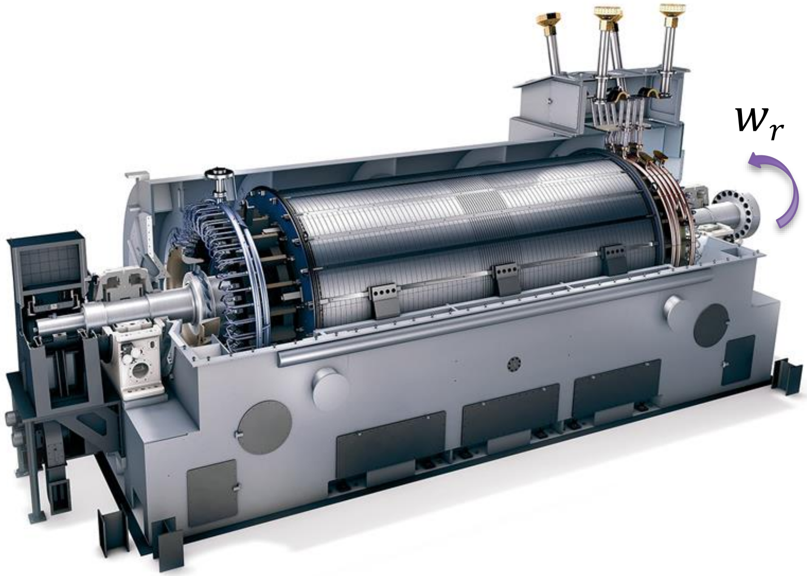
- Self-synchronization with different nature frequencies



https://www.youtube.com/watch?v=Aaxw4zbULMs

Source: Harvard Natural Sciences Lecture Demonstrations

Inertia of Synchronous Generator



$$E = \frac{1}{2} J {w_r}^2$$

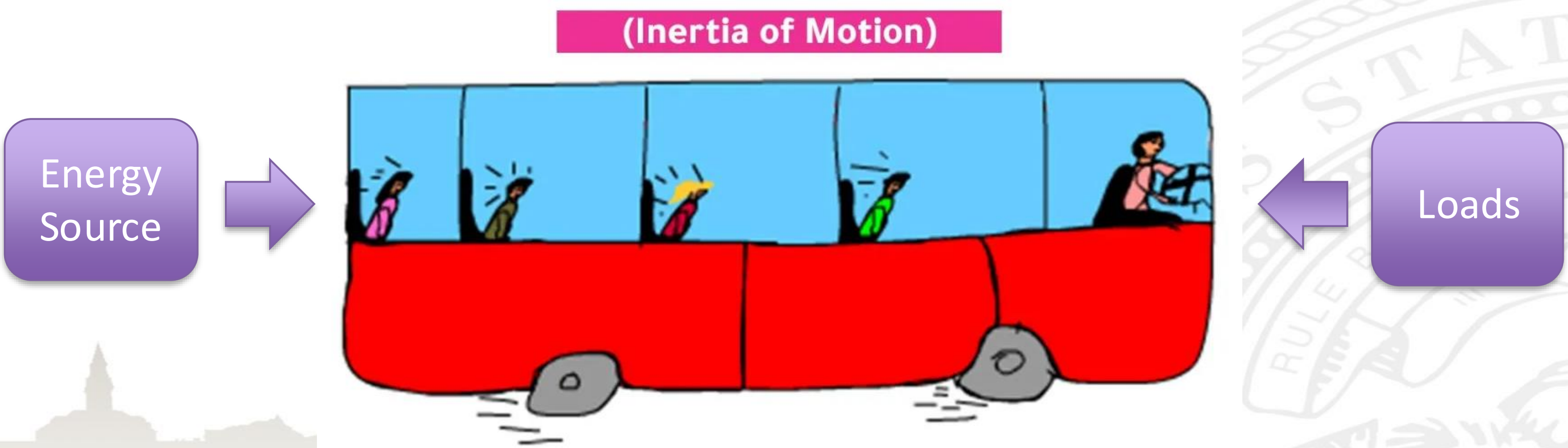
J: Moment of inertia of the rotor (Physical property)
E: Stored kinetic energy in rotor

Physical intuition

- Large, heavy rotors → large *J* → slower speed change
- Slim, compact rotors → small *J* → faster speed change

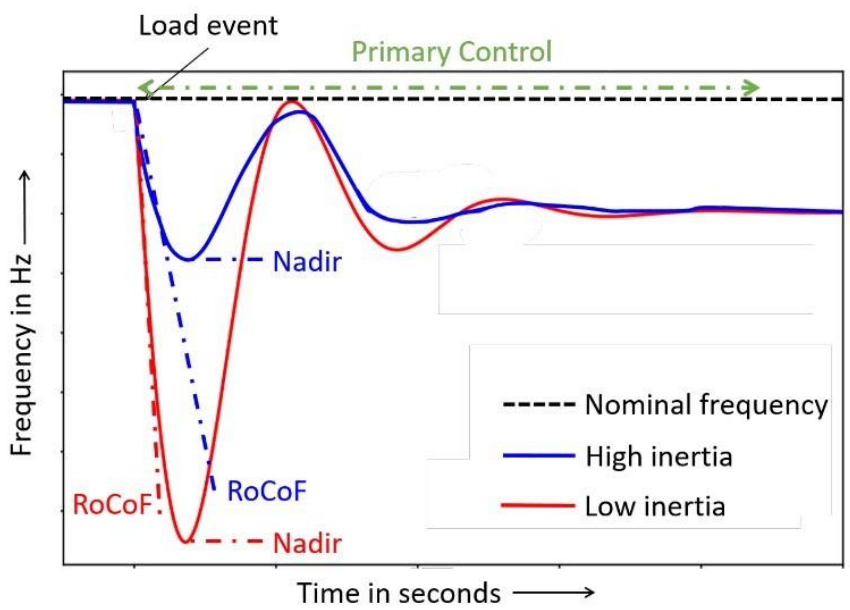
Importance of Inertia

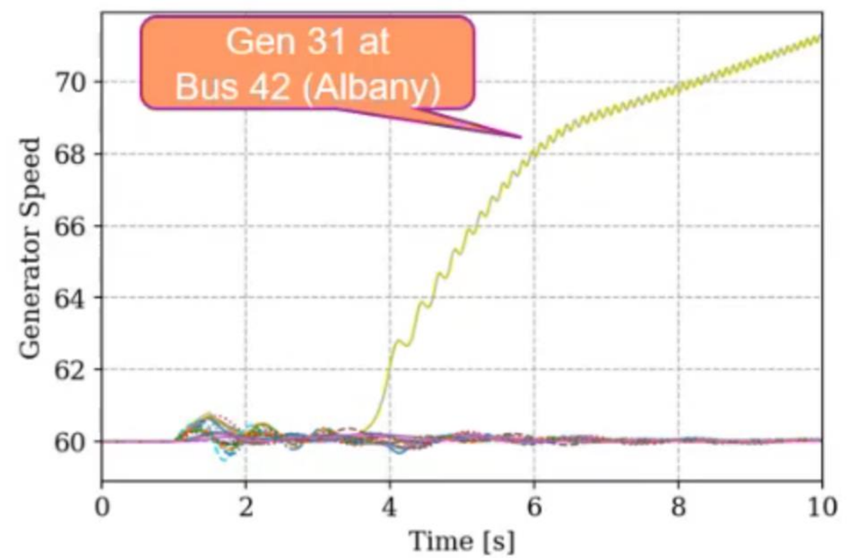
- The net effect of power system inertia provided by synchronous generators is to **reduce the severity of sudden frequency change** and **increase stability** during active power imbalances.



Importance of Inertia

- Low inertia can result in
  - High RoCof
  - Low nadir
  - High risk of loss of synchronization





RoCof: Rate of Change of Frequency

Reducing Physical Inertia

- Inverters have no physical and are decreasing the inertia of power systems.

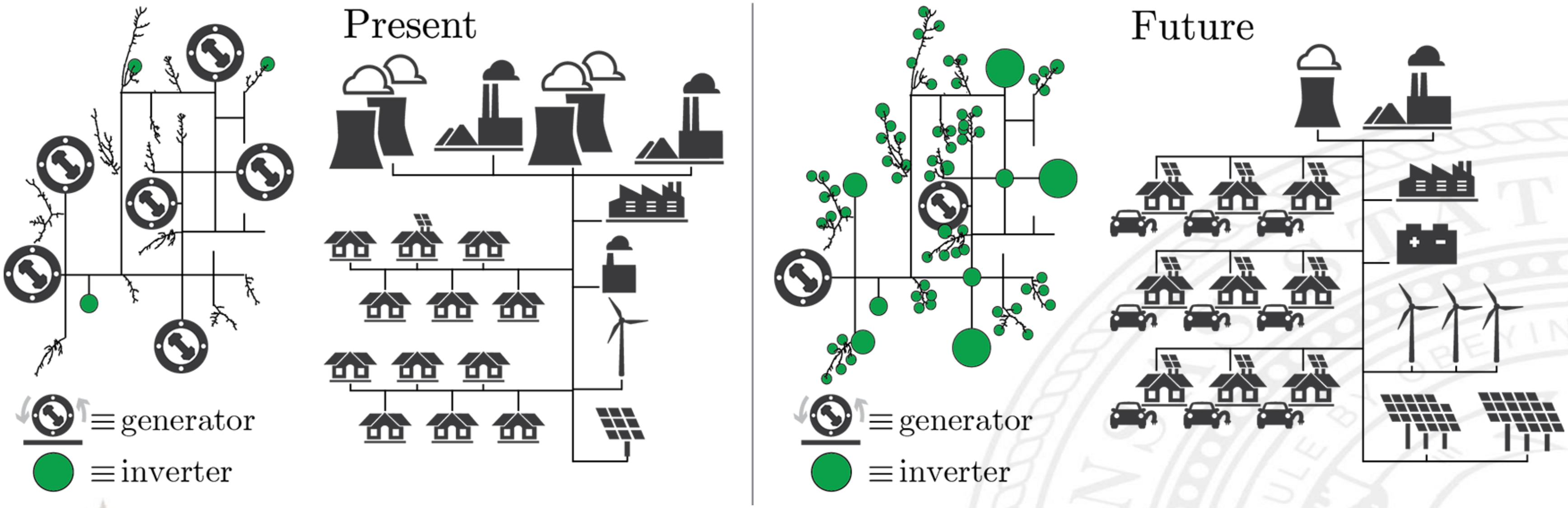
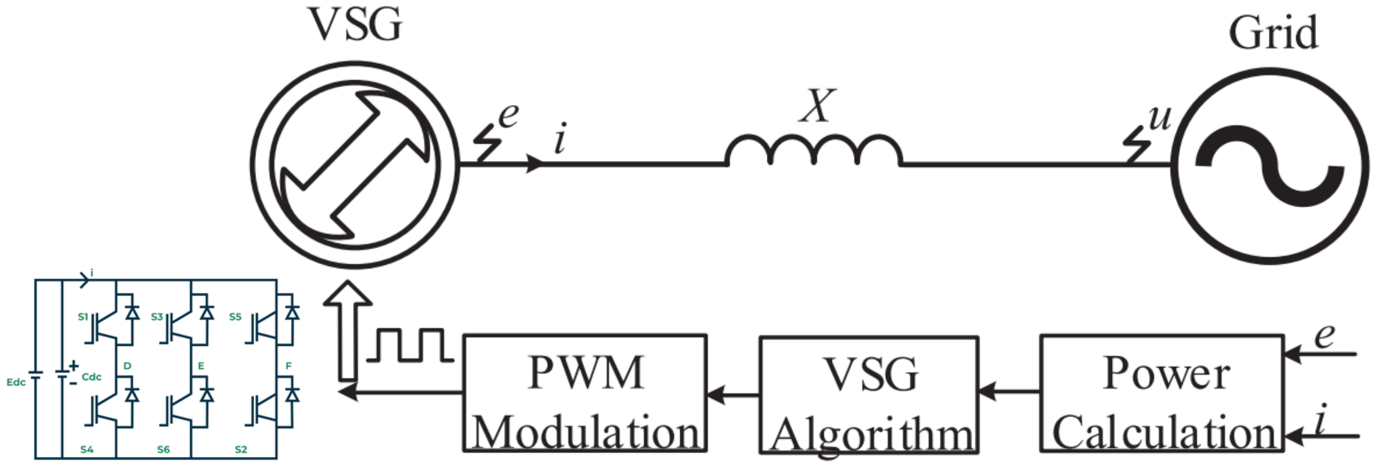


Figure Source: B. Kroposki et al., “Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy,” IEEE power & energy magazine.

Opportunities: Virtual Inertia Control

- Inverters are control-driven devices. They can emulate the inertia response of synchronous generators.



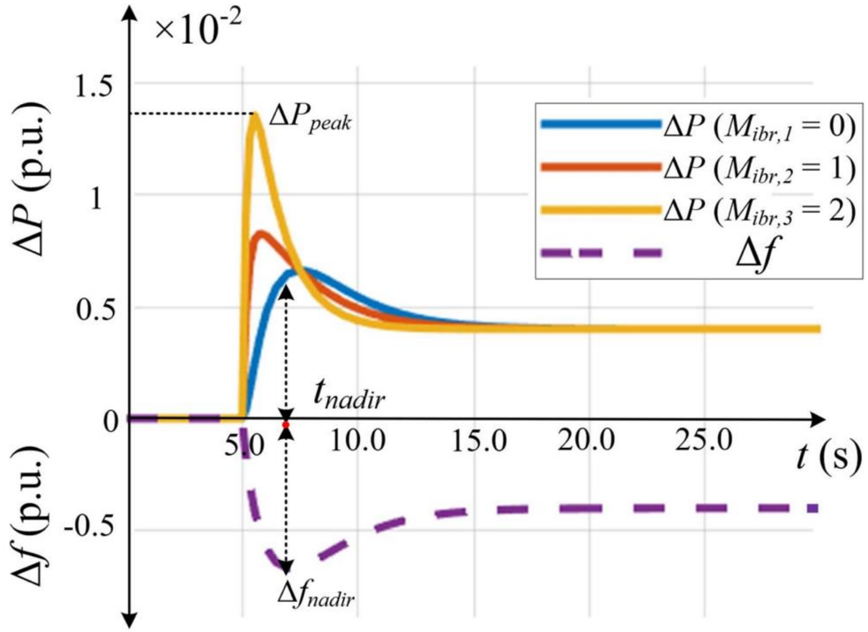
3-Phase Inverter

PWM: Pulse Width Modulation
VSG: Virtual Synchronous Generator

Challenges: Virtual Inertia Control

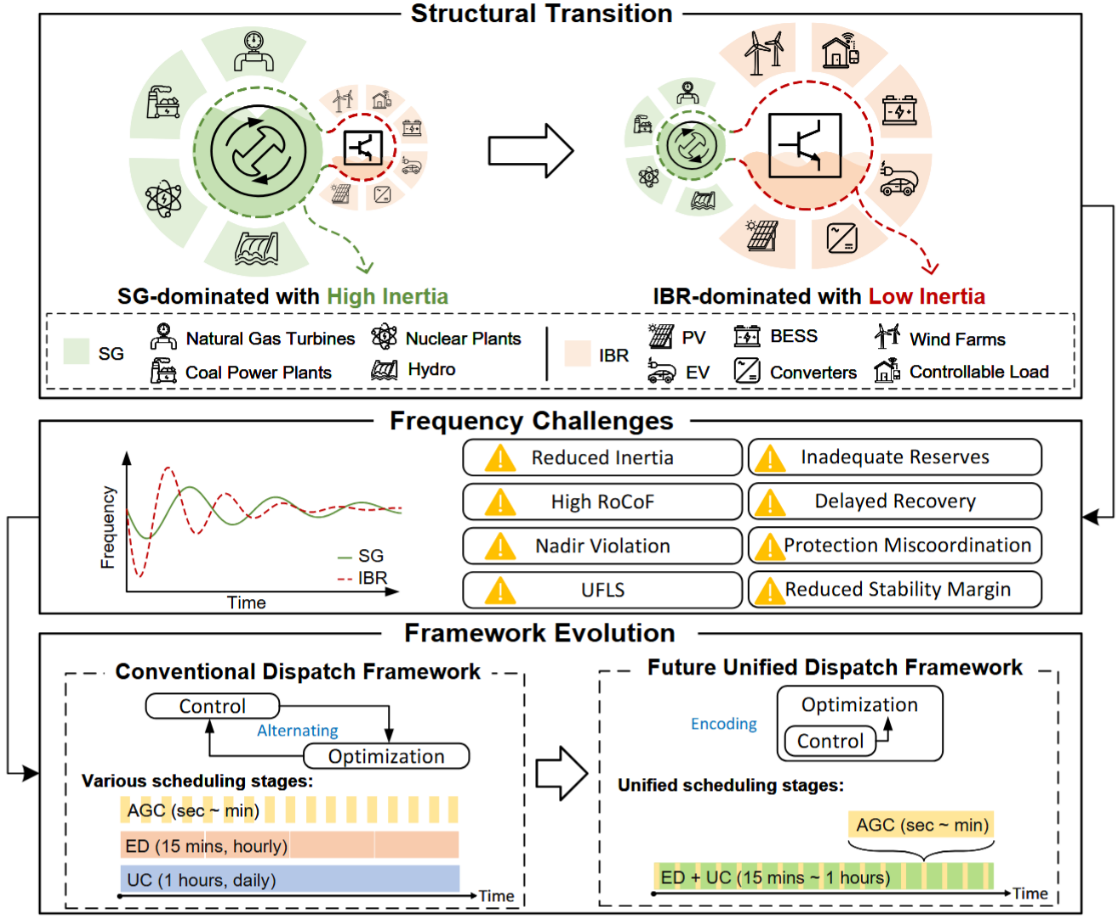
- Inverter-based inertia support is not a cost-free service.
- Additional power and energy immediately following a disturbance is needed to stabilize the system.

Typical power and frequency responses of inverters after step disturbance.



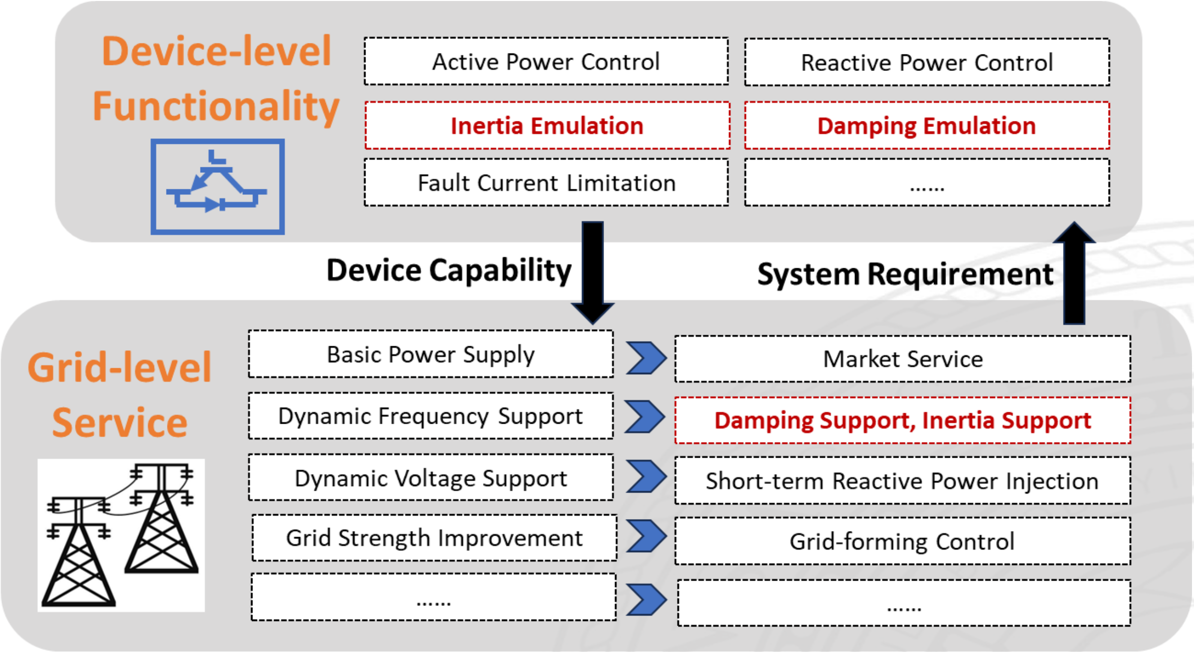
Background Summary

- Inertia is important to power system.
- Replacing SGs by IBR reduces system inertia.
- Low inertia increases frequency risks.
- New control and optimization framework are needed.



Background Summary

- IBR Role Transition from Passive Components to Active Participants.



Role Transition of IBRs in Future Power Systems

[1] Buxin She, Fangxing Li, Jinning Wang, Hantao Cui, Xiaofei Wang, and Rui Bo, "Virtual Inertia Scheduling for Microgrids with Static and Dynamic Security Constraints," *IEEE Transactions on Sustainable Energy*, April, 2025.

Virtual Inertia Scheduling (VIS)

Concept of Virtual Inertia Scheduling

- VIS is a unified inertia management framework that combines the device-level control and grid-level economic operation and leverages the inertia support capability of grid components.

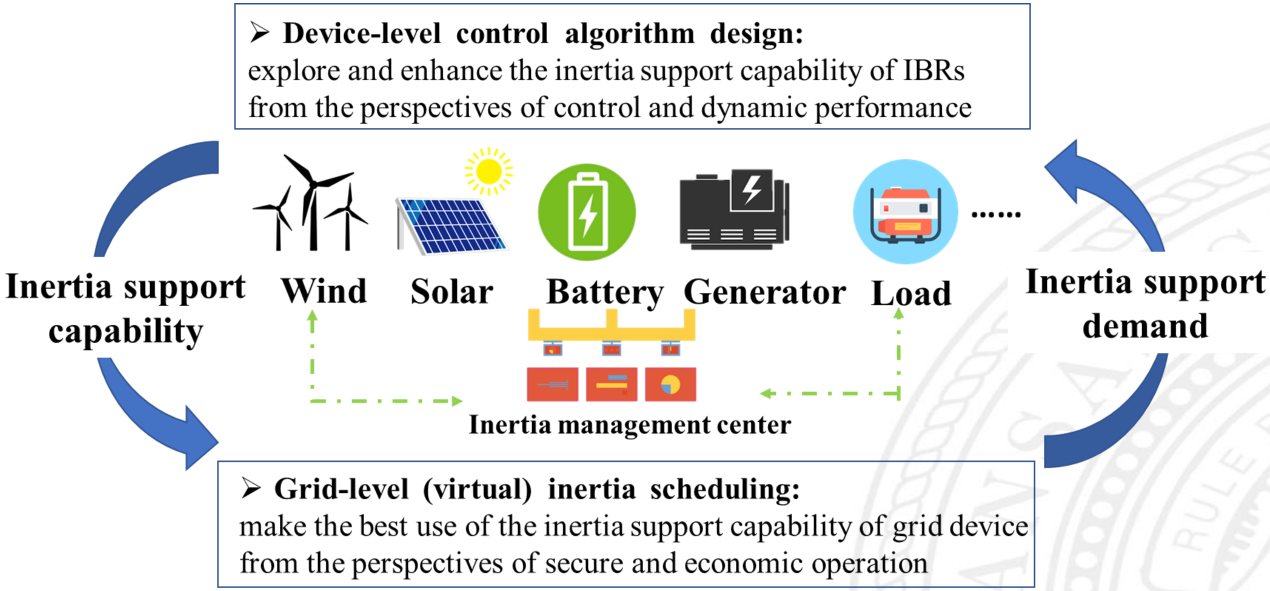


Diagram of virtual inertia scheduling

Generic Formulation of VIS

- Upgraded from the conventional economic dispatch, VIS is formulated as an optimization problem, aiming to achieve an economic objective function while satisfying physical constraints.

Dynamics Support Cost

$$\min_{\Theta} \sum_{t \in T} C_t^{gen} + C_t^{dyn}$$

Decision Set

Generation Cost

Optimization Interval For $\forall t = 1, 2, \ldots T$ and $\psi_t \in \Psi$, Contingency Set

$$s.t. \begin{cases} i). \text{ Static economic dispatch constraints} \\ ii). \text{ Transient performance constraints} \\ iii). \text{ Stability constraints} \end{cases}$$

Constraints

Conventional Scheduling (Economic Dispatch)

- Conventional economic dispatch minimizes generation cost while meeting demand and network constraints, assuming inertia is inherently provided by synchronous generators.

  - **Objective function:**

$$\min_{P} \sum_{t \in T} \Bigg[\underbrace{\sum_{i=1}^{N_{sg}} \left(a_{i,t}^{sg} P_{i,t}^{sg2} + b_{i,t}^{sg} P_{i,t}^{sg} + c_{i,t}^{sg} + b_{r,i,t}^{sg} P_{i,t,t}^{sg} \right)}_{SG}$$

$$+ \underbrace{\sum_{i=1}^{N_{ibr}} \left(a_{i,t}^{ibr} P_{i,t}^{ibr2} + b_{i,t}^{ibr} P_{i,t}^{ibr} + c_{i,t}^{ibr} \right) \Bigg]}_{IBR}$$

  - **Constraints:**

For $\forall t \in \{1, \ldots, T\}$, *s.t.*,

$$\sum_{i=1}^{N_{sg}} P_{i,t}^{sg} + \sum_{i=1}^{N_{ibr}} P_{i,t}^{ibr} - \sum_{i=1}^{N_l} L_{i,t} = 0$$

$$\sum_{i=1}^{N} GSF_{l,t} \left(P_{i,t}^{sg} + P_{i,t}^{ibr} - L_{i,t} \right) \leq LU_l$$

$$\sum_{i=1}^{N} GSF_{l,t} \left(P_{i,t}^{sg} + P_{i,t}^{ibr} - L_{i,t} \right) \geq -LU_l$$

$$P_{i,t}^{sg} + P_{i,ru,t}^{sg} \leq P_i^{\max,sg}$$

$$P_{i,t}^{sg} - P_{i,rd,t,}^{sg} \geq P_i^{\min,sg}$$

$$P_{i,t}^{ibr} \leq P_{i,t}^{\max,ibr}$$

$$P_{i,t}^{ibr} \geq P_{i,t}^{\min,ibr}$$

  - **Decision variables:** Power Output and reserve

Virtual Inertia Scheduling (VIS)

- **Updated objective function:**

$$\min_{P,M,D}\sum_{t\in T}[\underbrace{\sum_{i=1}^{N_{sg}}(a_{i,t}^{sg}P_{i,t}^{sg2}+b_{i,t}^{sg}P_{i,t}^{sg}+c_{i,t}^{sg}+b_{r,i,t}^{sg}\Delta P_{i,r,t}^{sg})}_{SG}$$

$$+\underbrace{\sum_{i=1}^{N_{ibr}}(a_{i,t}^{ibr}P_{i,t}^{ibr2}+b_{i,t}^{ibr}P_{i,t}^{ibr}+c_{i,t}^{ibr}+b_{r,i,t}^{ibr}\Delta P_{i,r,t}^{ibr})}_{IBR}]$$

Opportunity cost caused by inertia support

- **New Constraints:**

1) $$\begin{cases} P_{i,t}^{ibr}+P_{i,ru,t}^{ibr}+\Delta P_{i,peak,t}^{ibr}\le P_{i,t}^{\max,ibr} & \forall t\in\{1,\ldots,T\} \\ P_{i,t}^{ibr}-P_{i,rd,t}^{ibr}-\Delta P_{i,peak,t}^{ibr}\ge P_{i,t}^{\min,ibr} & \forall t\in\{1,\ldots,T\} \end{cases}$$

2) $$\begin{cases} -RoCof_{\lim}\le f_0\dfrac{\Delta P_{e,t}}{M_t}\le RoCof_{\lim}, & \forall t\in\{1,\ldots,T\} \\ f_{\min}\le f_0+\Delta f_{nadir,t}\le f_{\max}, & \forall t\in\{1,\ldots,T\} \end{cases}$$

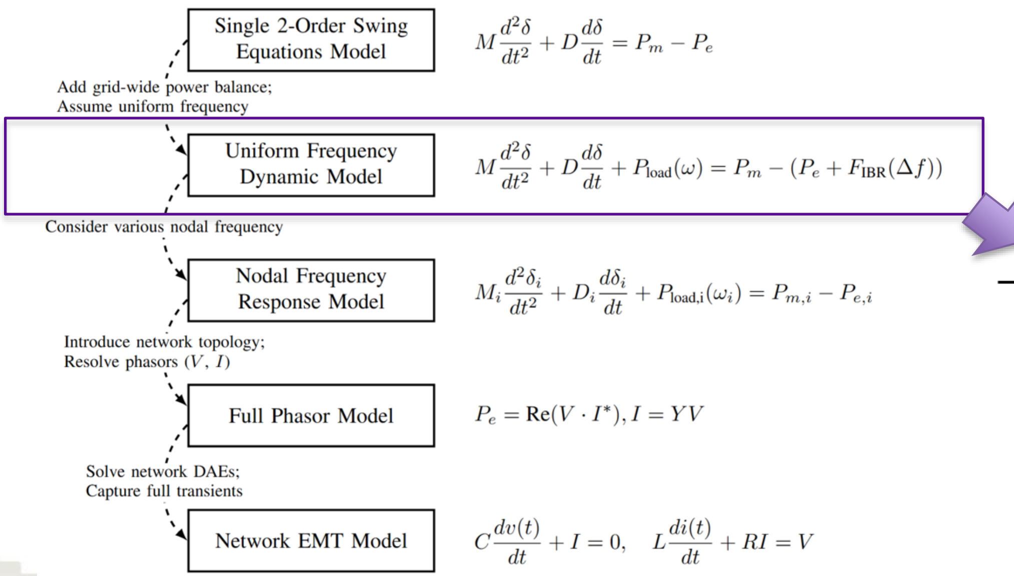
- **New Decision Variables:**

  ΔP, M, D

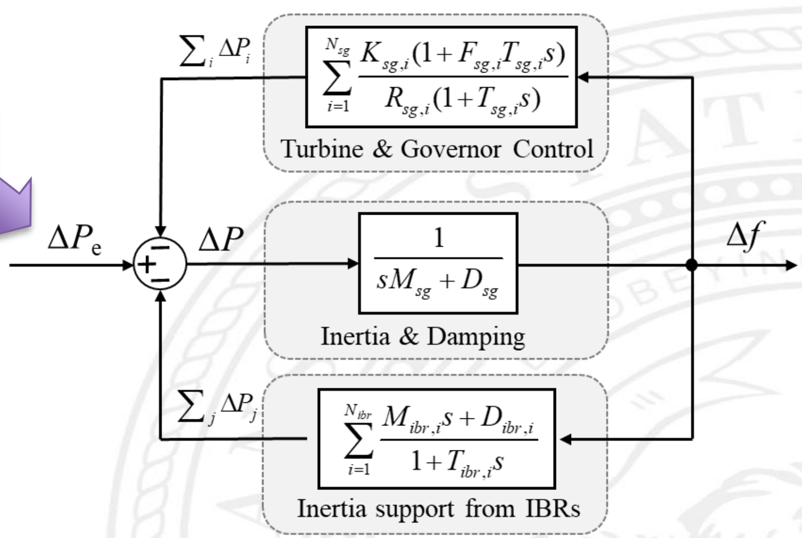
  - IBR Power reserve
  - Virtual inertia
  - Virtual damping

Dynamics Approximation

- VIS integrates **power** and **frequency** dynamics into scheduling, requiring suitable approximations and embedding into the decision framework.

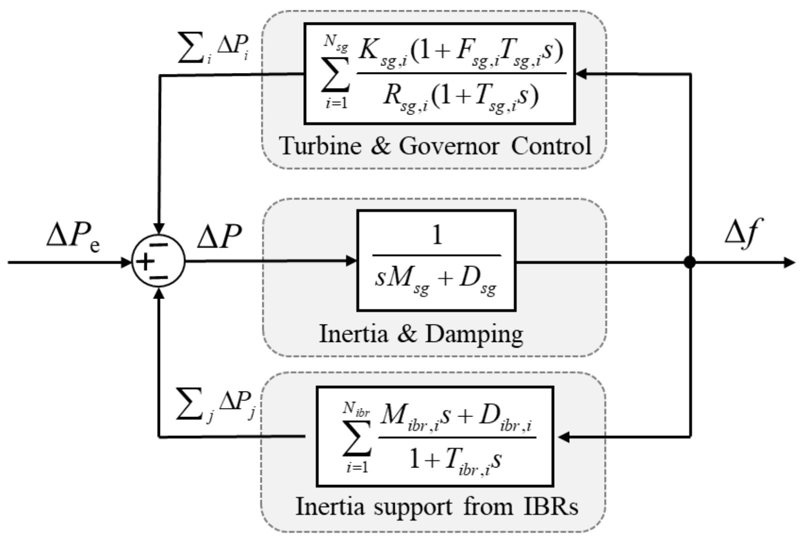


Models for quantifying frequency dynamics



Uniform frequency dynamic model

Analytical Results



Frequency domain dynamics

$$\Delta f(t) = \frac{\Delta P_e}{MTw_n^2}\left[1 - e^{-\zeta w_n t}\eta \sin\left(w_d t + \phi\right)\right]$$

$$\Delta P(t) = \frac{\Delta P_e D_{ibr}}{MTw_n^2}\left[-1 + \alpha\eta' e^{-\zeta w_n t} \sin\left(w_d t + \phi'\right)\right]$$

$$\begin{cases} \Delta f_{nadir} = \dfrac{\Delta P_e}{MTw_n^2}\left[1 - \sqrt{1-\zeta^2}\,\eta e^{-\zeta w_n t_m}\right] \\ \Delta P_{\max}^{ibr} = \dfrac{\Delta P_e D_{ibr}}{MTw_n^2}\left[-1 + \alpha\eta' e^{-\zeta w_n t_m'} \sin(w_d t + \phi')\right] \end{cases}$$

Time-domain dynamics

[1] Buxin She, Fangxing Li, Hantao Cui, Jingning Wang, Qiwei Zhang, and Rui Bo. " Virtual Inertia Scheduling for Power Systems with High Penetration of Inverter-based Resources ". *IEEE Transaction on Sustainable Energy*, 26 September, 2024.

Neural Network-assistant Linearization

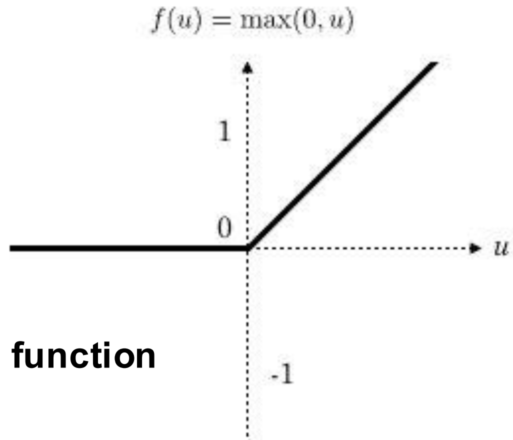
- Neural Network Fitting

$$\begin{cases} \Delta f_{nadir} = \dfrac{\Delta P_e}{MTw_n^2}\left[1-\sqrt{1-\zeta^2}\eta e^{-\zeta w_n t_m}\right] \\ \Delta P_{\max}^{ibr} = \dfrac{\Delta P_e D_{ibr}}{MTw_n^2}\left[-1+\alpha\eta' e^{-\zeta w_n t_m'}\sin(w_d t+\phi')\right] \end{cases} \Rightarrow \begin{cases} \Delta f_{nadir} = NN_1(\Delta P_e, M, D, R, F, T) \\ \Delta P_{\max}^{ibr} = NN_2(\Delta P_e, M, D, R, F, T) \end{cases}$$

- Linearization
  - m^{th} hidden layer of neural network (NN) with ReLU activation function:

$$\begin{cases} \hat{z}_m = W_m z_{m-1} + b_m \\ z_m = \max(\hat{z}_m, 0) \end{cases}$$

  - *Linearization by big M method*:



ReLU function

Extension to Stability Constraints

- Extend from dynamic power and frequency constraints to more generalized stability constraints

$$RoCoF, \Delta f_{nadir}, \Theta^{ss}, \Theta^{ts} = NN(\Theta, \psi)$$

Small signal stability (Θ^{ss}) *Transient stability* (Θ^{ts})

$$\Theta^{ss} \Rightarrow eig_{\max}^{real}$$

$$\Theta^{ts} \Rightarrow \Delta\delta_{\max}$$

$$\Delta\delta_{\max} = \max(|\Delta\delta_j(t) - \Delta\delta_k(t)|), \forall j,k \in \Omega^G$$

Example: Two-machine System

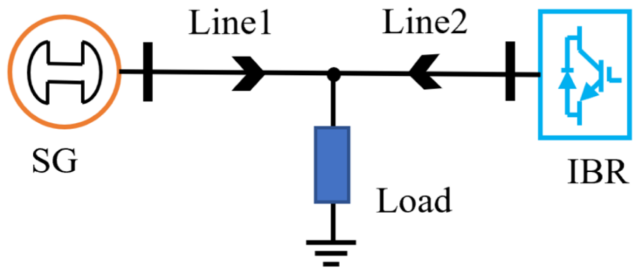


Diagram of two-machine system

Step 1: *Pre-train NN based on the data generated by analytical models*

$$\begin{cases} \Delta f_{nadir} = NN_1(\Delta P_e, M, D, R, F, T) \\ \Delta P_{\max}^{ibr} = NN_2(\Delta P_e, M, D, R, F, T) \end{cases}$$

Step 2: *Solve VIS Optimization Model*

$$\min_{P_{sg}, P_{ibr}, M_{ibr}, D_{ibr}} \quad a^{sg}(P^{sg})^2 + b^{sg}P^{sg} + c^{sg} + b_r^{sg}P_r^{sg}$$

$$+a^{ibr}(P^{ibr})^2 + b^{ibr}P^{ibr} + c^{ibr} + b_r^{ibr}P_r^{ibr}$$

$$s.t. \quad P_{sg} + P_{ibr} - L = 0$$

$$-LU_1 \leq P_{sg} \leq LU_1$$

$$-LU_2 \leq P_{ibr} \leq LU_2$$

$$P^{sg} + P_{ru}^{sg} \leq P^{\max,sg}$$

$$P^{sg} - P_{rd}^{sg} \geq P^{\min,sg}$$

$$P^{ibr} + \Delta P_{peak}^{ibr} \leq P^{\max,ibr}$$

$$P^{sg} - \Delta P_{peak}^{ibr} \geq P^{\min,ibr}$$

$$M^{\min,ibr} \leq M^{ibr} \leq M^{\max,ibr}$$

$$D^{\min,ibr} \leq D^{ibr} \leq D^{\max,ibr}$$

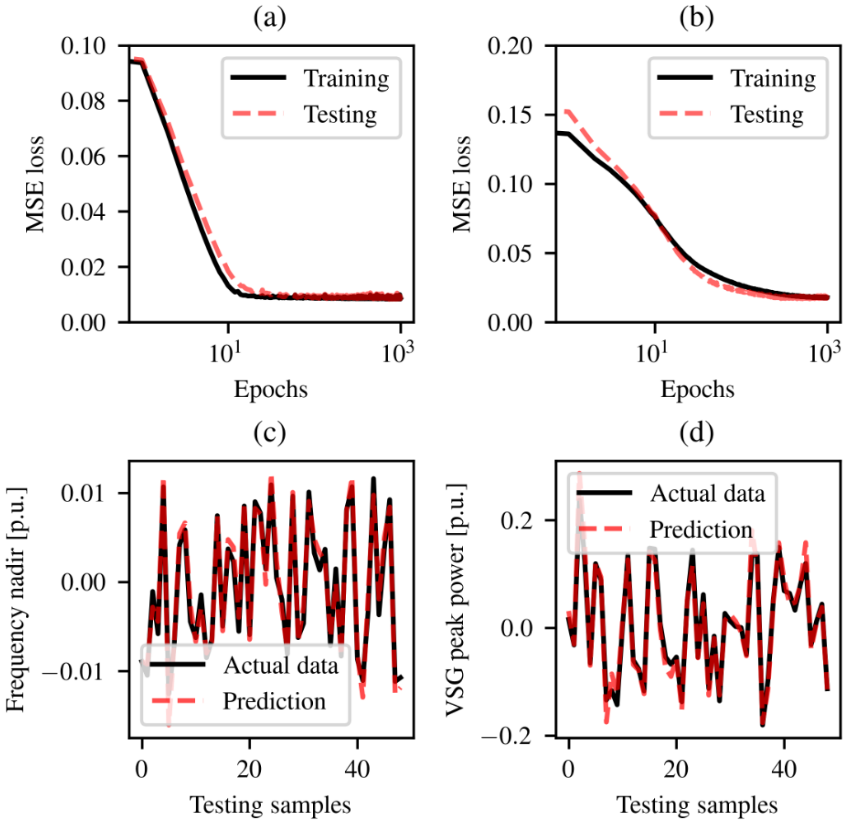
$$-\mathrm{RoCoF}_{\lim} \leq f_0 \frac{\Delta P_e}{M} \leq \mathrm{RoCoF}_{\lim}$$

$$-\Delta f_{\lim} \leq \Delta f_{\mathrm{nadir},t} \leq \Delta f_{\lim}$$

Example: Two-machine System

- Neural network training Results

$$\begin{cases} \Delta f_{nadir} = NN_1(\Delta P_e, M, D, R, F, T) \\ \Delta P_{\max}^{ibr} = NN_2(\Delta P_e, M, D, R, F, T) \end{cases}$$

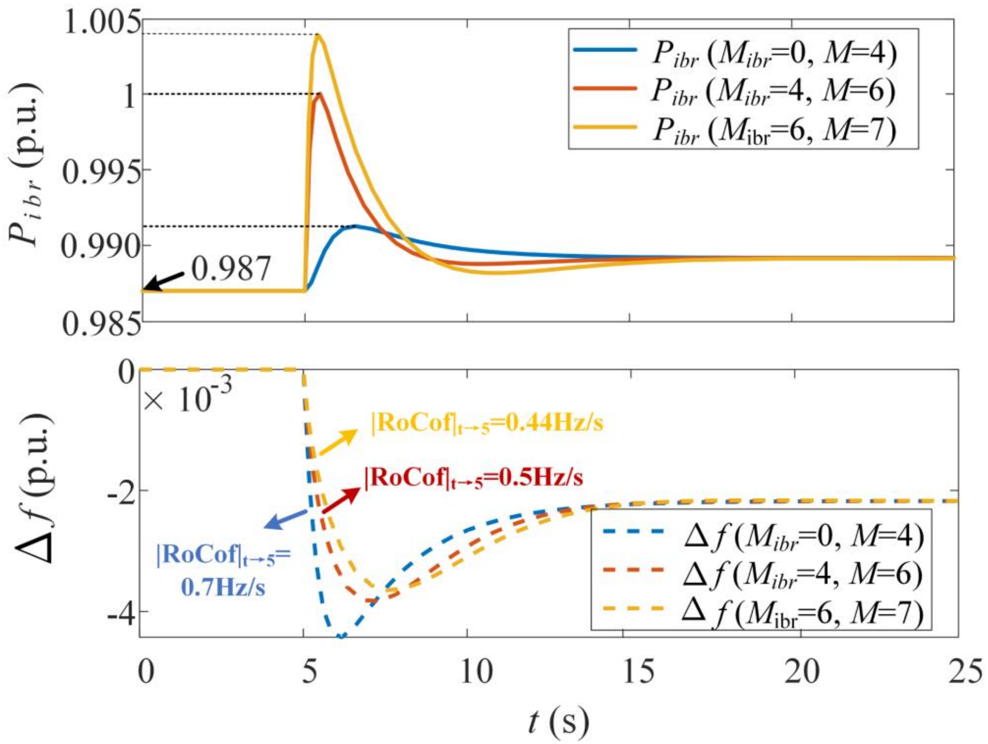


(a) Training loss of frequency nadir prediction
(b) Training loss of IBR peak power prediction

(c) Testing of frequency nadir prediction
(d) Testing of IBR peak power prediction

Example: Two-machine System

Step 3: *Validate Power and Frequency Performance*



Dynamic performance of the two-machine system

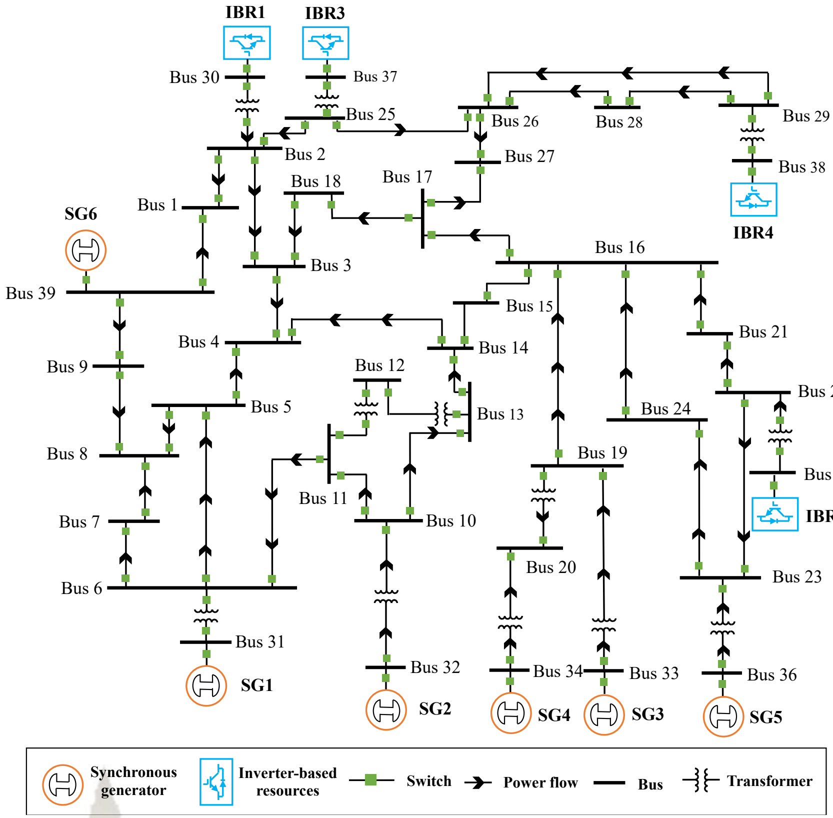
Power and frequency threshold:

- P_{max} = 1 p.u.
- $RoCof_{max}$=0.5 Hz/s

VIS Scheduling results (**Red curve**):

1) The peak IBR power output reaches its rated capacity (1 p.u.).
2) RoCof becomes the binding constraint (0.5 Hz/s) following a disturbance.

Example: IEEE 39-Bus System



Single-line diagram of modified IEEE-39bus system

- Validation on a modified IEEE 39-bus system, followed by a one-hour dispatch-dynamic time-domain simulation.

[1] Buxin She, Fangxing Li, Hantao Cui, Jingning Wang, Qiwei Zhang, and Rui Bo. " Virtual Inertia Scheduling for Power Systems with High Penetration of Inverter-based Resources ". *IEEE Transaction on Sustainable Energy*, 26 September, 2024.

Conclusions

- Although IBRs present **low inertia** characteristics, their **controllability** and **flexibility** allow for the design of an advanced scheduling framework for future low-inertia power system. IBR role transition from passive components to active participants.

- **Virtual inertia scheduling (VIS)** is an inertia management framework that targets **security-constrained** and **economy-oriented** inertia scheduling and generation dispatch of power systems with a large scale of IBRs.

Acknowledgement

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Other Contributors: Fangxing Li, Hantao Cui, Jinning Wang, Hang Shuai, Oroghene Oboreh-Snapps, Rui Bo, Nattapat Praisuwanna, Jingxin Wang, Leon M. Tolbert