A Framework for Analysing Mechanical-Electronic Composite Power Systems

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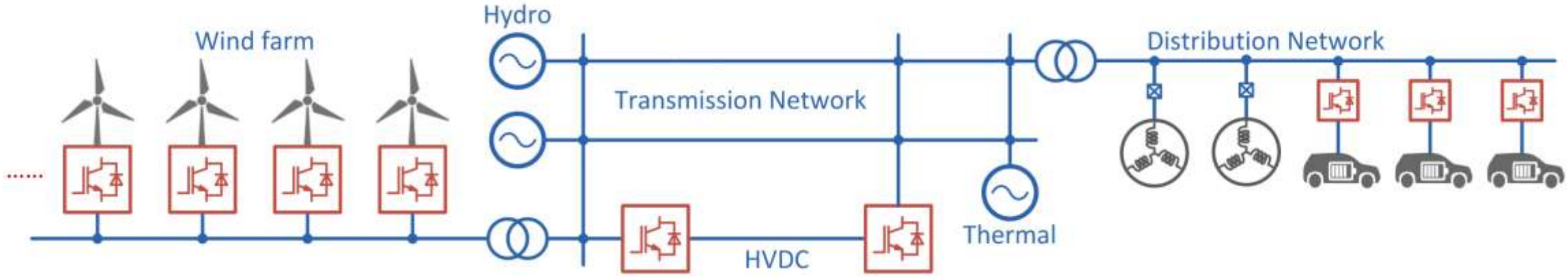
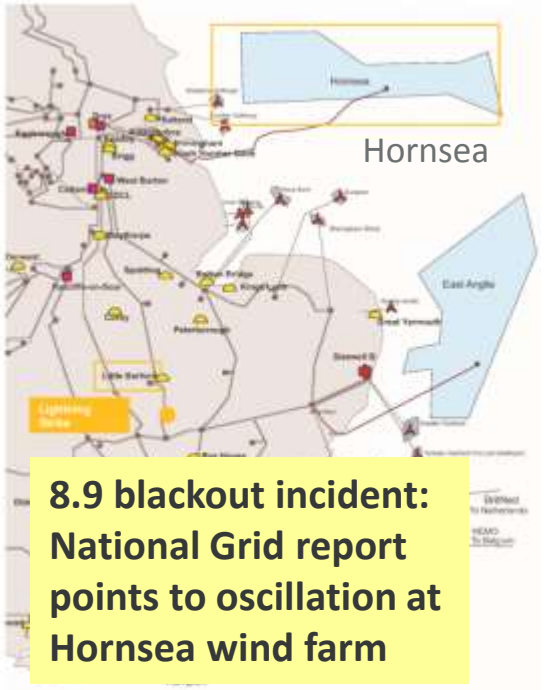
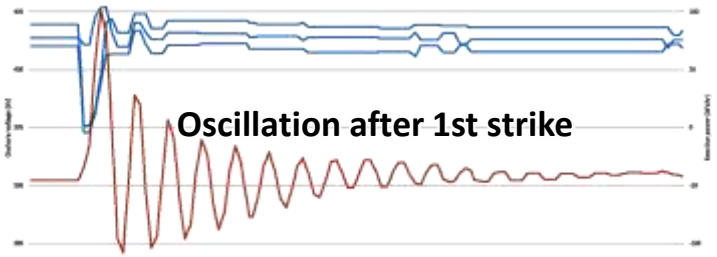
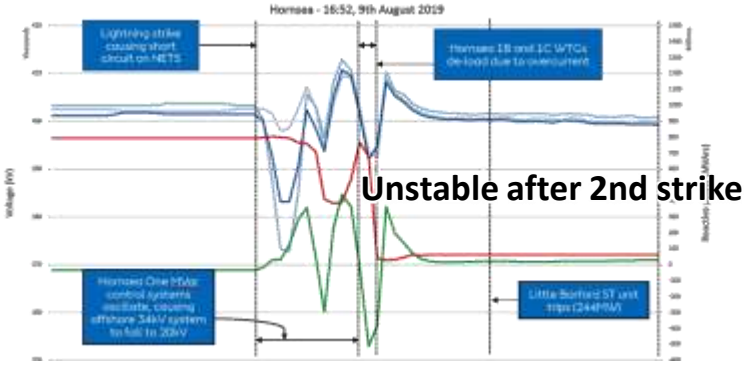
More-Electronic Power Systems: A Pandora's Box?

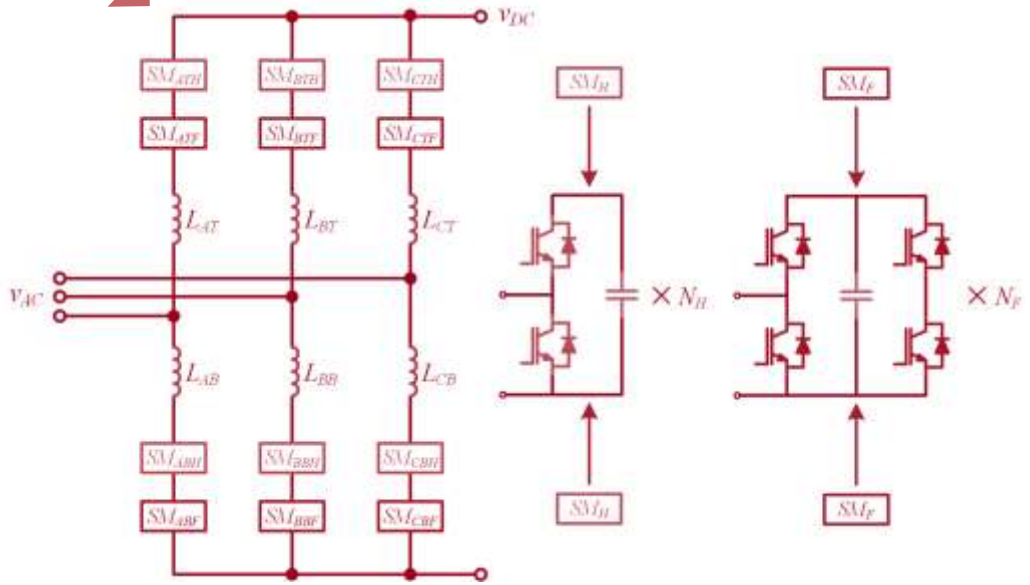




8.9 blackout incident: National Grid report points to oscillation at Hornsea wind farm







A single converter with many (>100) sub-modules

Power Electronic Timeline

1930s

Mercury Arc Valve
HVDC

1960s

Diode
Rectifier

1970s

Thyristor
Exciter & HVDC

1980s

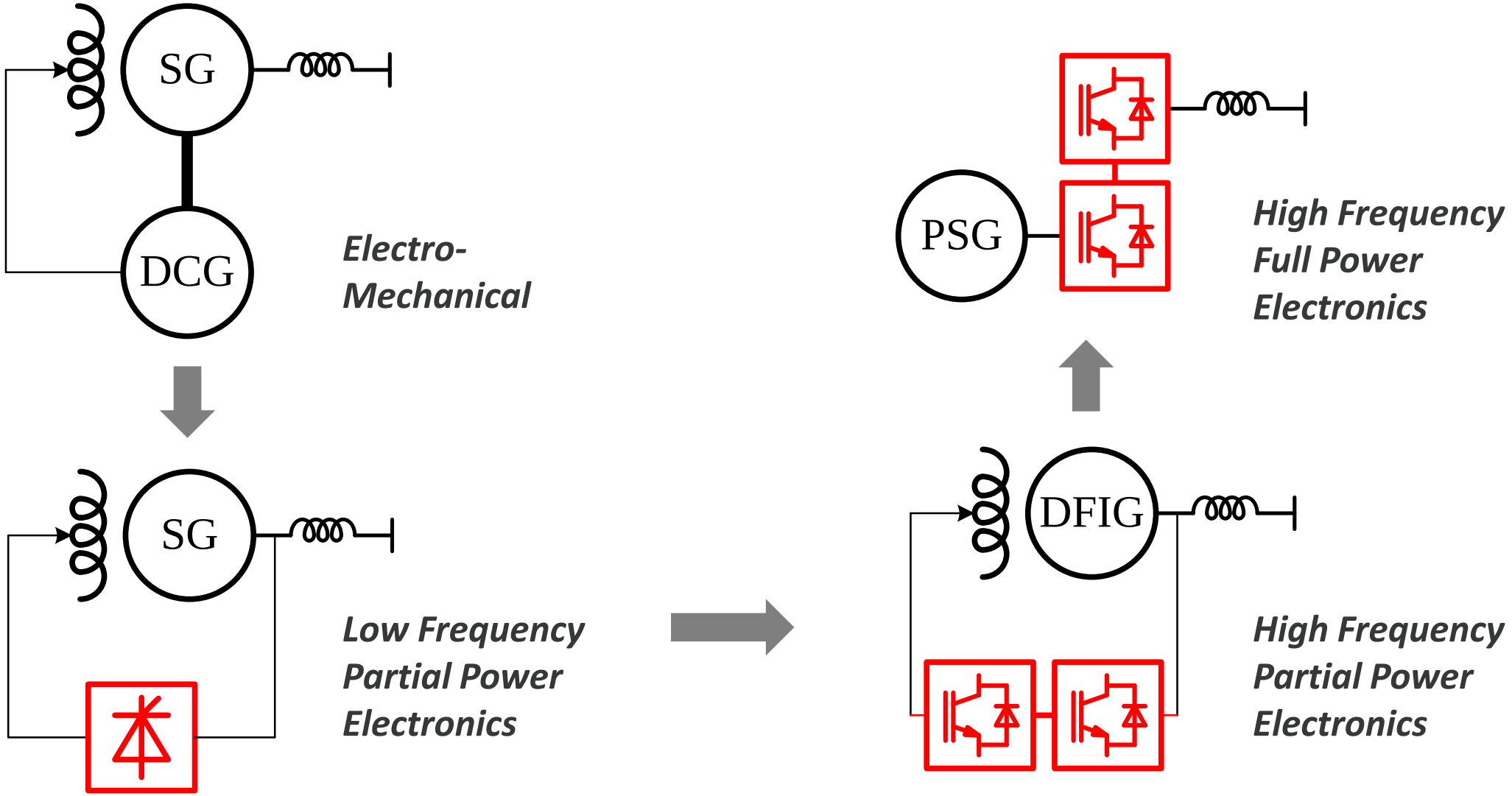
MOSFET
Power Supply

2000s

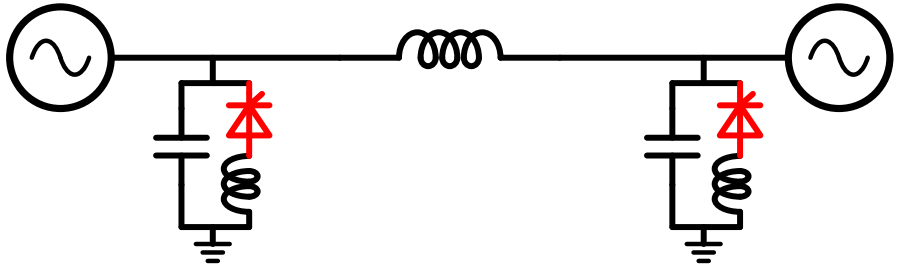
IGBT
Inverter & HVDC

- *Thyristor Exciters are widely used in power generation since **1970s***
- *MOSFET Power Supplies are widely used in power consumption since **1980s***
- *Why we start talking about more-power-electronic grid now, not thirty years ago?*

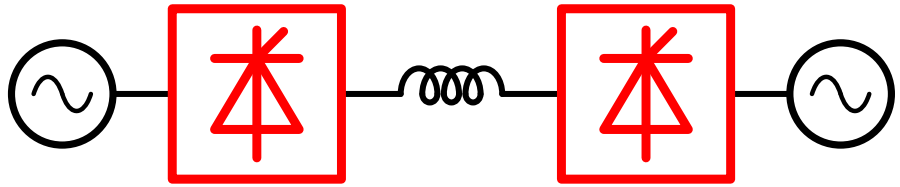
The Rise of Electronics in Power Generation



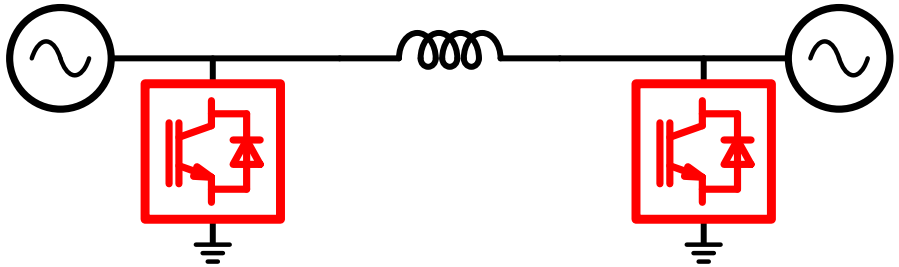
The Rise of Electronics in Power Transmission



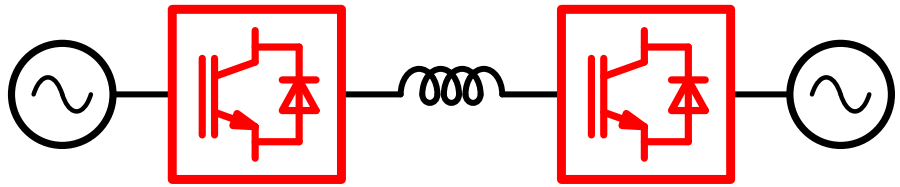
Low-Frequency Partial-Power Electronics



Low-Frequency Full-Power Electronics

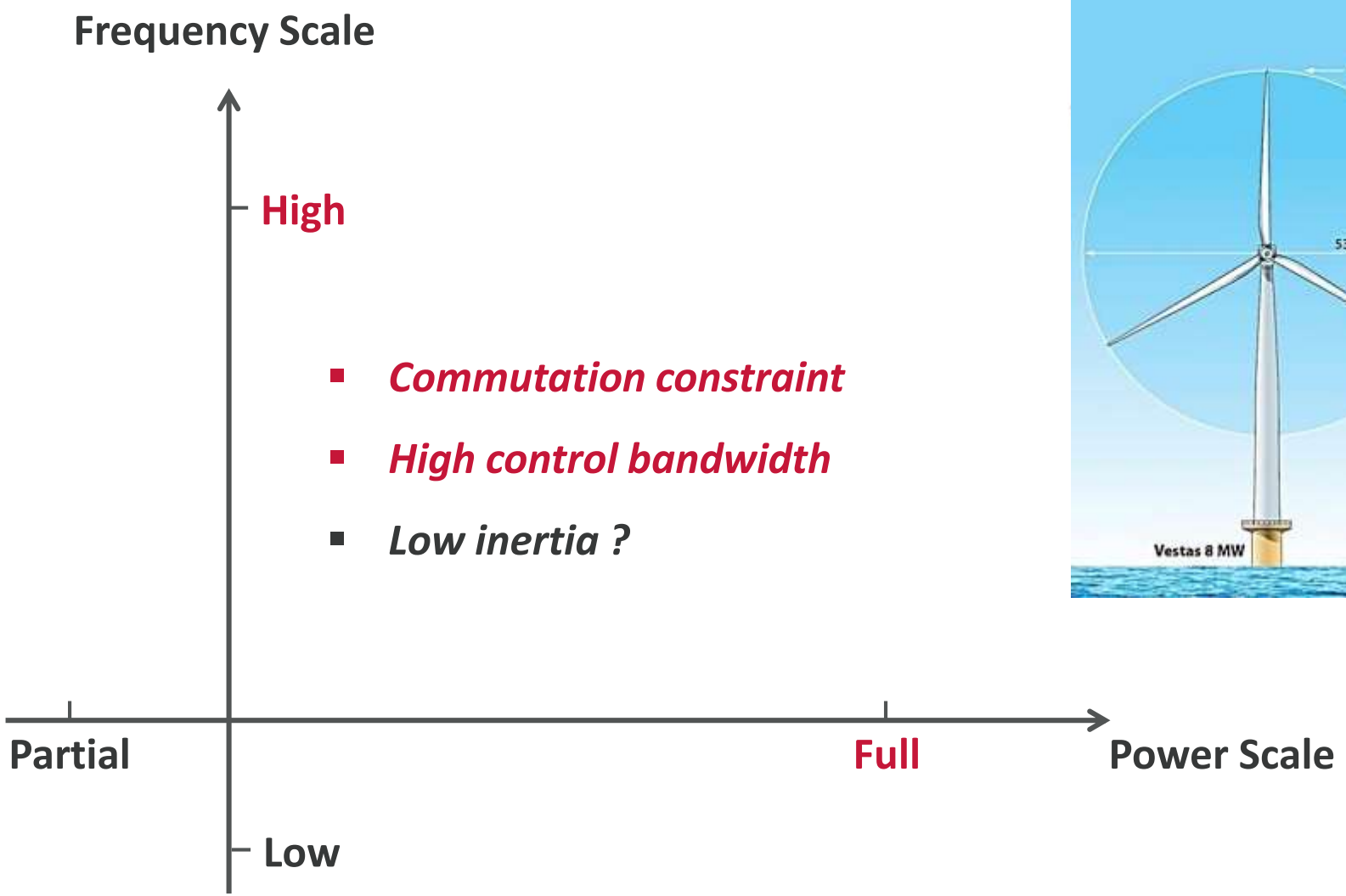


High-Frequency Partial-Power Electronics



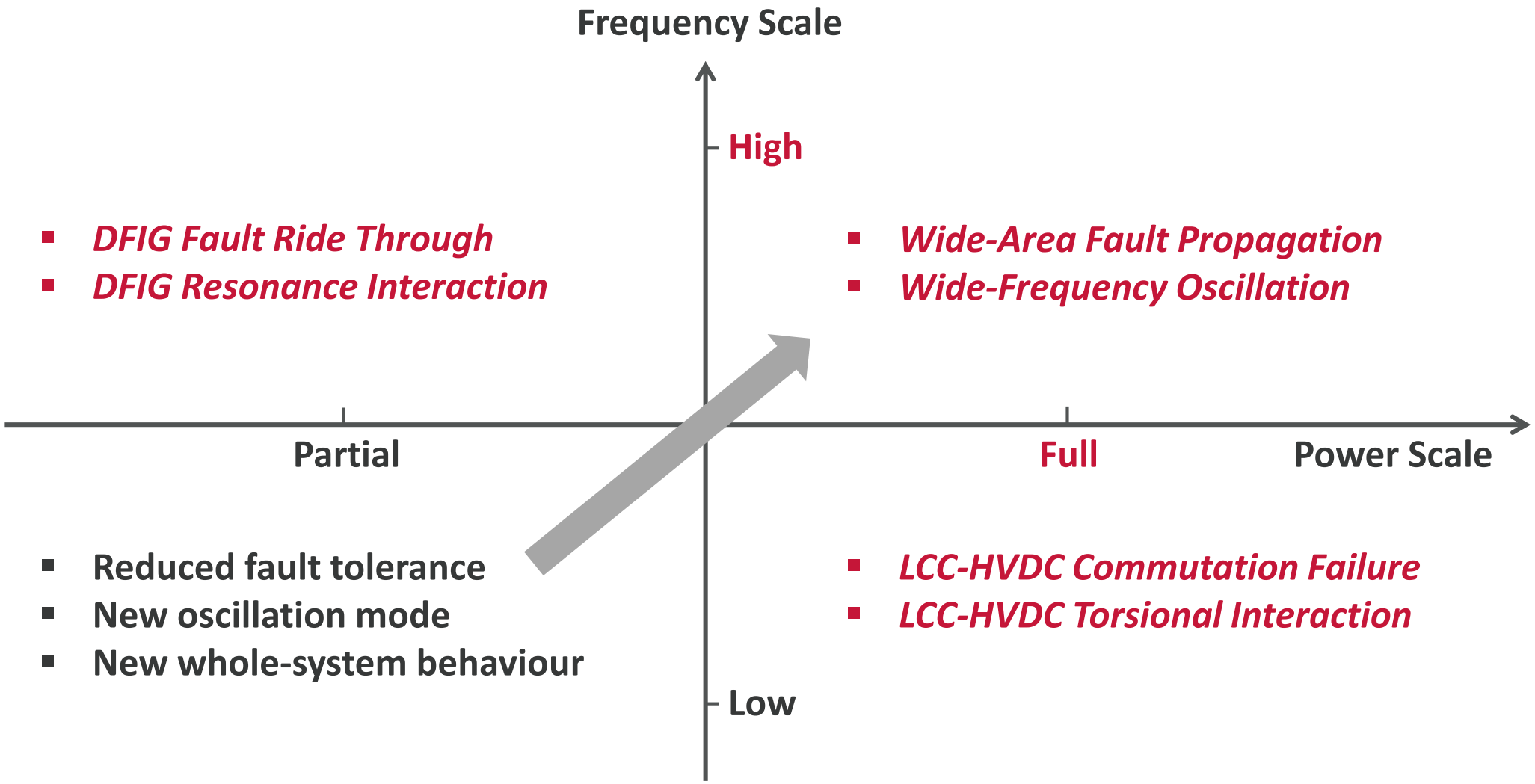
High-Frequency Full-Power Electronics

What Makes the Difference?

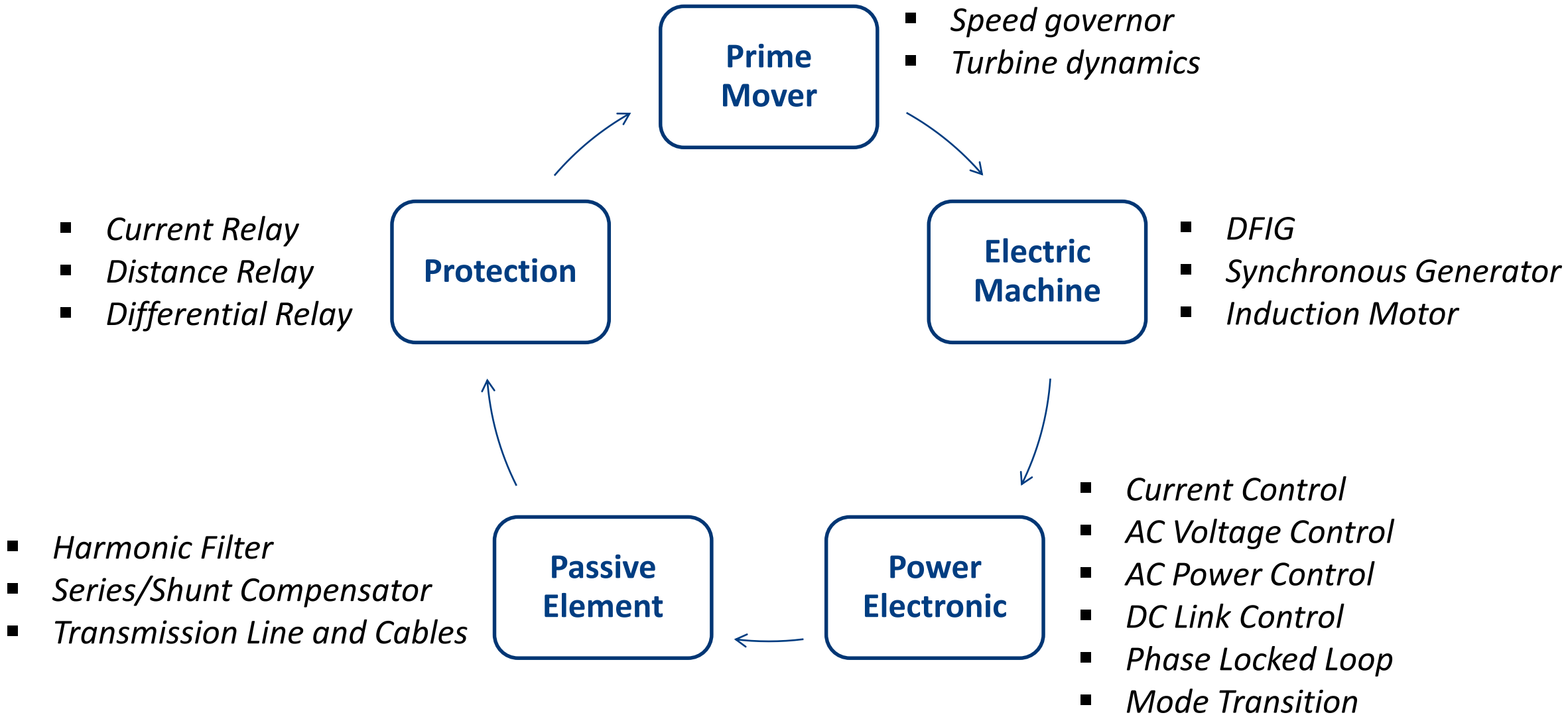


- *Commutation constraint*
- *High control bandwidth*
- *Low inertia ?*

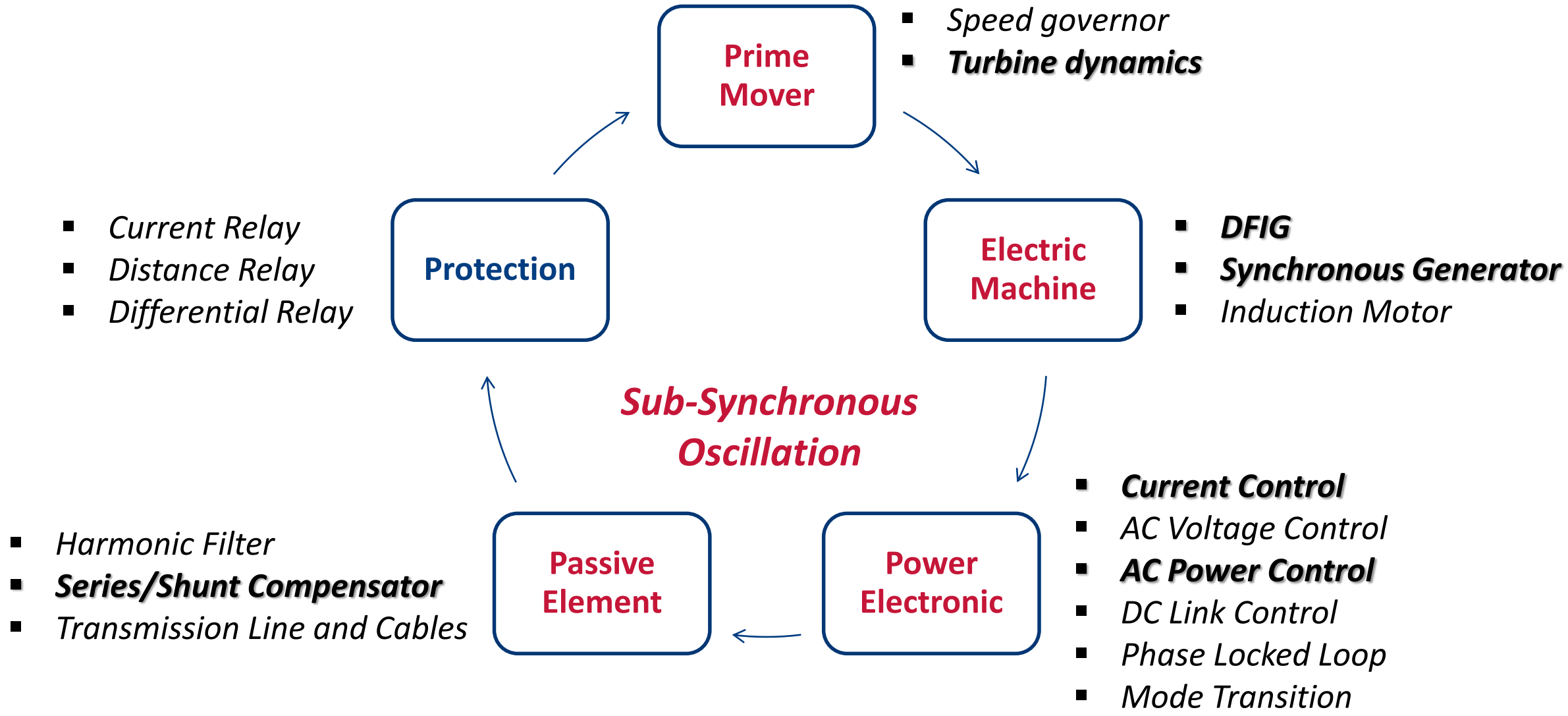
What Are the Consequences?



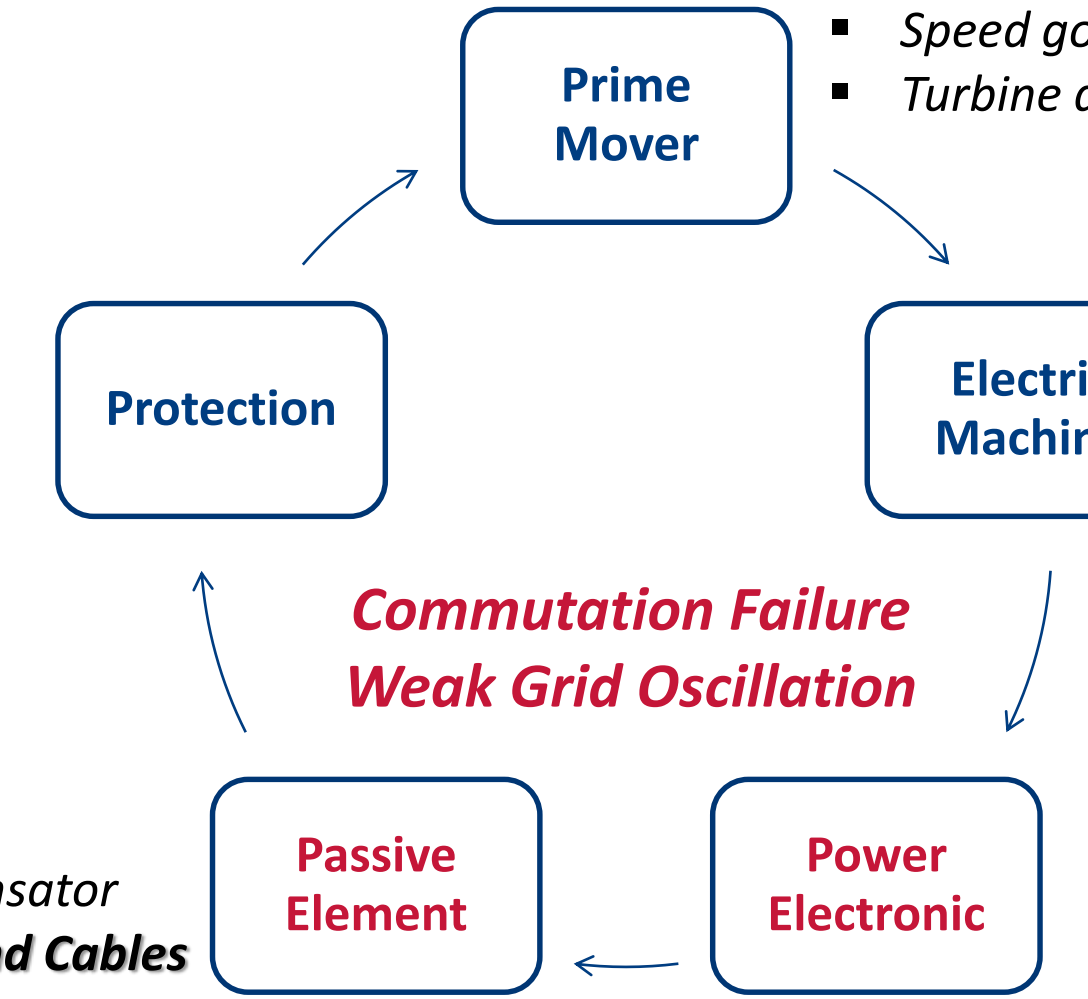
Whole System Interaction



Whole System Interaction



Whole System Interaction



- *Speed governor*
- *Turbine dynamics*

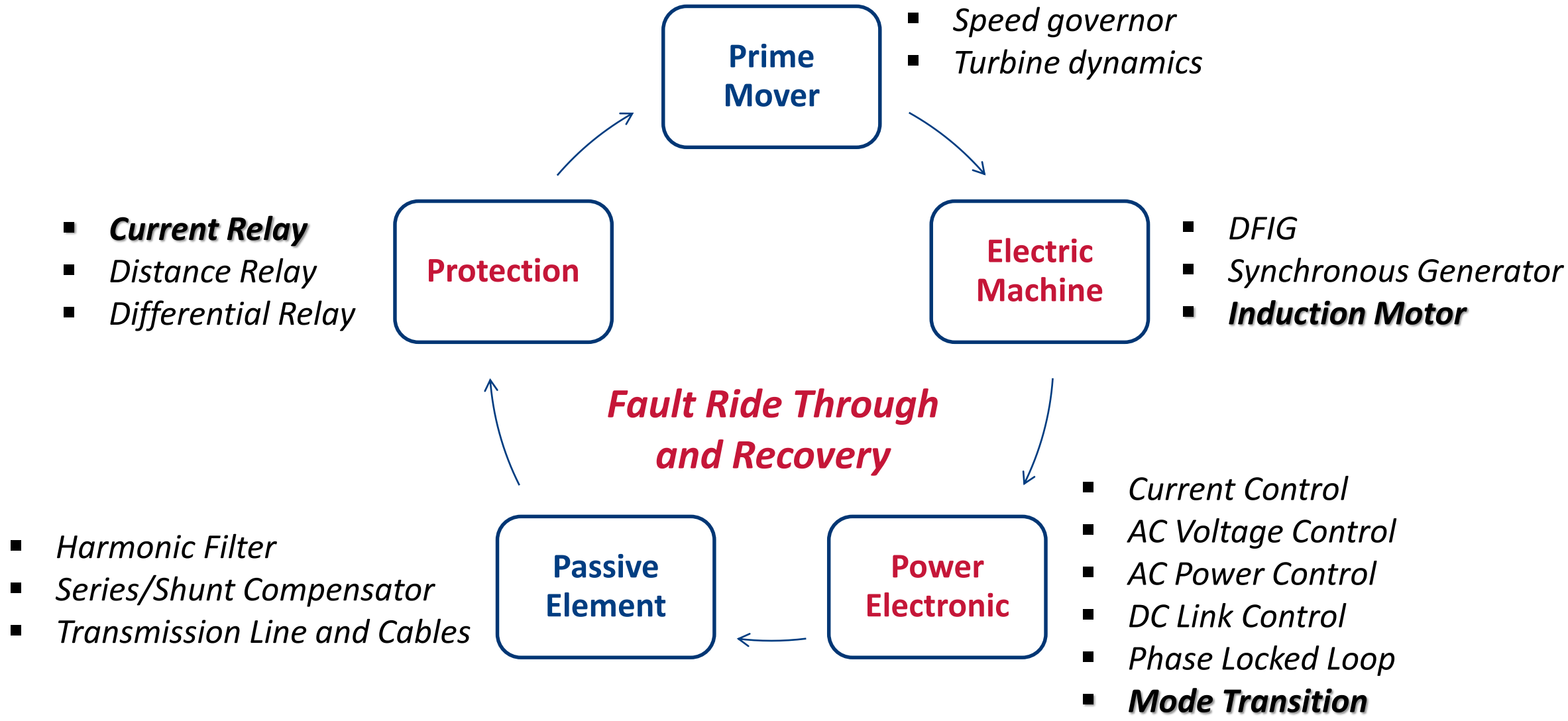
- *DFIG*
- *Synchronous Generator*
- *Induction Motor*

- *Current Control*
- ***AC Voltage Control***
- ***AC Power Control***
- ***DC Link Control***
- ***Phase Locked Loop***
- *Mode Transition*

- *Harmonic Filter*
- *Series/Shunt Compensator*
- ***Transmission Line and Cables***

- *Current Relay*
- *Distance Relay*
- *Differential Relay*

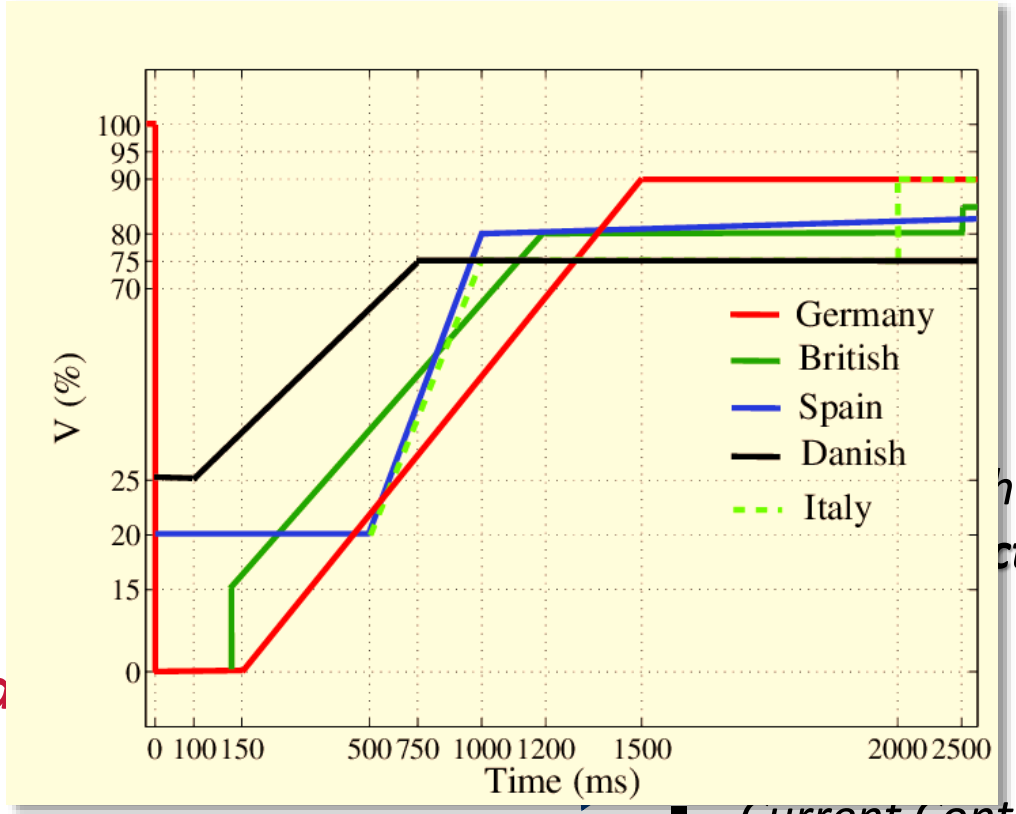
Whole System Interaction



Whole System Interaction

- ***Current Relay***
- *Distance Relay*
- *Differential Relay*

Protection



hronous Generator
ction Motor

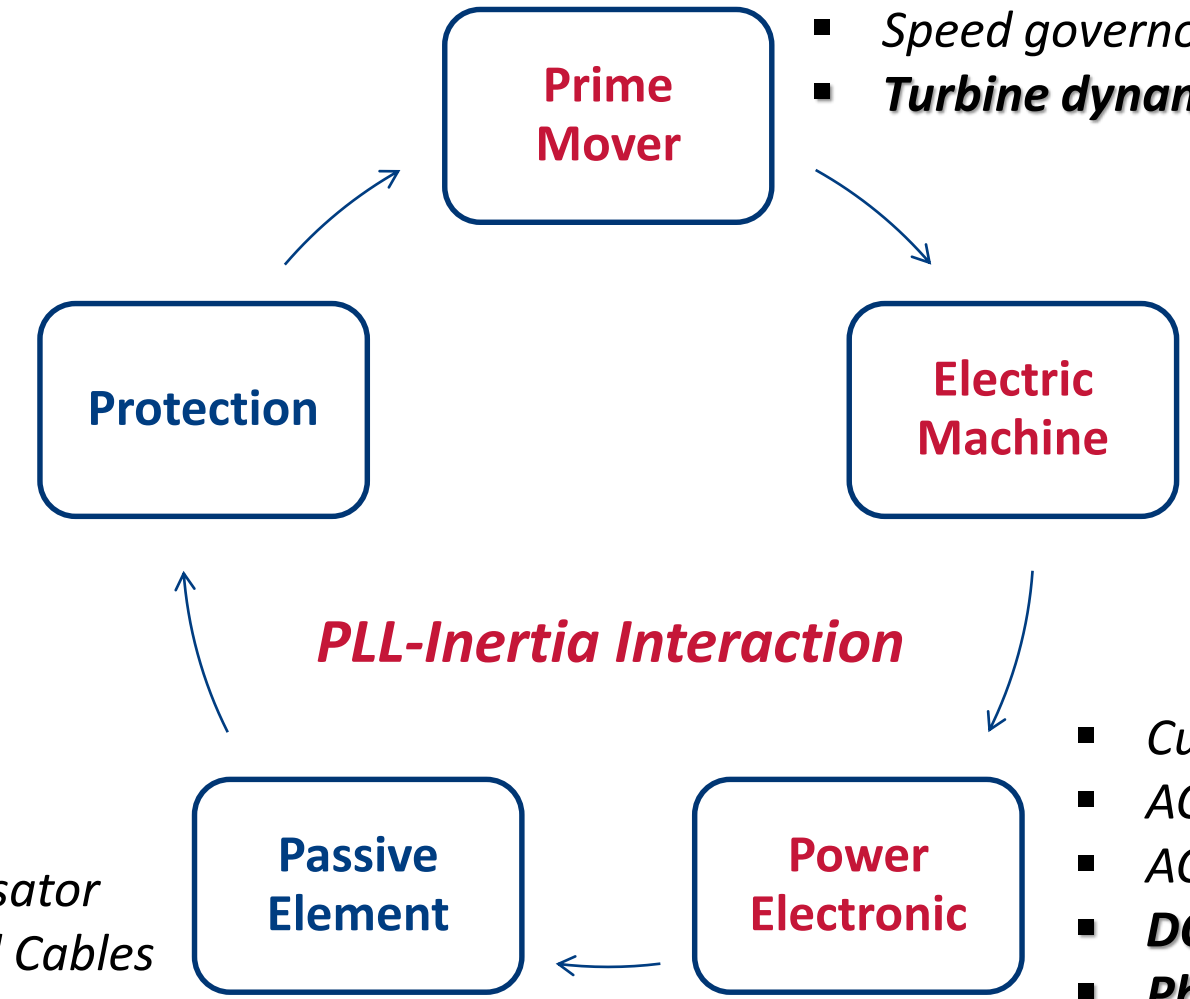
- *Current Control*
- *AC Voltage Control*
- *AC Power Control*
- *DC Link Control*
- *Phase Locked Loop*
- ***Mode Transition***

Power Electronic

Passive Element

- *Harmonic Filter*
- *Series/Shunt Compensator*
- *Transmission Line and Cables*

Whole System Interaction



- *Speed governor*
- ***Turbine dynamics***

- *DFIG*
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- *Induction Motor*

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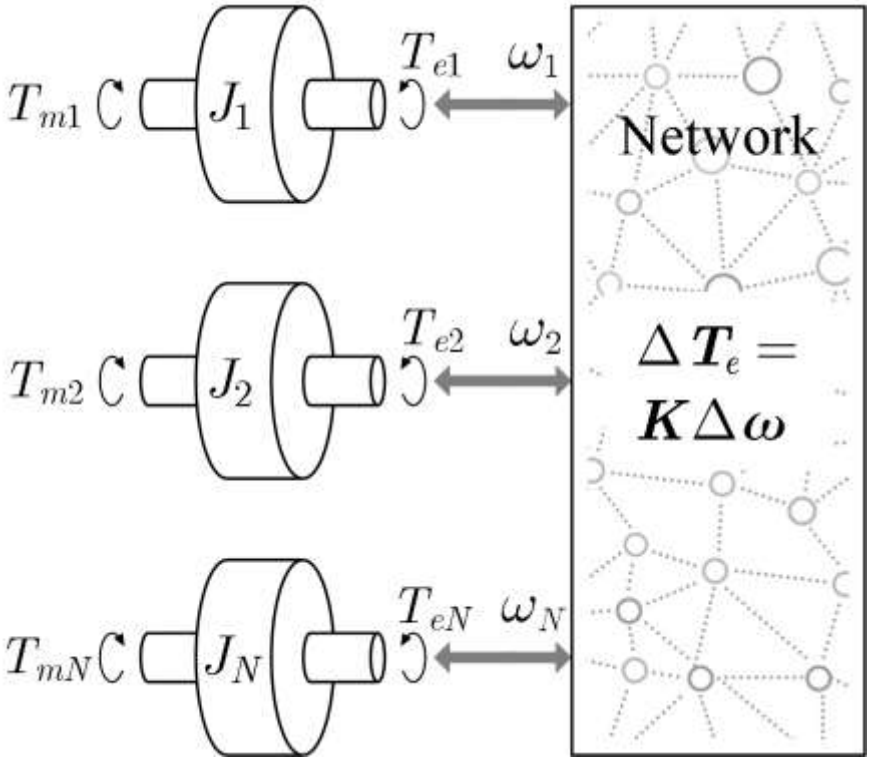
- *Harmonic Filter*
- *Series/Shunt Compensator*
- *Transmission Line and Cables*

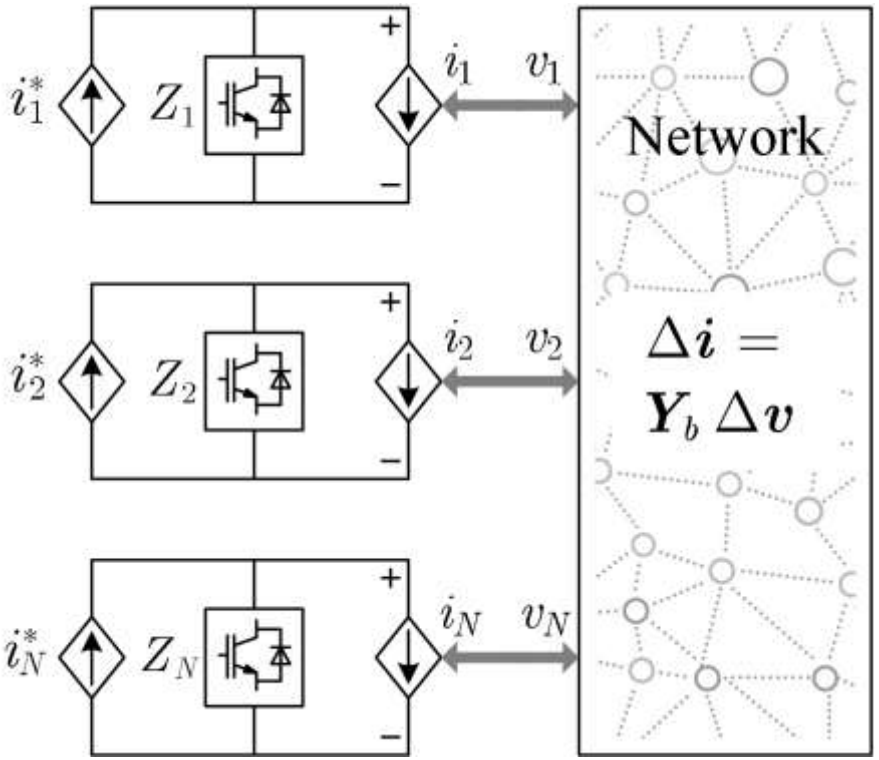
- *Current Relay*
- *Distance Relay*
- *Differential Relay*

Two Physical Views

Mechanical-Centric: Torque Coefficient



Electronic-Centric: Impedance/Admittance



Two Mathematical Tools

State-Space: Preserve Structure

$$\begin{pmatrix} \dot{x}_1 \\ x_2 \\ \vdots \\ x_3 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_3 \end{pmatrix}$$

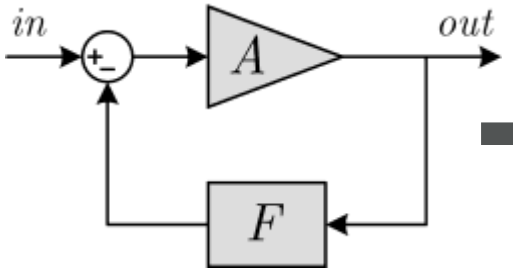
$$\boldsymbol{x} = \boldsymbol{\Phi z},\ \boldsymbol{z} = \boldsymbol{\Psi x}$$

$$\begin{pmatrix} \dot{z}_1 \\ z_2 \\ \vdots \\ z_3 \end{pmatrix} = \begin{pmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_n \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_3 \end{pmatrix}$$

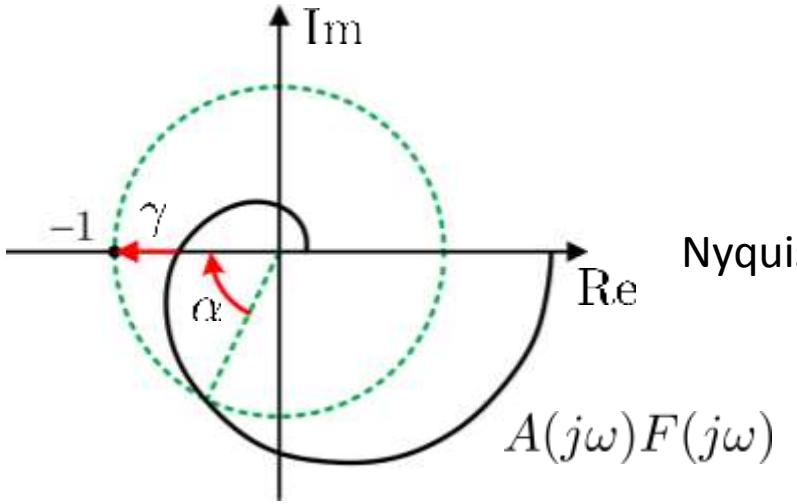
Eigenvalue

$p_{nk} = \phi_{nk}\psi_{nk}$ ***Participation Factor***

Transfer-Function: Directly Measurable



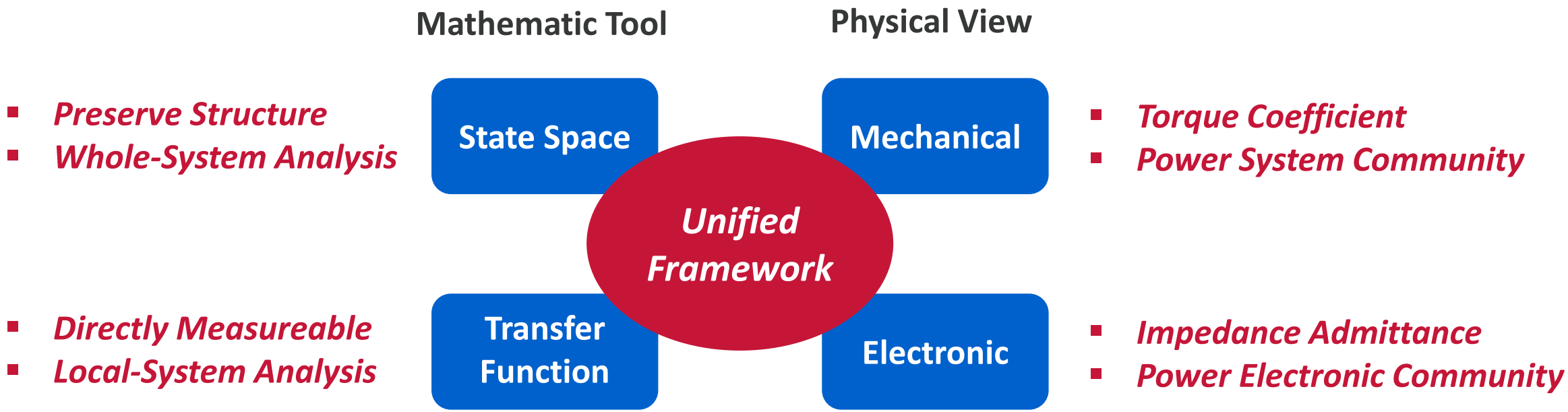
$$G(s) = \frac{A(s)}{1 + A(s)F(s)}$$



Nyquist Curve

$\alpha,\ \gamma$ ***Phase Margin, Gain Margin***

Unified Framework for Whole System Integration



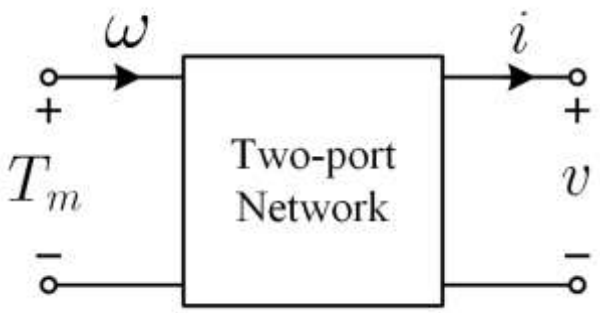
- *Preserve Structure*
- *Whole-System Analysis*

- *Torque Coefficient*
- *Power System Community*

- *Directly Measureable*
- *Local-System Analysis*

- *Impedance Admittance*
- *Power Electronic Community*

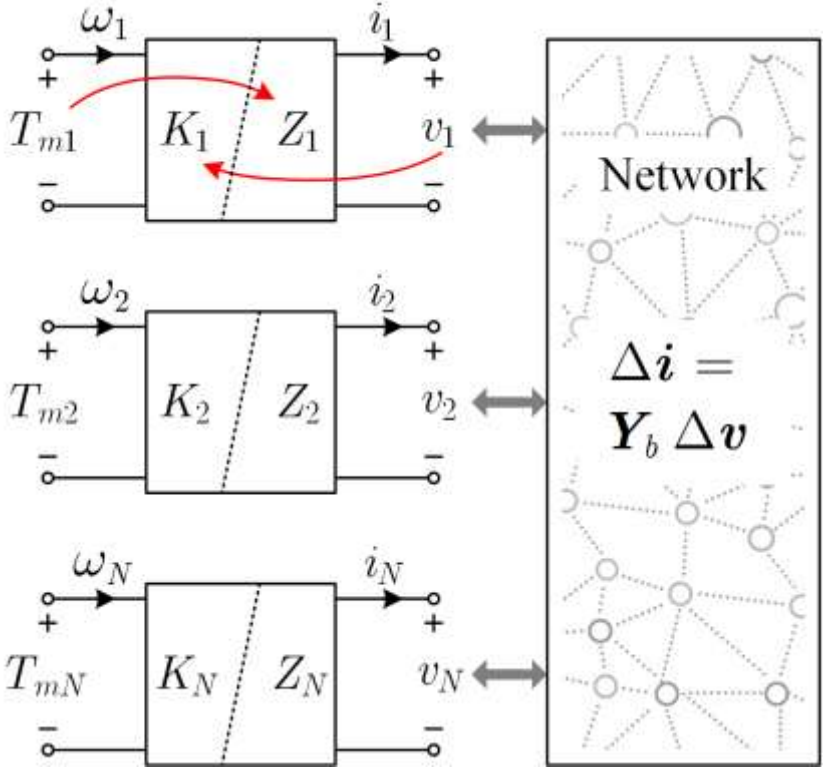
Unification of Mechanical and Electronic Views



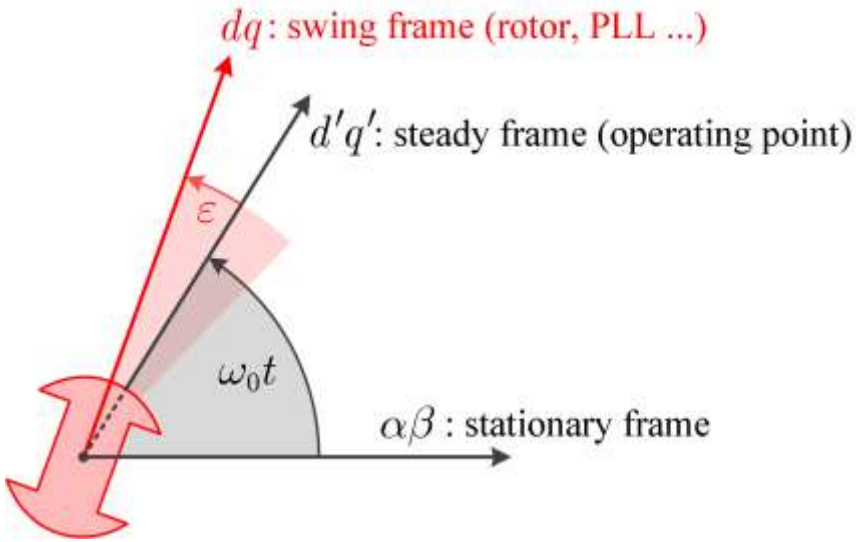
Mechanical Interaction

$$\begin{pmatrix} \Delta\omega \\ \Delta i \end{pmatrix} = \begin{pmatrix} G_{T\omega} & G_{v\omega} \\ G_{Ti} & G_{vi} \end{pmatrix} \begin{pmatrix} \Delta T_m \\ \Delta v \end{pmatrix}$$

Interaction Electronic



Mechanical → Electronic



Reflecting mechanical dynamics in impedance/admittance

$$\begin{pmatrix}\Delta\omega\\ \Delta i\end{pmatrix}=\begin{pmatrix}G_{T\omega} & G_{v\omega}\\ G_{Ti} & G_{vi}\end{pmatrix}\begin{pmatrix}\Delta T_m\\ \Delta v\end{pmatrix}$$

$$\downarrow$$

$$\begin{pmatrix}\Delta\omega\\ \Delta i' - I_0\frac{\Delta\omega}{s}\end{pmatrix}=\begin{pmatrix}G_{T\omega} & G_{v\omega}\\ G_{Ti} & G_{vi}\end{pmatrix}\begin{pmatrix}\Delta T_m\\ \Delta v' - V_0\frac{\Delta\omega}{s}\end{pmatrix}$$

$$\downarrow$$

$$\begin{pmatrix}\Delta\omega\\ \Delta i'\end{pmatrix}=\begin{pmatrix}G'_{T\omega} & G'_{v\omega}\\ G'_{Ti} & G'_{vi}\end{pmatrix}\begin{pmatrix}\Delta T_m\\ \Delta v'\end{pmatrix}$$

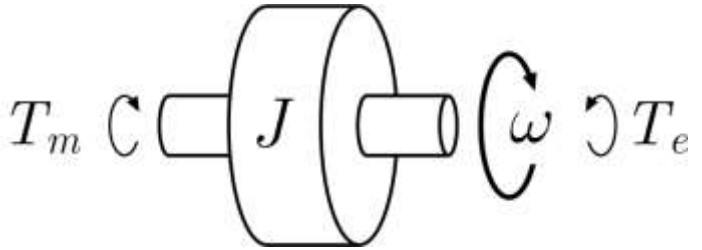
$$\downarrow$$

$$G'_{vi}=G_{vi}+(I_0-G_{vi}V_0)(s+G_{v\omega}V_0)^{-1}G_{v\omega}$$

$$\downarrow$$

$$Z'=Y'^{-1}=-G'^{-1}_{vi}$$

Electronic → Mechanical

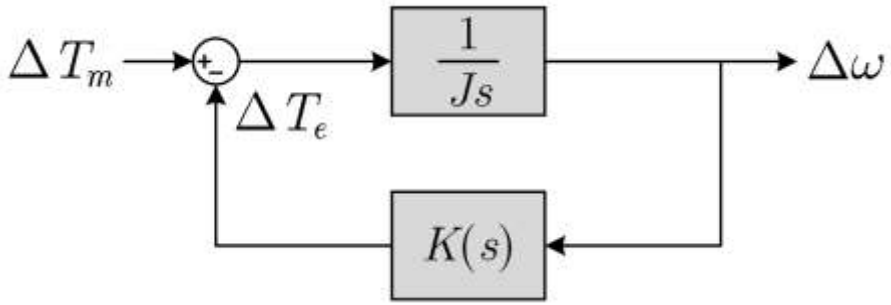


Reflecting electronic dynamics in torque coefficient

$$\begin{pmatrix}\Delta\omega\\ \Delta i'\end{pmatrix} = \begin{pmatrix}G'_{T\omega} & G'_{v\omega}\\ G'_{Ti} & G'_{vi}\end{pmatrix}\begin{pmatrix}\Delta T_m\\ \Delta v'\end{pmatrix}$$

$$\Delta i' = Y'_{sys}\Delta v'$$

$$G''_{T\omega} = G'_{T\omega} + G'_{v\omega}(Y'_{sys} + Y')^{-1}G'_{Ti}$$



$$K(s) = G''^{-1}_{T\omega} - Js$$

Unification of State-Space and Transfer-Function Methods

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x}$$

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$$
$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x}$$

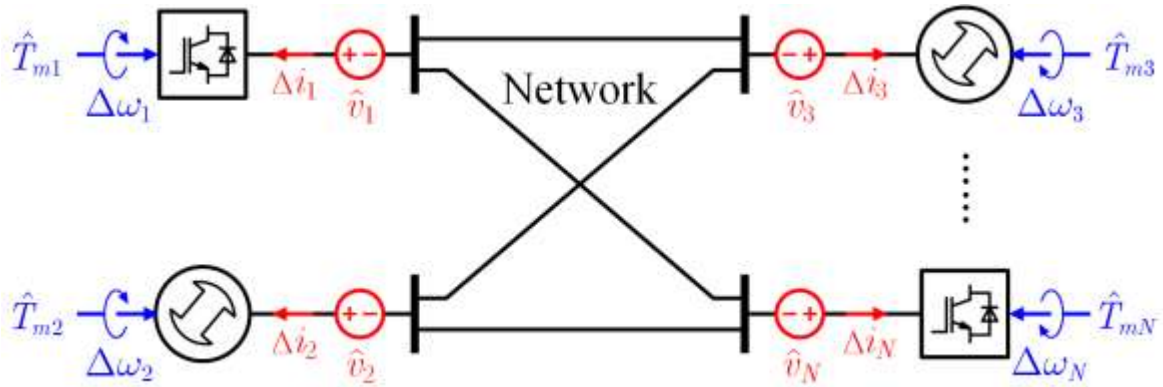
$$\boldsymbol{u} = \begin{pmatrix} \hat{\boldsymbol{v}} \\ \hat{\boldsymbol{T}}_m \end{pmatrix} \quad \boldsymbol{y} = \begin{pmatrix} \Delta\boldsymbol{i} \\ \Delta\boldsymbol{\omega} \end{pmatrix}$$

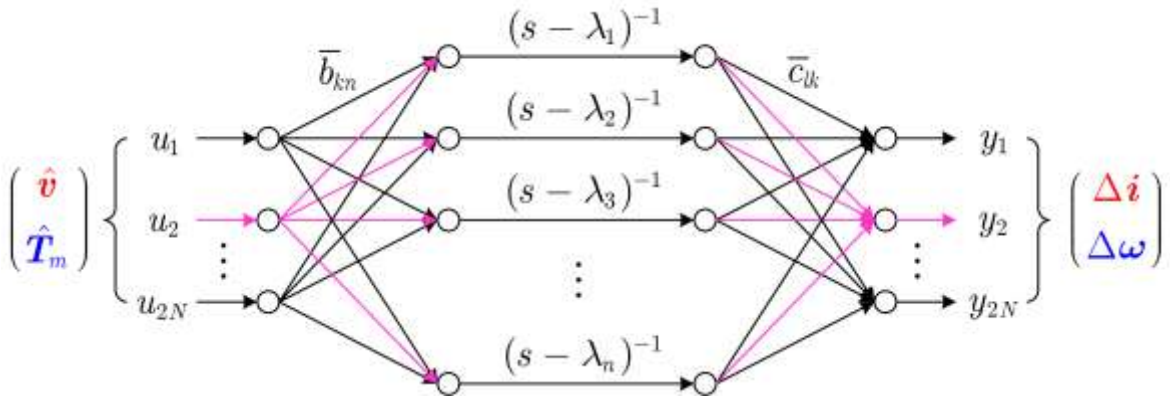
$$\boldsymbol{x} = \boldsymbol{\Phi}\boldsymbol{z}$$

$$\dot{\boldsymbol{z}} = \bar{\boldsymbol{A}}\boldsymbol{z} + \bar{\boldsymbol{B}}\boldsymbol{u}$$
$$\boldsymbol{y} = \bar{\boldsymbol{C}}\boldsymbol{z}$$

$$G_{u_n \to y_l} = \sum_k \frac{\bar{c}_{lk}\bar{b}_{kn}}{s - \lambda_k}$$

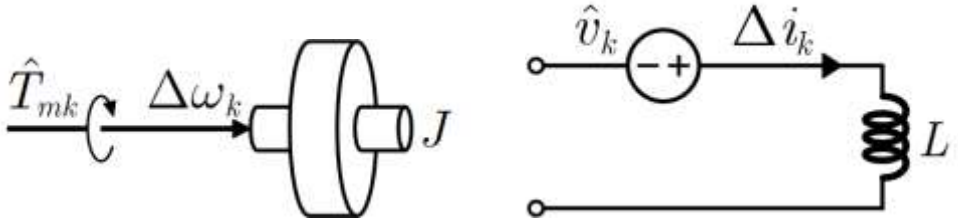
Residue

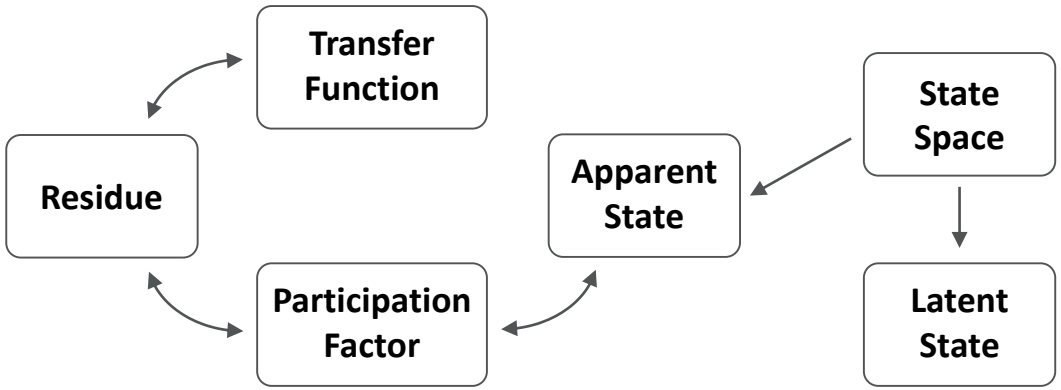




Residue is Participation Factor

Input and output are acting on the same apparent state





Apparent State

$$\begin{cases} \boldsymbol{B}_{:n} = (0, \ldots\ldots, 0, b_n, 0, \ldots, 0)^\top \\ \boldsymbol{C}_{n:} = (0, \ldots\ldots, 0, c_n, 0, \ldots, 0) \end{cases}$$

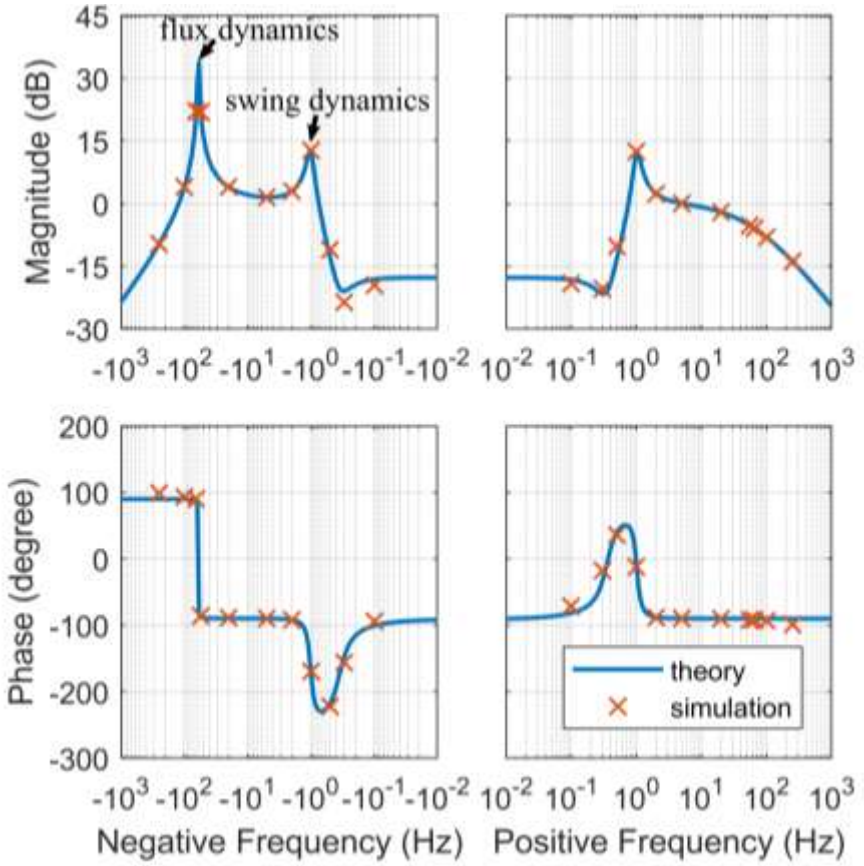
$$\bar{c}_{nk} = c_n \phi_{rk},\ \bar{b}_{kn} = b_n \psi_{kr}$$

$$G_{u_n \to y_n} = \sum_k \frac{\bar{c}_{nk}\bar{b}_{kn}}{s - \lambda_k} = c_n b_n \sum_k \frac{p_{rk}}{s - \lambda_k}$$

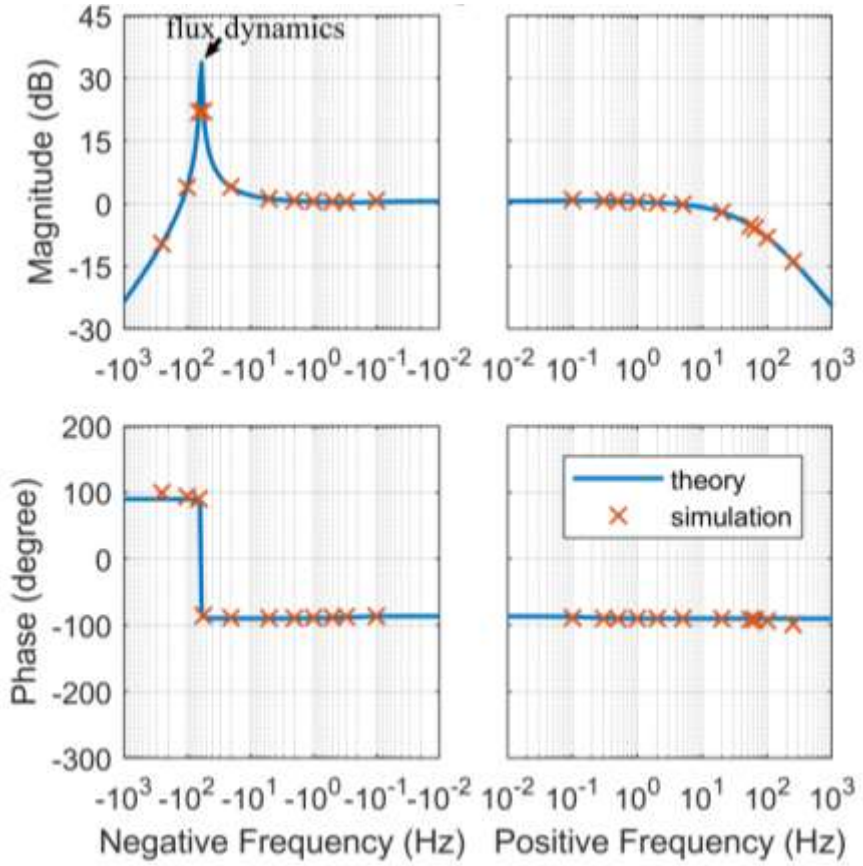
Residue is equivalent to the participation factor !

Example: Synchronous Generator

Y'_{sg} : mechanical dynamics embedded

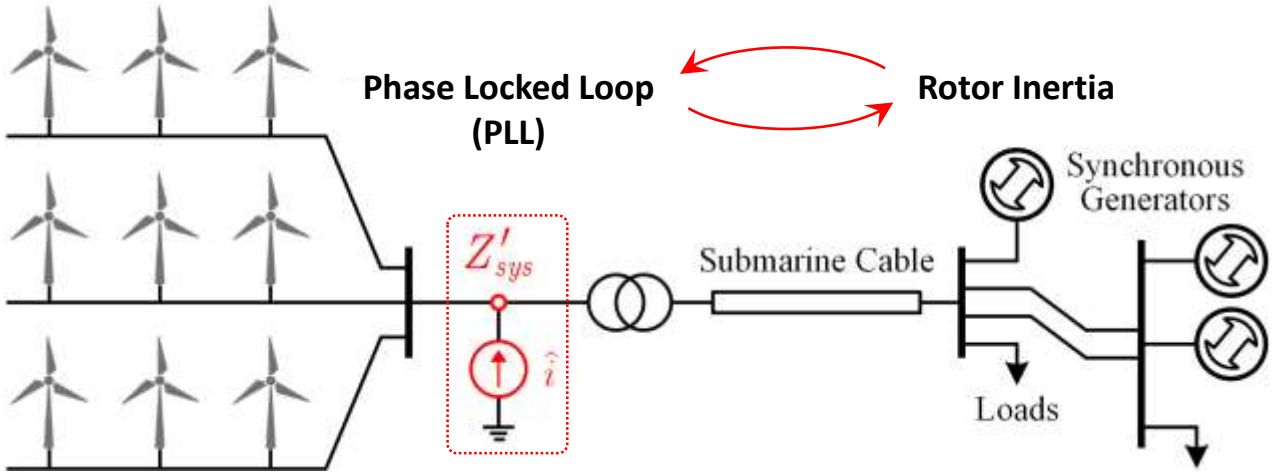


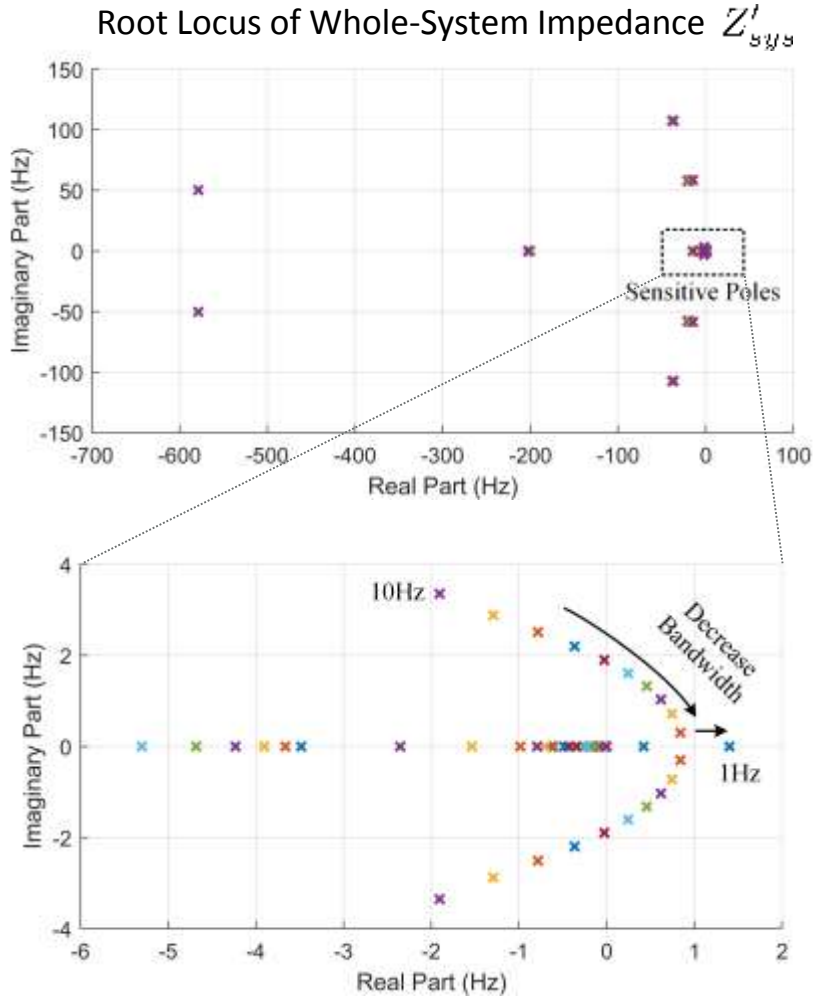
Y_{sg} : mechanical dynamics not embedded



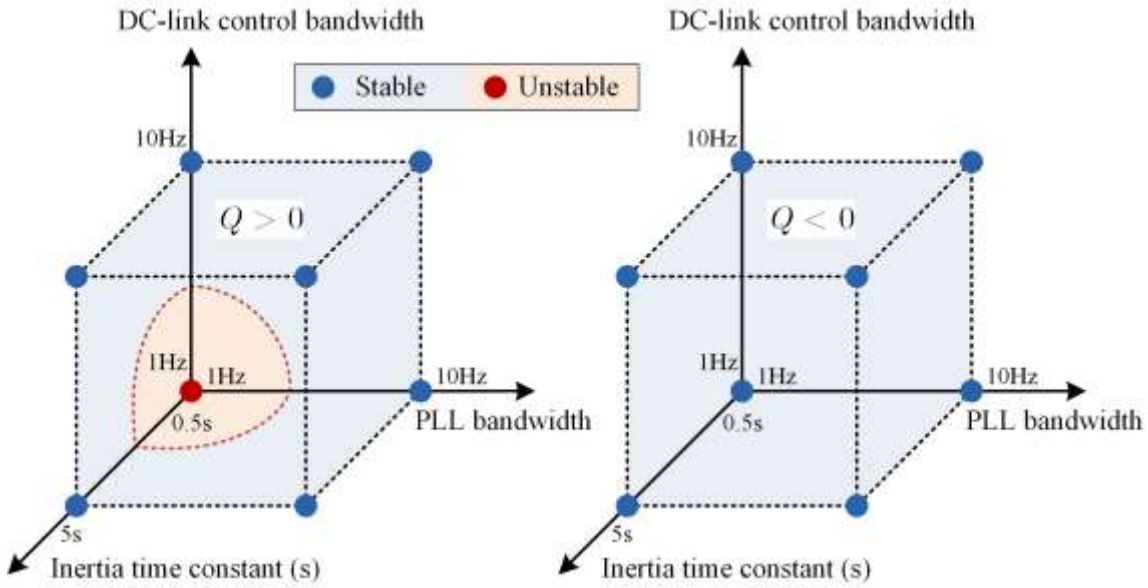
Admittance of a synchronous generator with and without mechanical dynamics reflected

PLL-Inertia Interaction : Z-Representation (Electronic)





PLL-Inertia Interaction : Z-Representation (Electronic)



Impedance of a synchronous generator with mechanical dynamics

$$Z'_{sg} = \overbrace{\begin{pmatrix} Z_L(s_{+1}) & \\ & Z_L(s_{-1}) \end{pmatrix}}^{\text{electronic}} + \overbrace{\frac{1}{M(s)} \begin{pmatrix} s_{+1} & s_{+1} \\ s_{-1} & s_{-1} \end{pmatrix}}^{\text{mechanical}}$$

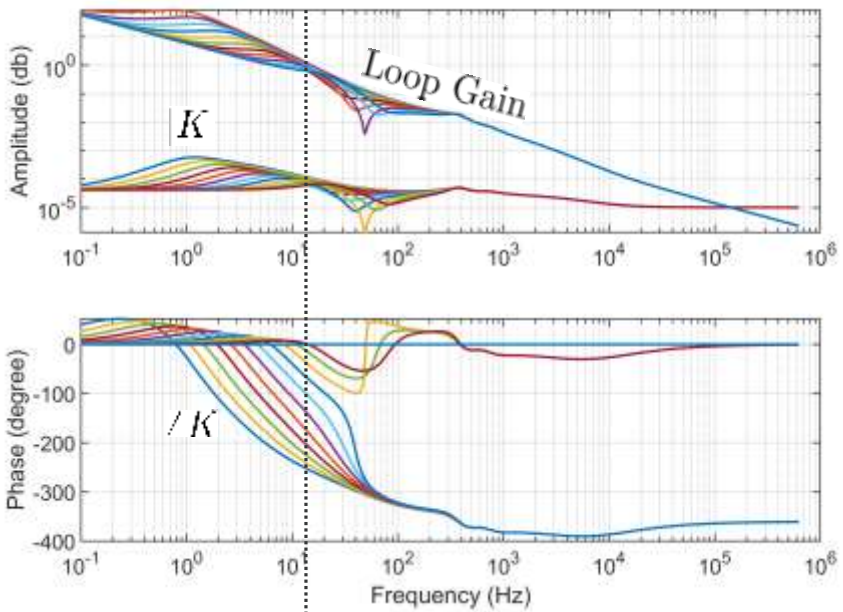
$$M(s) = 2/\psi_f^2 \cdot \left(Js^2 + Ds - i_{q0}\psi_f\right)$$

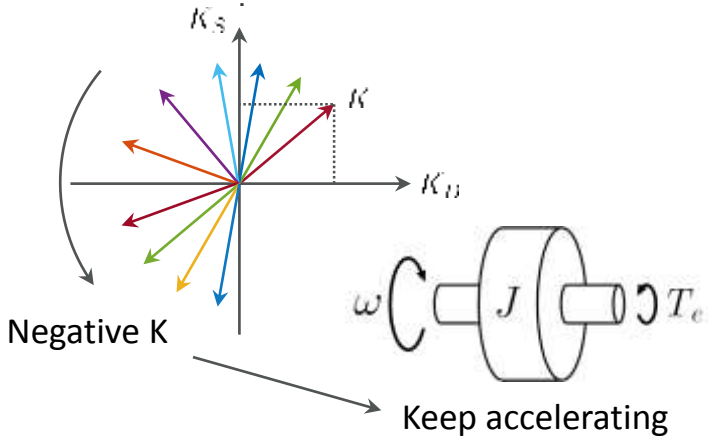
Poles in the right half plane

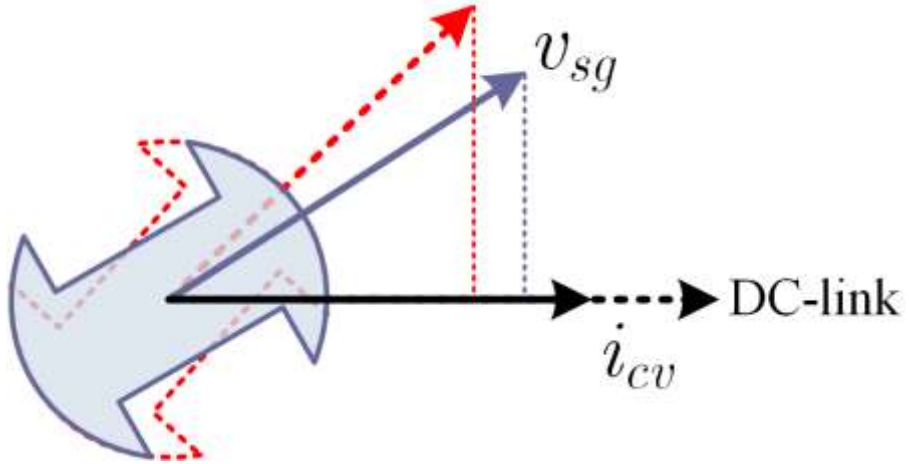
- *Synchronous generator impedance has unstable poles at positive reactive power (over excitation)*
- *Converter ≈ current source when PLL and dc-link control is slower than inertia timescale*

PLL-Inertia Interaction : K-Representation (Mechanical)

Bode Plot of Torque Coefficient K







5Hz	PLL / DC-Link Control	50Hz
Inertia Dynamics (Mechanical)	⟷	Flux Dynamics (Electronic)

Thank You!