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Multi-timescale dynamic issues of power electronised power systems and multi-scale magnitude-phase dynamic theory

POWER ELECTRONICSUK Underpinning Research

EPSRC Pioneering research and skills

Amplitude-Phase Dynamics
A Theory for
Power Electronics Based
Power Systems Dynamics

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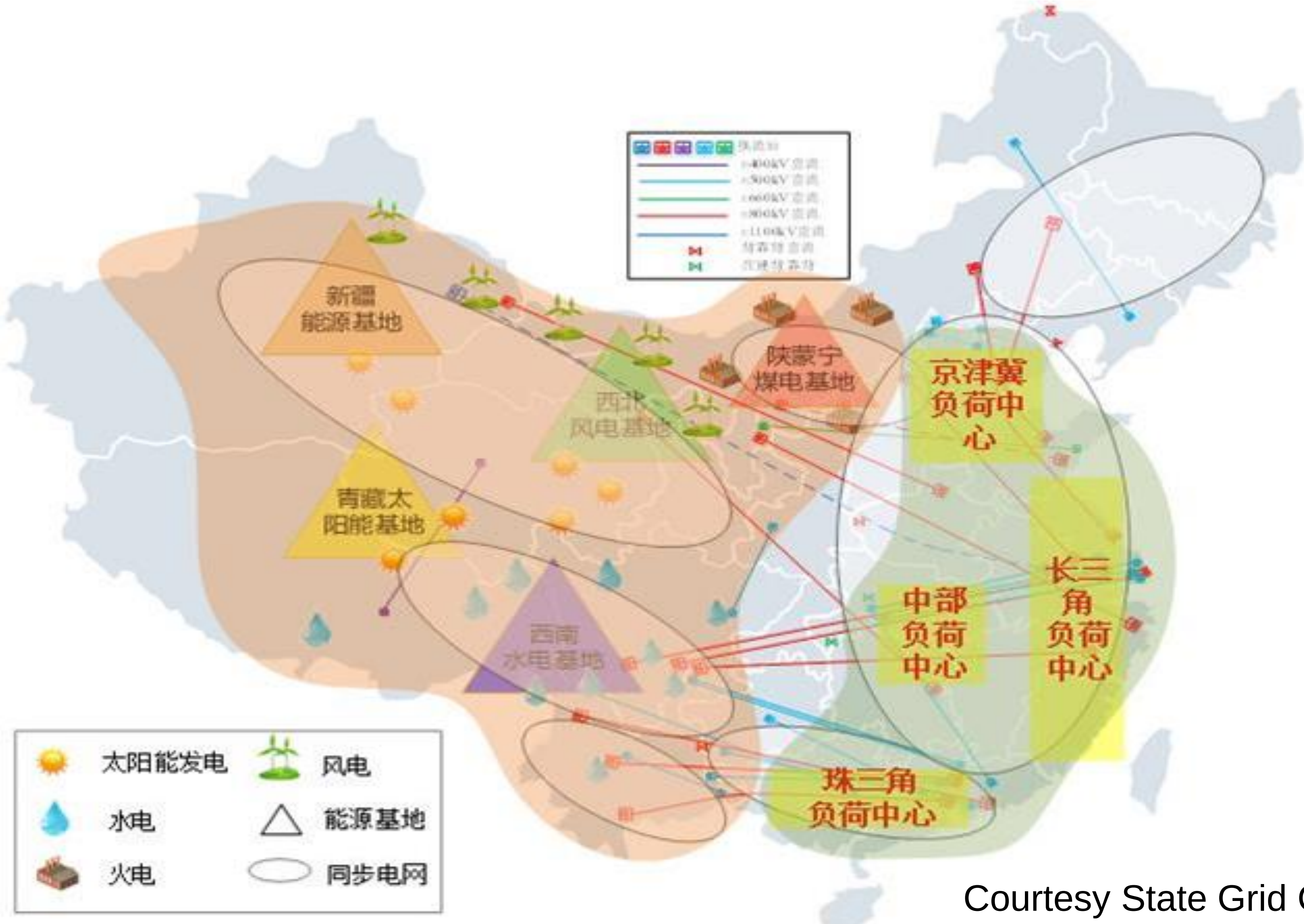
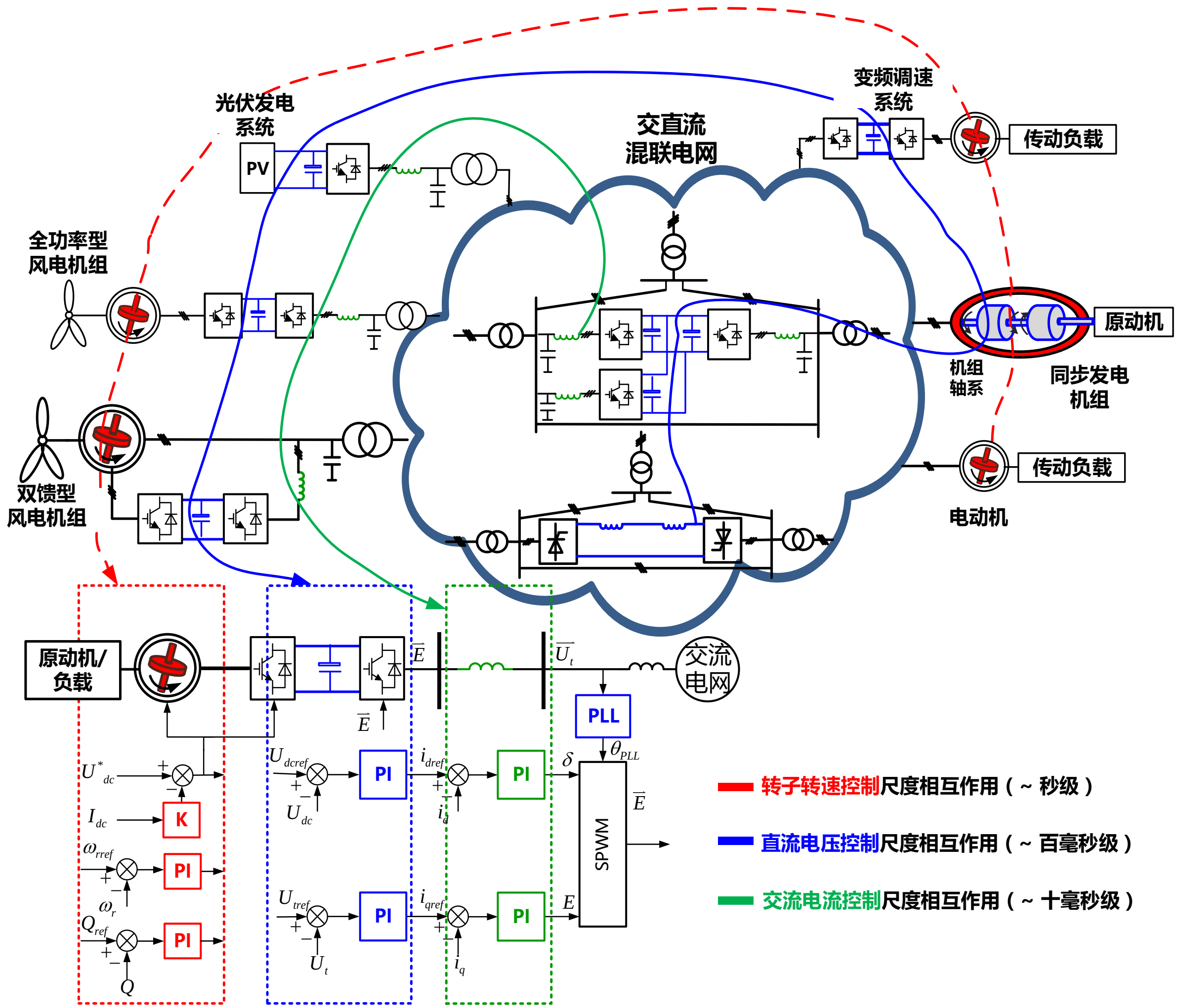
Grid China: Machines to Power Electronics



Courtesy State Grid China

System Dynamics: New Scenario



Dynamical behavior: machines and power electronics

Operating the system: simulation and mechanism

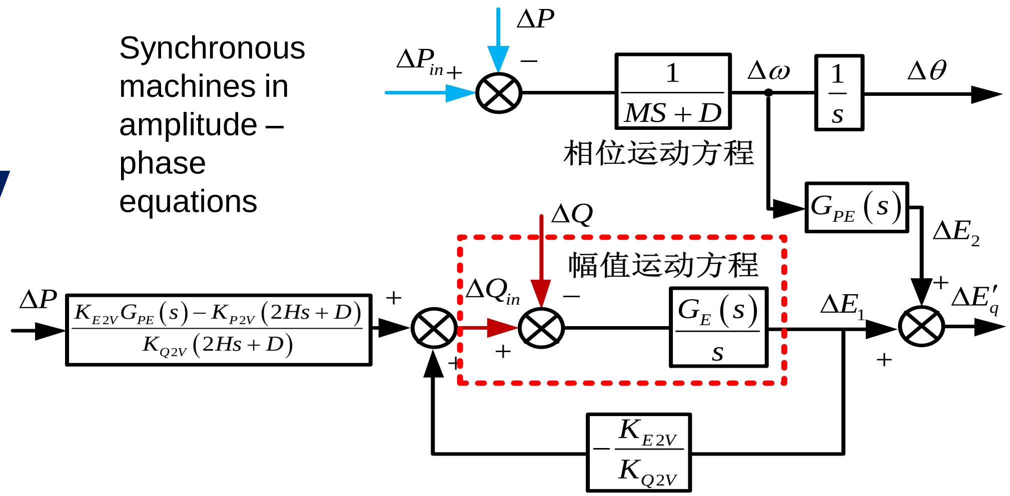
- **Concepts for Understanding Characteristics**

- **Methodologies for Analyzing Dynamics**

Amplitude-Phase Equations for Nodes

Power balancing excitation – internal voltage response key I/O factors

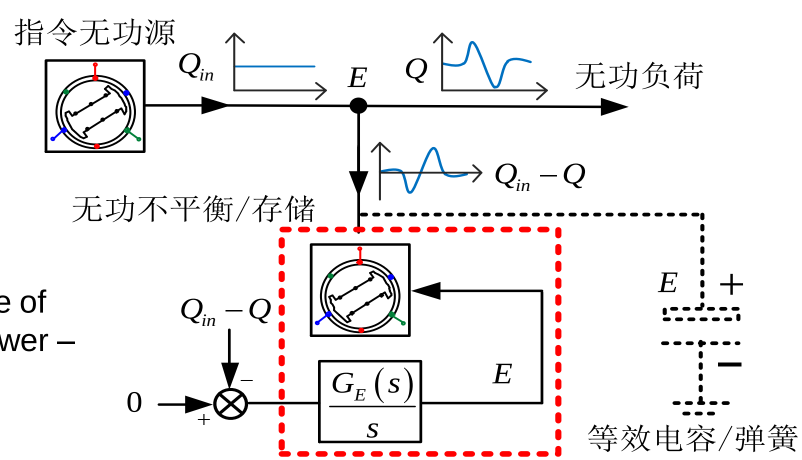
Synchronous machines in amplitude – phase equations



Mathematics and physics (mass/spring/damping) of relations

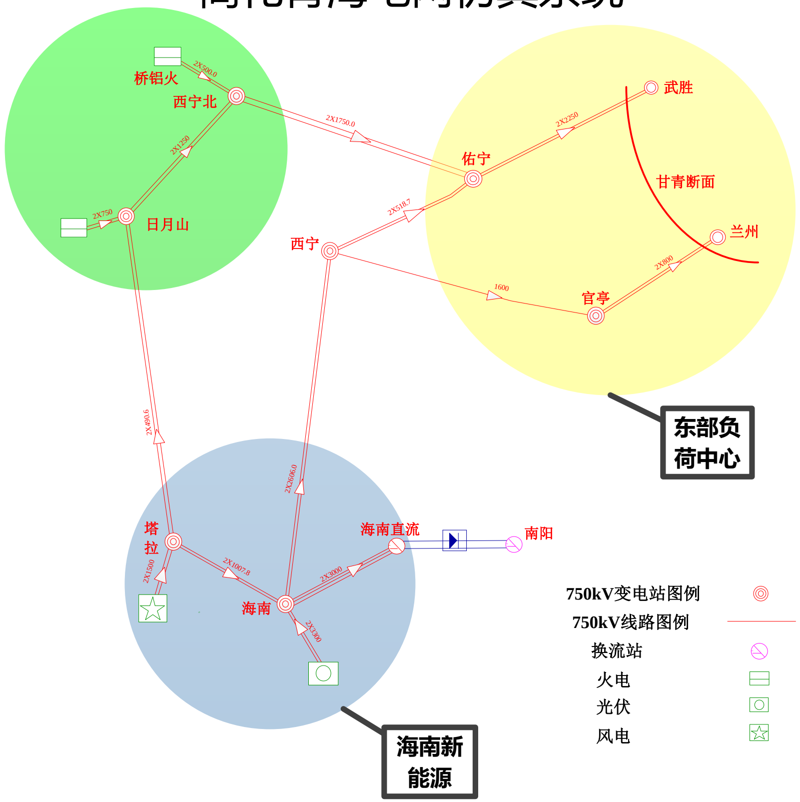
Properties and laws governing the relations

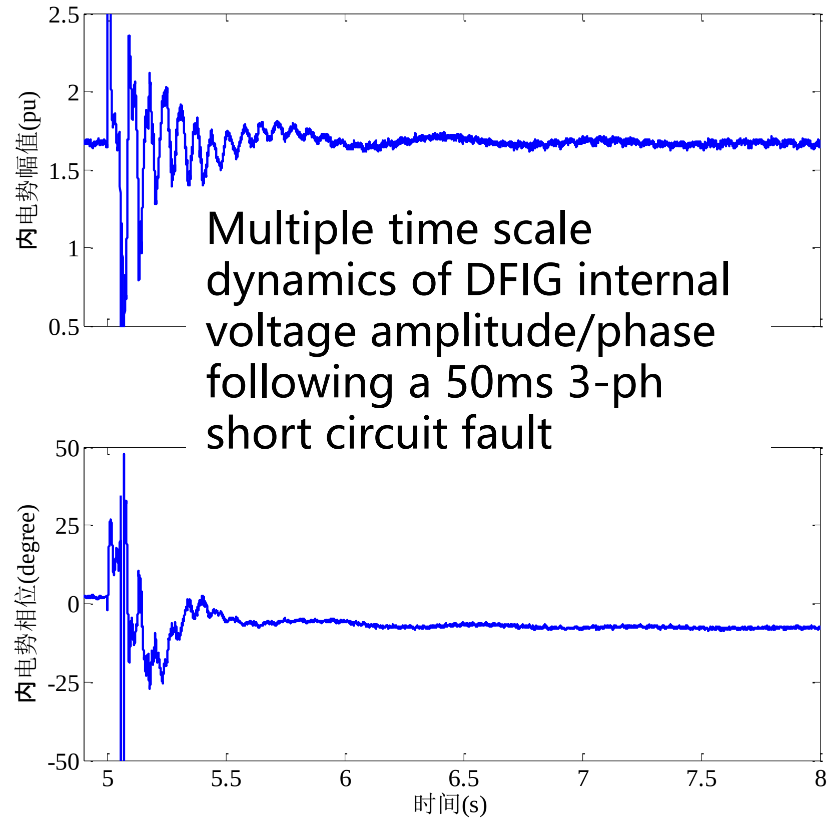
Physical equivalence of reactive power – amplitude relations



Multi-time scale controlled characteristics

简化青海电网仿真系统



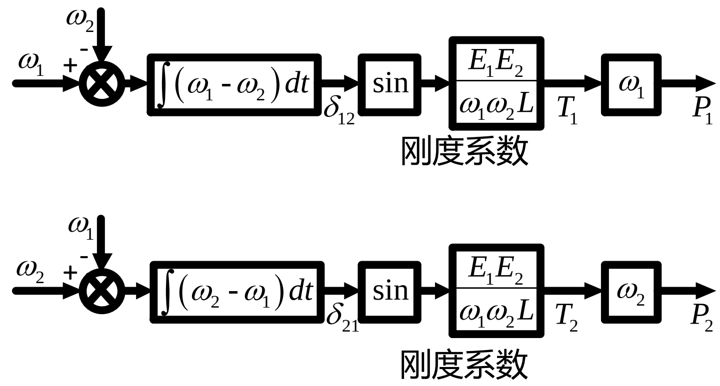


Multiple time scale dynamics of DFIG internal voltage amplitude/phase following a 50ms 3-ph short circuit fault

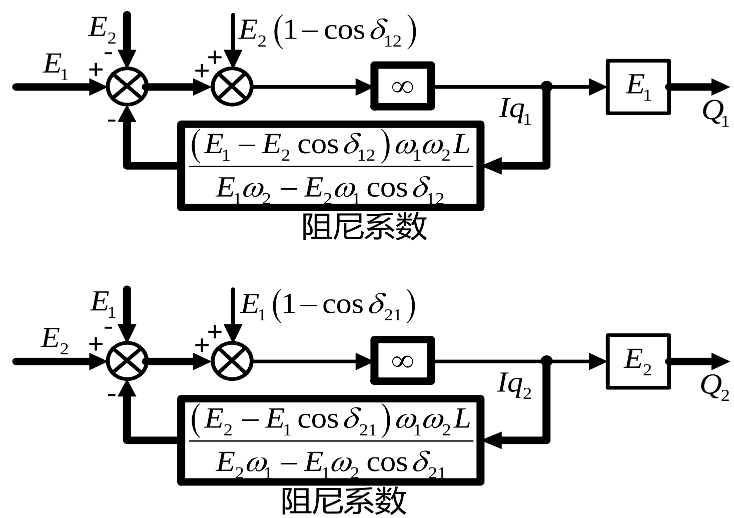
From single time scale, low order, linear, continuous, decoupled system of synchronous machines to multi time scale, high order, non-linear, switching, coupled system of power electronics converters

Amplitude–Phase Equations for Networks

Internal voltage excitation – power balancing response key I/O factors



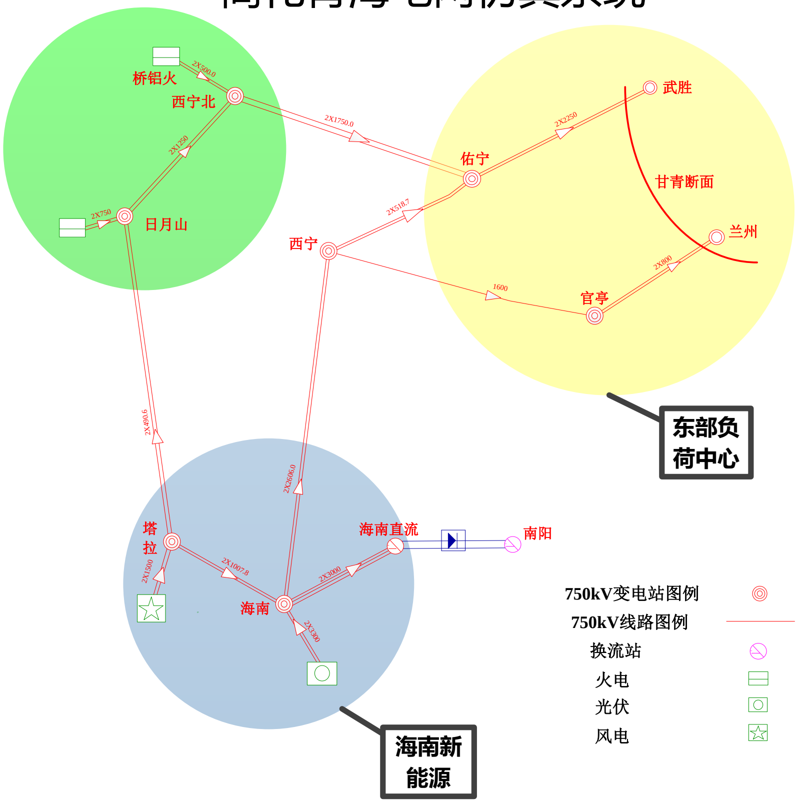
Mathematics and physics (mass/spring/damping) of the relations



Properties and laws governing the relations

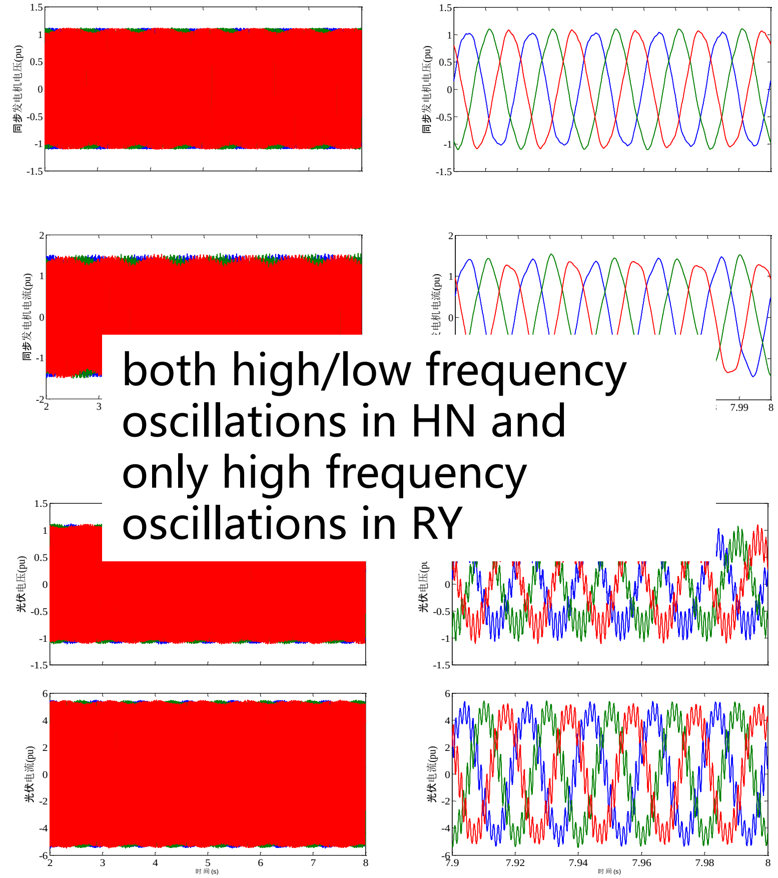
Multi-time scale excited characteristics

简化青海电网仿真系统



节点电压电流波形 日月山火电

节点电压电流波形 海南光伏发电



both high/low frequency oscillations in HN and only high frequency oscillations in RY

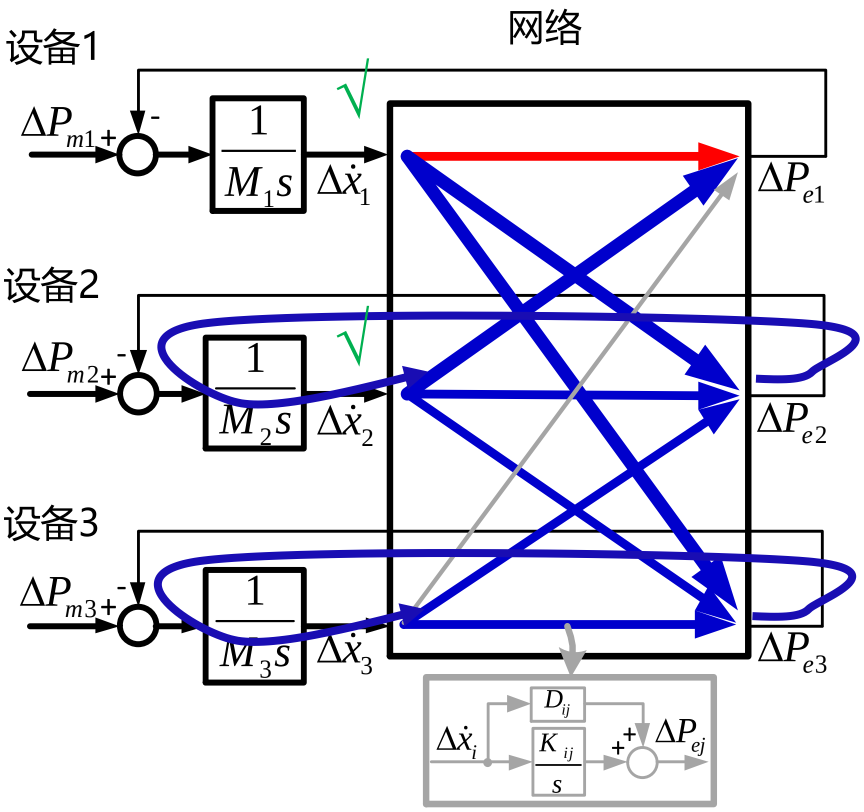
From single time scale, static, nonlinear system under synchronous machine excitation to multiple time scale, dynamic, nonlinear system under power electronics excitation

Stabilization Paths for Interactions

Cross-coupled paths between power balancing and internal voltage of machines

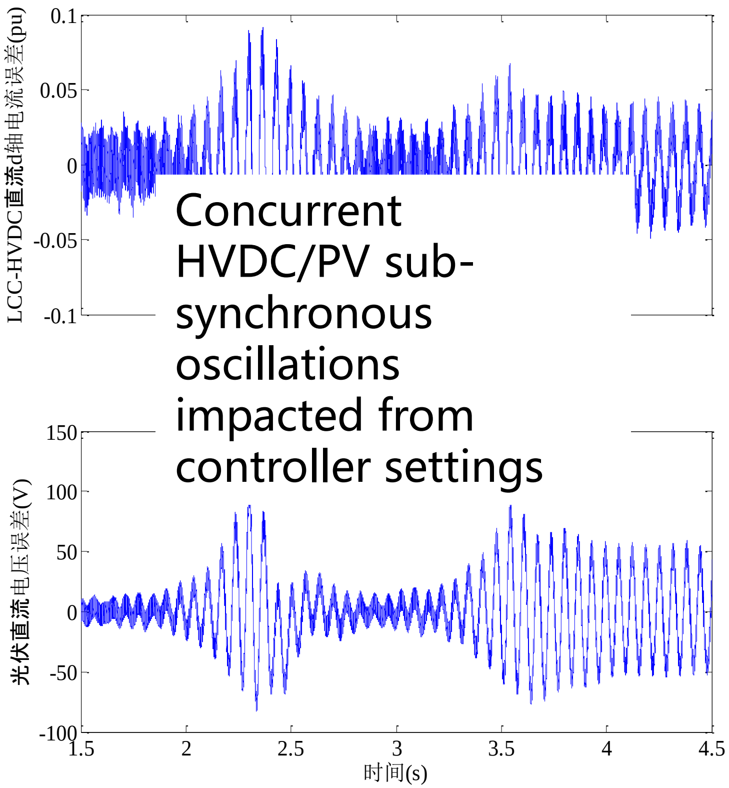
Mathematics and physics of the interaction relations

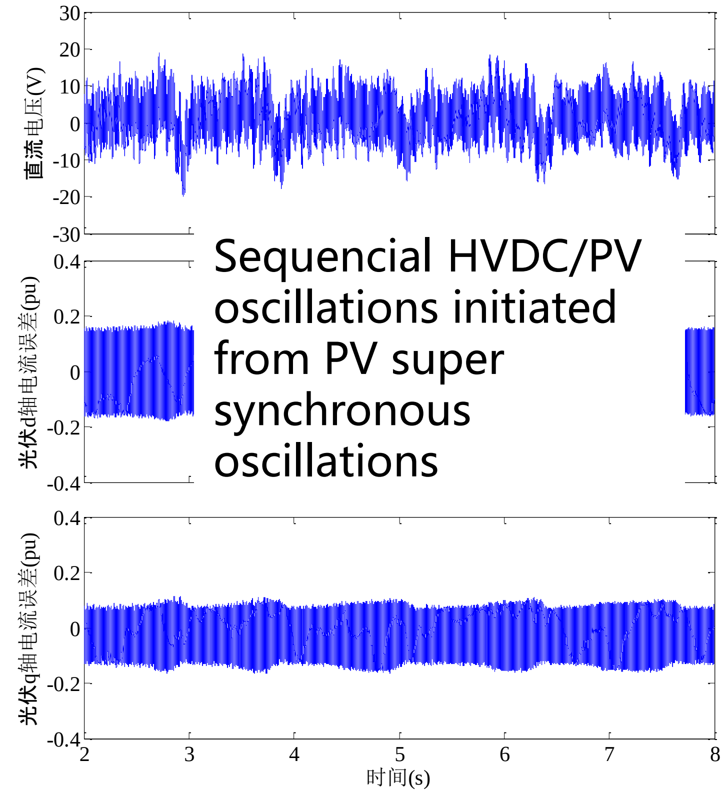
Properties and laws governing the interaction relations



En-stabilizing paths of machine 2 to machine 1 following disturbance to machine 1

Sequencial and Concurrent Interactions





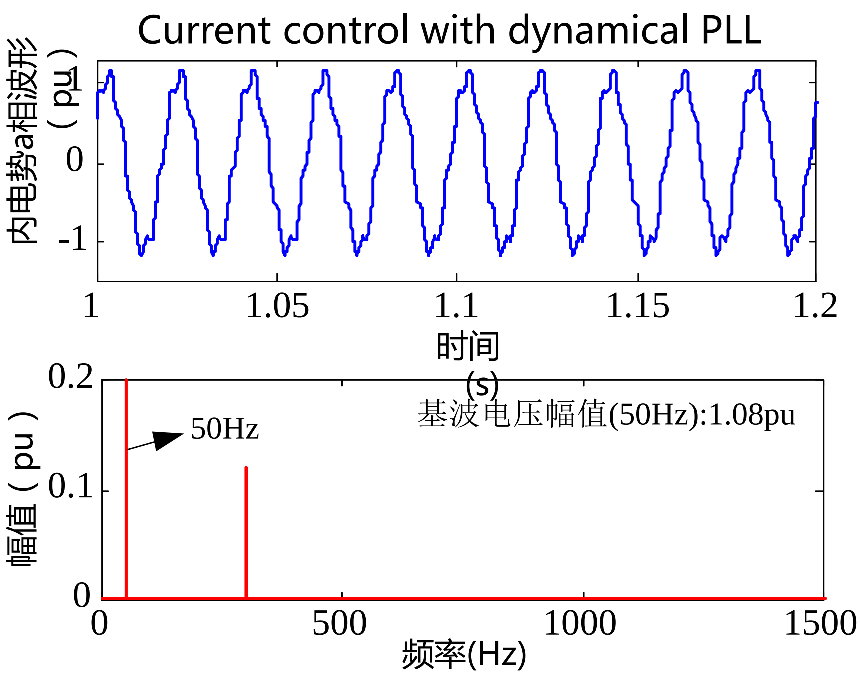
From only intra-time scale concurrent interactions to also inter-time scale sequencial interactions

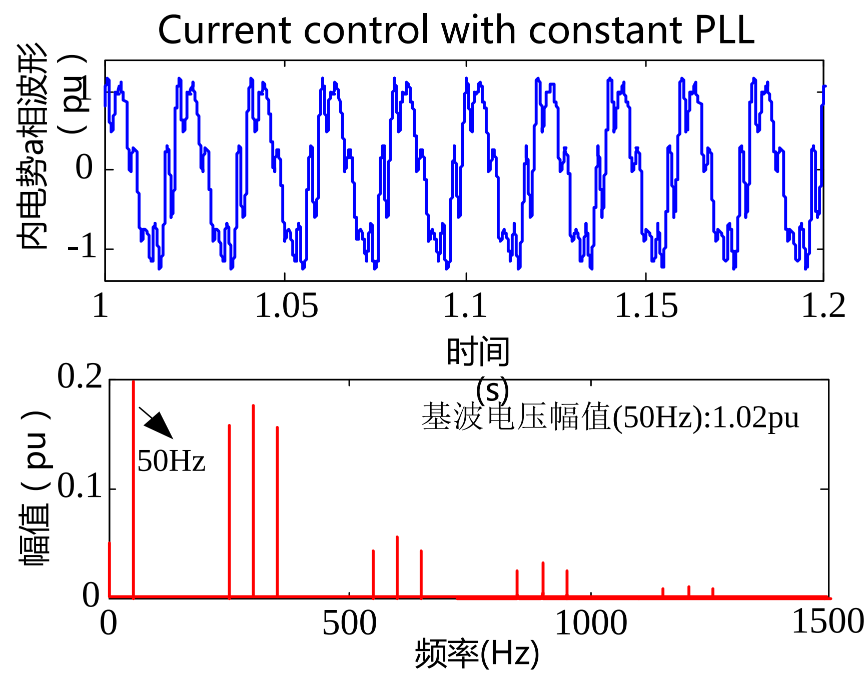
- Concepts for Understanding Characteristics

- Methodologies for Analyzing Dynamics

Modulation vs. Harmonics Linearization

Internal voltage dynamics – harmonics vs. modulation



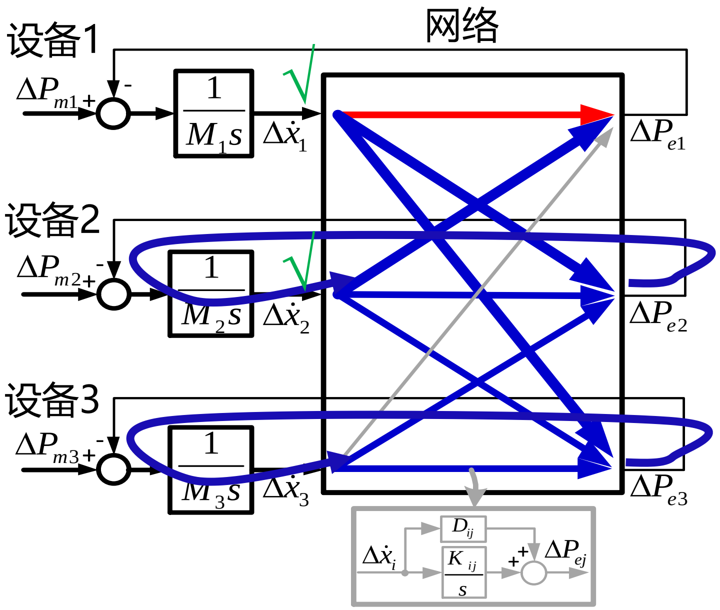


Amplitude/frequency modulated signal – integration/differentiation

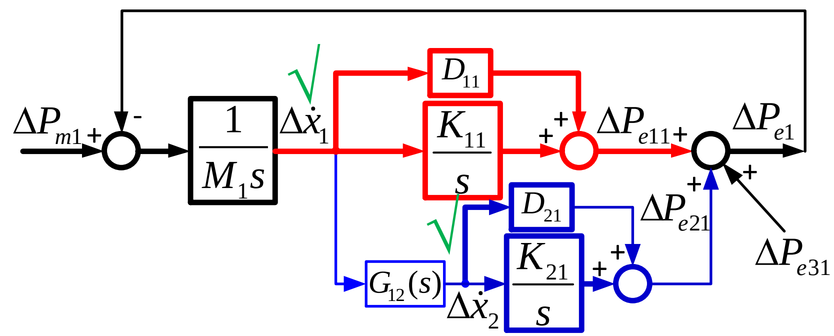
$$\int_{t_0}^{t} A(t)\cos\left(\int \omega(t)dt\right)dt = \int_{t_0}^{t} \frac{A(t)}{\omega(t)} d\sin\left(\int \omega(t)dt\right) = \frac{A(t)}{\omega(t)}\sin\left(\int \omega(t)dt\right)\Bigg|_{t_0}^{t} - \int_{t_0}^{t} \sin\left(\int \omega(t)dt\right) d\frac{A(t)}{\omega(t)}$$

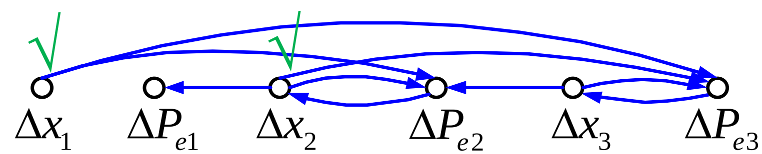
Open Loop Interaction Path Analysis

interaction path of machine 2 to 1
following disturbance to 1



simplified signal flow for a
two-machine system





balancing equation (machine 1)

$$M_1\ddot{x}_1 + \left(D_{11}\dot{x}_1 + \underline{D_{21}\dot{x}_2} + D_{31}\dot{x}_3\right) + \left(K_{11}x_1 + K_{21}x_2 + K_{31}x_3\right) = 0$$

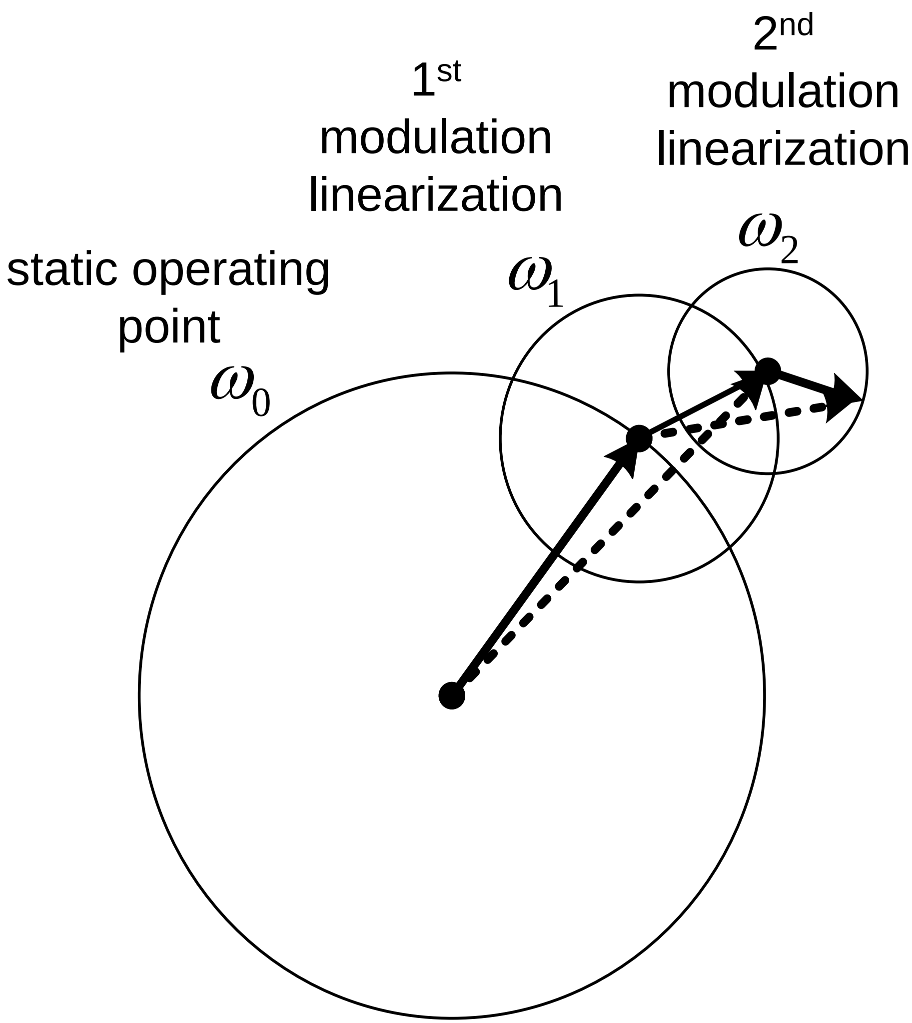
equivalent balancing equation

$$M_1\ddot{x}_1 + \left(D_{11} + \underline{G_{12}(s)D_{21}} + G_{13}(s)D_{31}\right)\underline{\dot{x}_1} + \left(K_{11} + G_{12}(s)K_{21} + G_{13}(s)K_{31}\right)x_1 = 0$$

Iterative Modulation Linearization

Linearize the system at its current operating point when mode from the last linearization twists

Iterative modulation of last linear mode forms non-linear mode of system



Conclusions

Modeling and characterization from structure and mathematics based to function and mechanism based, universal approach to characterize nodes, networks and their interactions in systems

State pattern and linearization from varying sinusoidal and its harmonics to constant amplitude/frequency and its modulation, modulation vs. harmonics linearization, milestone approach for AC systems

MIMO system analysis from matrix/mathematics based oscillation mode analysis to SISO/mechanism based interaction path analysis, toward essence of interactions and roles in system dynamics

Non-linear system analysis from simulation to analytical based solutions, via iterative modulation linearization, milestone foundation to nonlinear system dynamics