

New System Strength Metrics

Prof Tim Green, Dr Yue Zhu

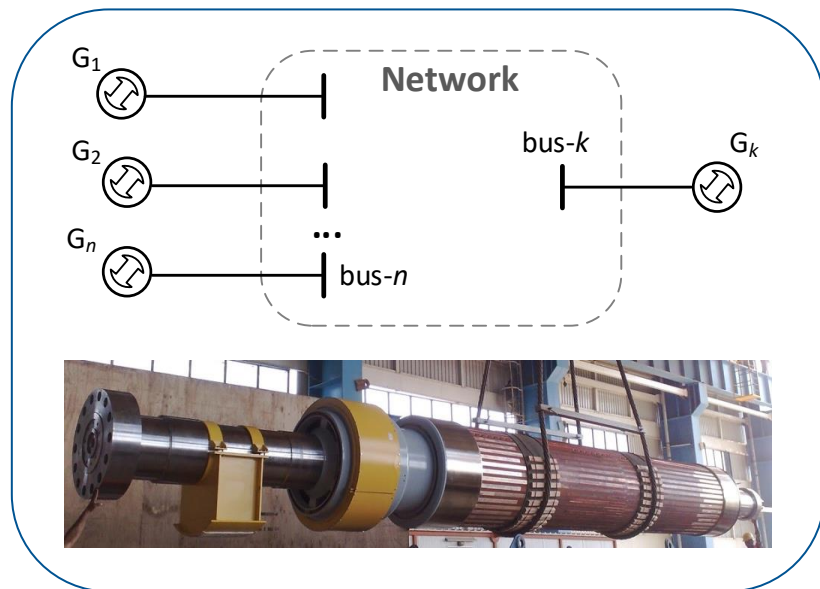
Presenter: Dr Yue Zhu (Research Associate)

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Background

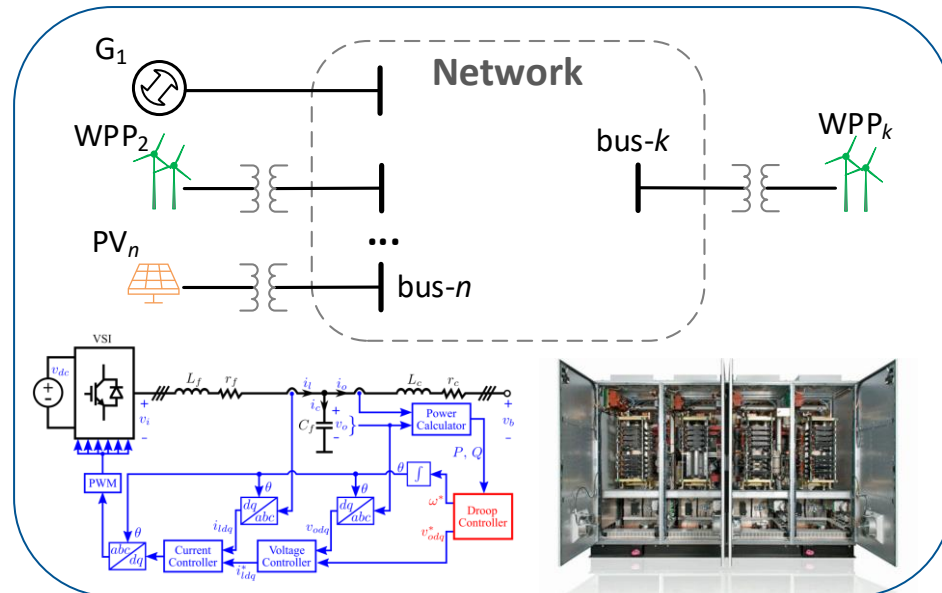
System with Renewables Implemented



Traditional generators: create 50 Hz AC from a rotating electro-magnet. Dynamics are described by well-known physics equations

$$\frac{d^2\delta}{dt^2} = \frac{p}{J} \left(T_{Mech} - \frac{E_S V_G}{\omega_{Rotor} X_S} \sin(\delta) - D \frac{d\delta}{dt} \right)$$

Physically defined behavior

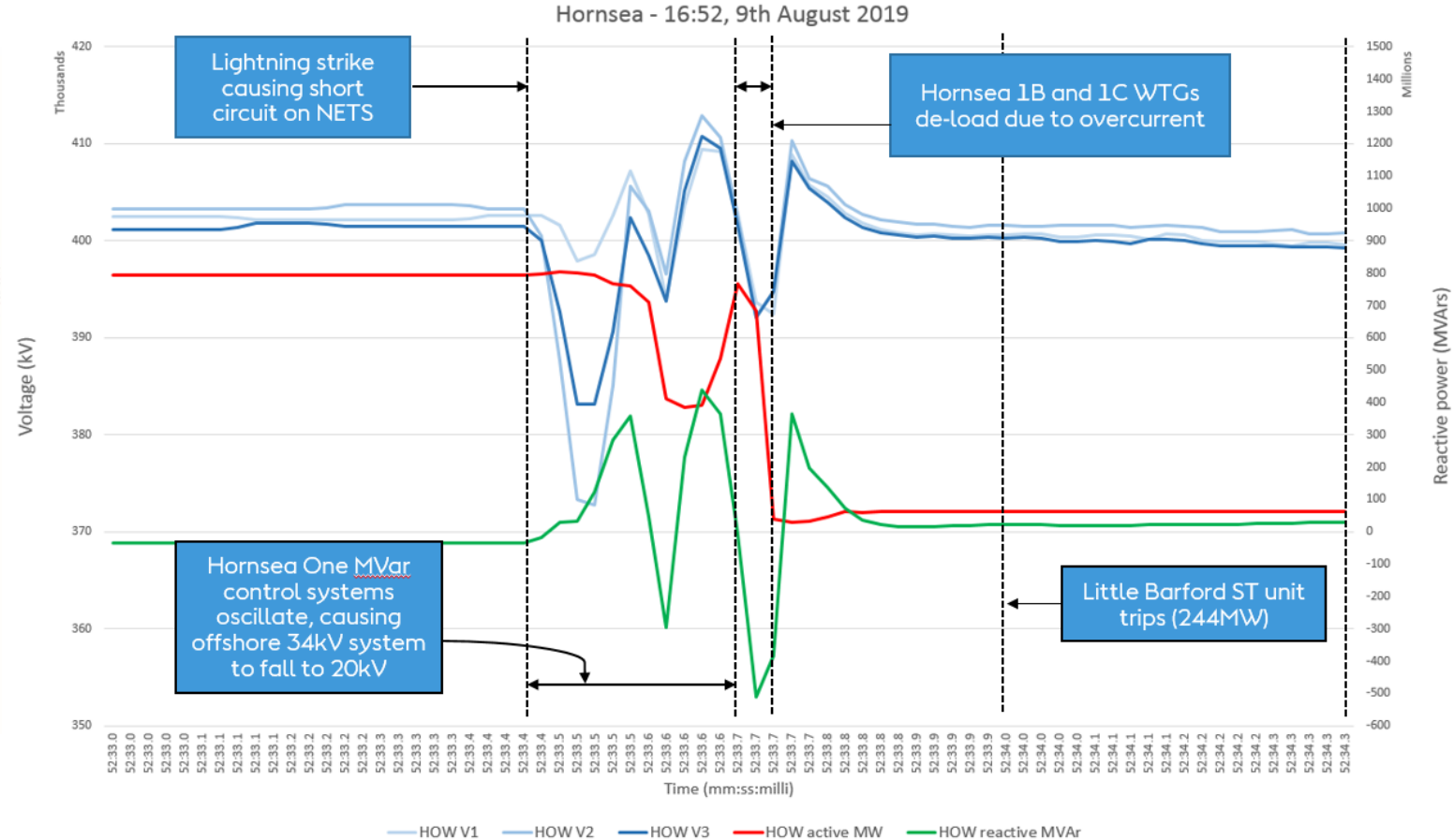
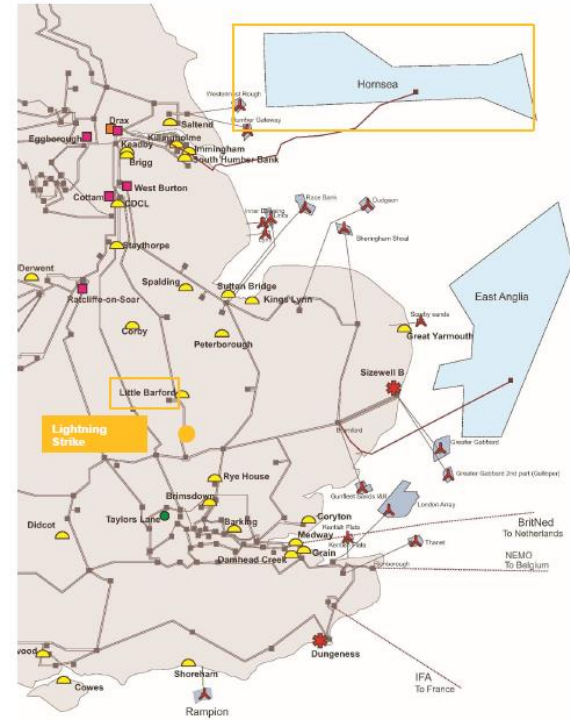


Inverter-based resources (IBR): dynamics are set by control software and behaves differently as traditional synchronous generators.

Control defined behavior

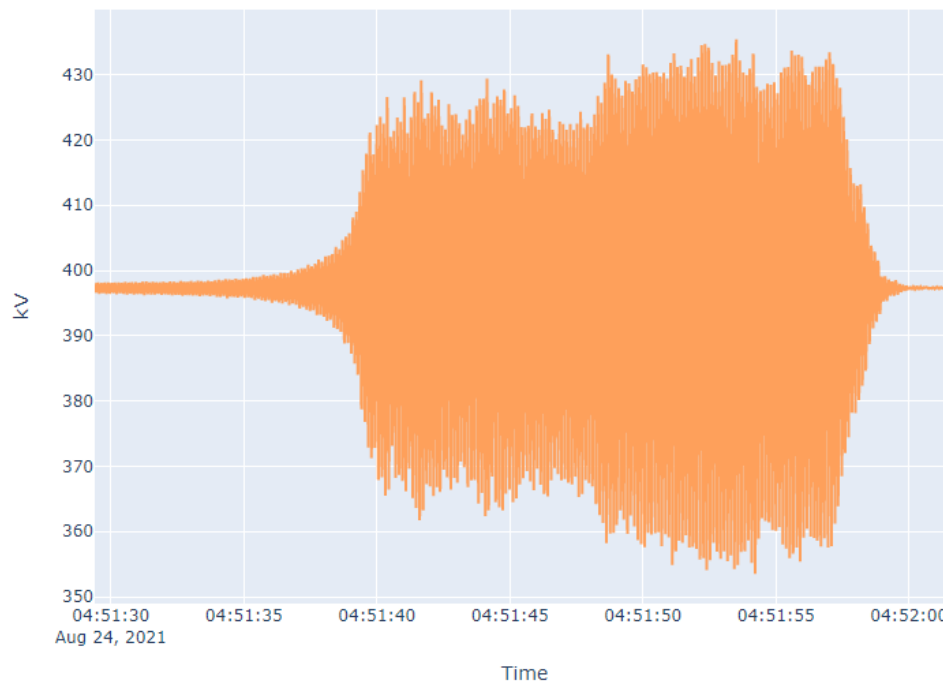
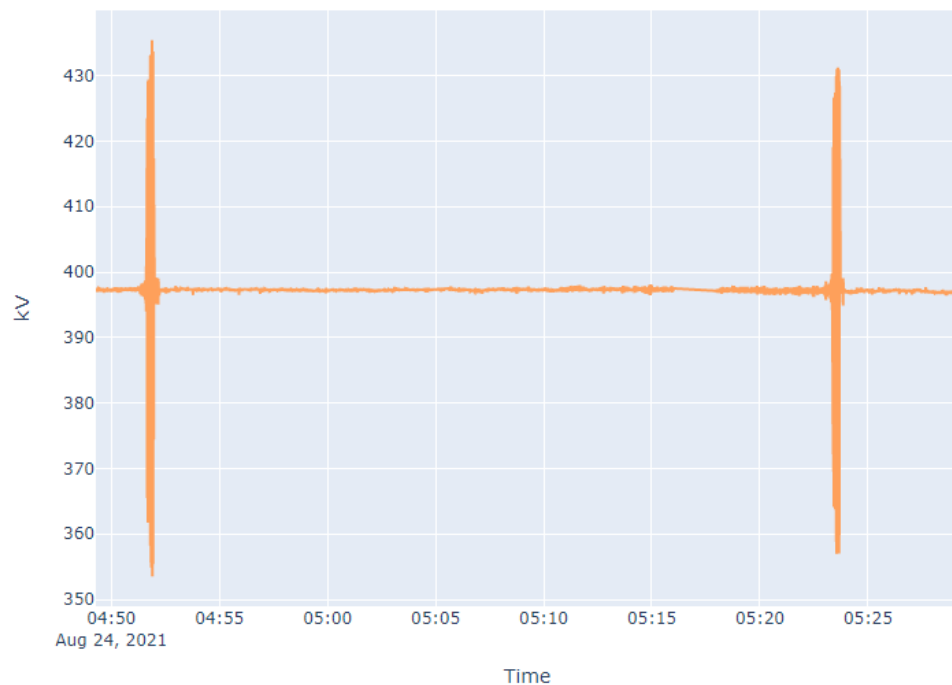


Oscillation at Hornsea Offshore Windfarm: Voltage Instability



Scotland 'Double Heart Attack' with 8 Hz Oscillation

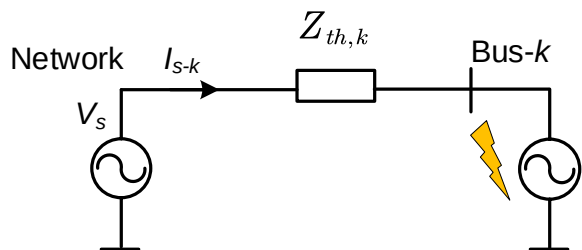
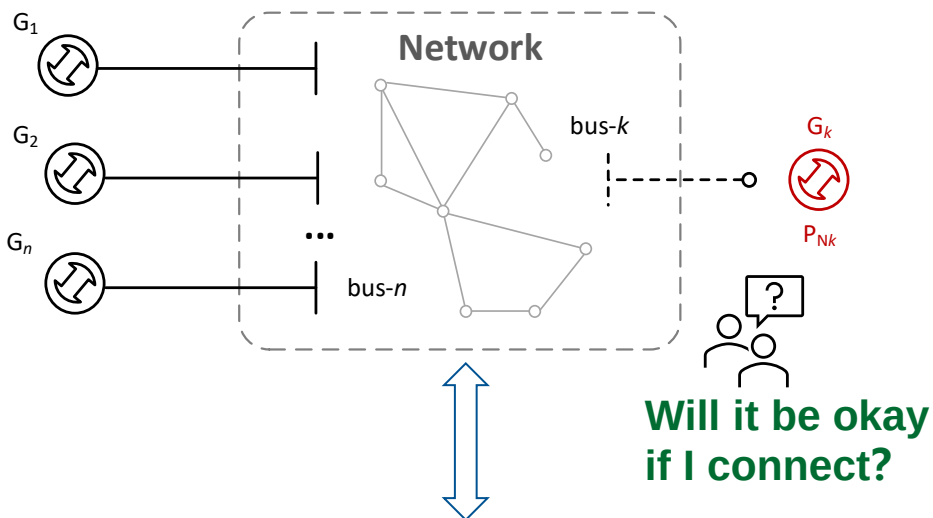
Scotland, two so-called 'heart attacks' occurred in the grid 24/08/2021.
They were induced, it appears, by progressively increasing renewable output.
Some users were tripped off during the disturbance.



Grid Strength

Strength to Connect: Short Circuit Ratio (SCR)

Grid Strength ↔ Connectivity



$Z_{th,k}$: Thevenin impedance of bus-k, the equivalent impedance seen from bus-k.

Short-circuit capacity (SCC):
$$SCC_k = \frac{|V_s|^2}{|Z_{th,k}|}$$

Short-circuit ratio (SCR):
$$SCR_k = \frac{SCC_k}{P_{Nk}} = \frac{1}{|Z_{th,k,p.u.}| \cdot P_{Nk,p.u.}}$$

SCR of bus-k is defined as the ratio between the SCC (the maximum power that the system can supply to this bus during a fault) and the rated power of the device connected to bus-k, thus refers to the (voltage) strength of a bus to connect a device.

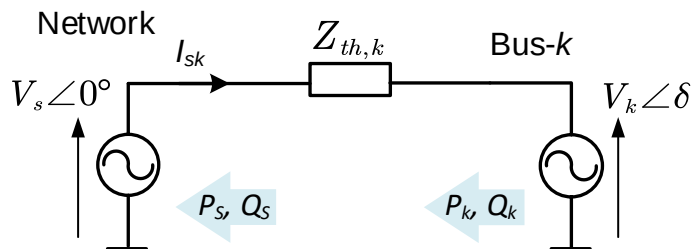
Per unit symbol will be omitted for following discussion for simplicity.

Larger SCR → better strength

- **SCR > 5 : strong**
- **3 < SCR < 5: weak**
- **1 < SCR < 3: very weak**

Understanding SCR from a Power or Impedance Perspective

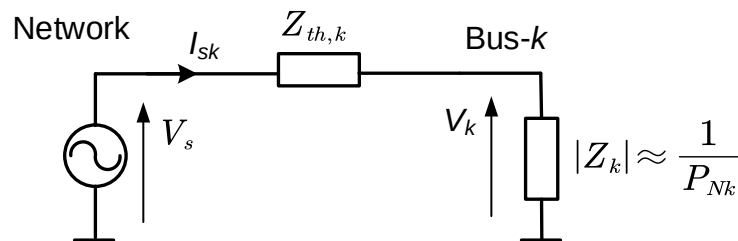
A voltage source trying to deliver it's nominal power



Impedance equivalence for
operation at rated power



A current source / load at nominal power trying to maintain the bus voltage



- When $\delta = -90^\circ$, the system reaches the maximum absorbable power

$$P_{kMAX} \approx \frac{1}{|Z_{th,k}|}, \quad SCR = \frac{P_{kMAX}}{P_{Nk}}$$

- When $|Z_k| < |Z_{th,k}|$, the voltage at bus-k will collapse.

$$|Z_k|_{MIN} = |Z_{th,k}|, \quad SCR = \frac{|Z_k|}{|Z_k|_{MIN}}$$

$$SCR = \frac{1}{|Z_{th,k}| \times P_{Nk}}$$



Power

$$\frac{P_{kMAX}}{P_{Nk}}$$



Impedance

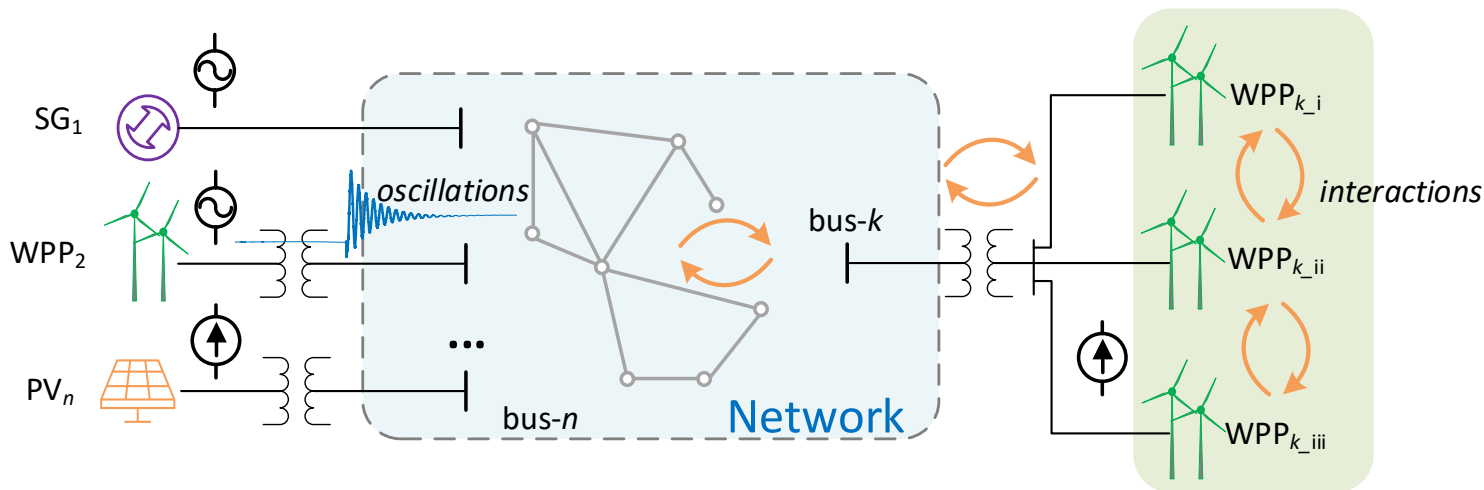
$$\frac{|Z_k|}{|Z_k|_{MIN}}$$



Admittance

$$\frac{|Y_k|_{MAX}}{|Y_k|}$$

Challenge for “Strength to Connect”



Control-defined behavior of
IBR & tight constraints

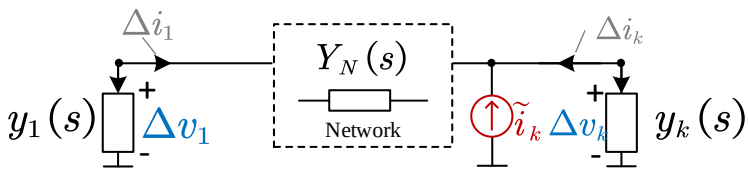


Reducing grid (voltage) strength

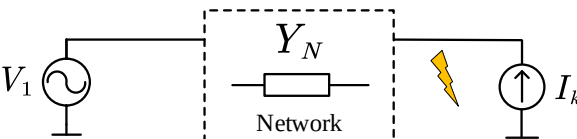
- Emerging problems:
 - inadequate voltage regulation,
 - increased recovery times from voltage dips,
 - potential instability of grid-following inverters, and
 - mal-operation of protection.
- SCR is no longer a good all-purpose indicator

Classification of the New Grid Strength Metrics

Small-signal Strength



Large-signal Strength



Features

- **Small perturbations** around operation point
- Frequency-domain analysis
- Analysis In **small-signal** scope

Targets

- Potential instability caused by inverters, and small-signal interactions among inverters

Explorations

- Grid strength impedance metric (GSIM) [University of Strathclyde]
- Small-signal generalized short-circuit ratio (gSCR) [Zhejiang University]
- **Impedance Margin Ratio (IMR)**

- **Large perturbations**
- Fundamental frequency analysis, 50 Hz or 60 Hz
- A further **extension of SCR**

- Interactions among IBRs
- Increased recovery times from voltage dips,
- low fault current,
- inadequate voltage regulation,
- mal operation of protection.

- Composite short-circuit ratio (CSCR)
- Weighted short-circuit ratio (WSCR)
- Equivalent short-circuit ratio (ESCR)
- Site-dependent short-circuit ratio (SDSCR)
- **Type-dependent short-circuit ratio (TDSCR)**

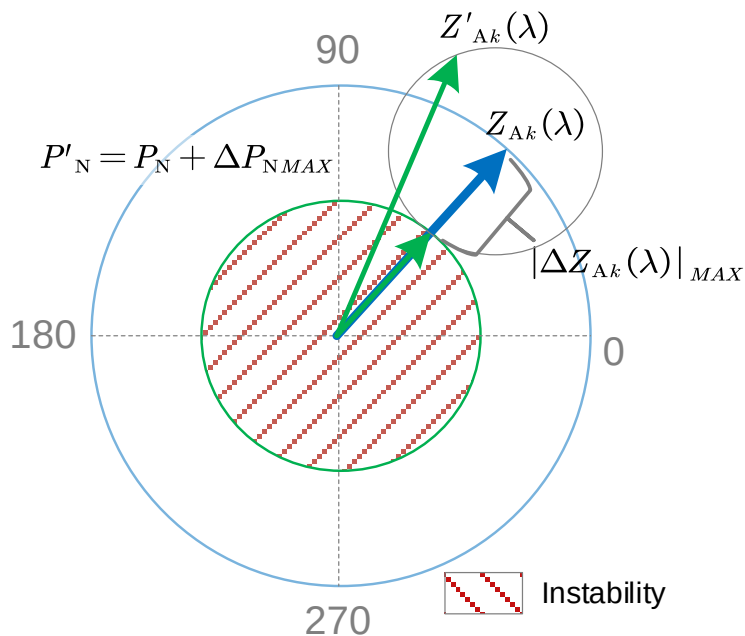
Small-Signal Strength

Impedance Margin Ratio: IMR

$$IMR = \frac{1}{1 - \frac{|\sigma|}{|Re[\langle -Res_{\lambda}^* Y_{kk}^{sys}, Z_{Ak}(\lambda) \rangle]|}}$$

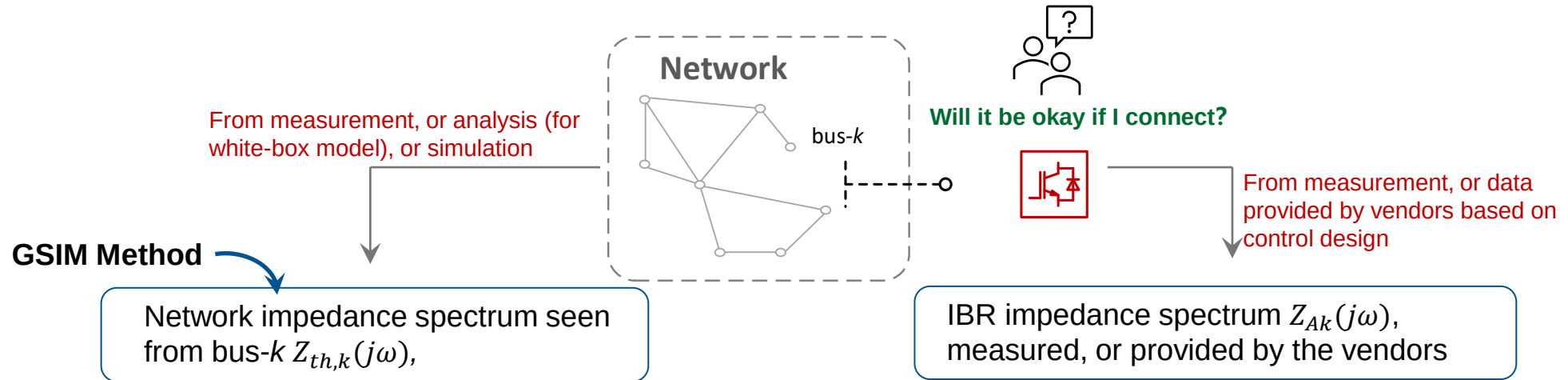
We also have Admittance Margin Ratio (AMR), which is equivalent to IMR with same values

IMR refers to the ratio between the maximum allowable nominal power (for which mode λ remain in LHP) and the nominal power. Small-signal strength at bus- k is determined by its minimum IMR.



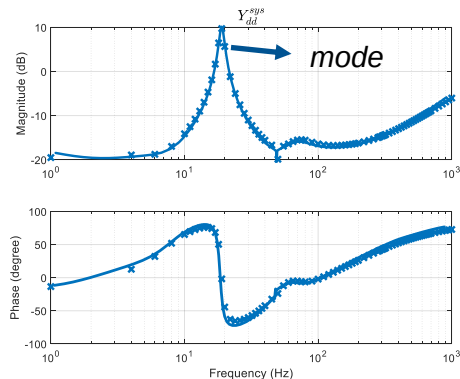
- A large IMR means the mode is relatively insensitive to the connected apparatus.
- $IMR > 1$ is required for stability system, which is aligned with SCR.
- IMR is based on small-signal analysis, hence is only valid in a small range around an operation point.
- For assessment over a large range, it needs to be used iteratively.

IMR Application: Strength to Connect



Assembly of Spectrum

$$Y_{kk}^{sys}(j\omega) = (Z_{th,k}(j\omega) + Z_{Ak}(j\omega))^{-1}$$



$$Y_{kk}^{sys}(s) = \sum_{i=1}^m \frac{R_{ki}}{s - \lambda_i}, \quad \xrightarrow[\text{Residues}]{\text{Poles}}$$

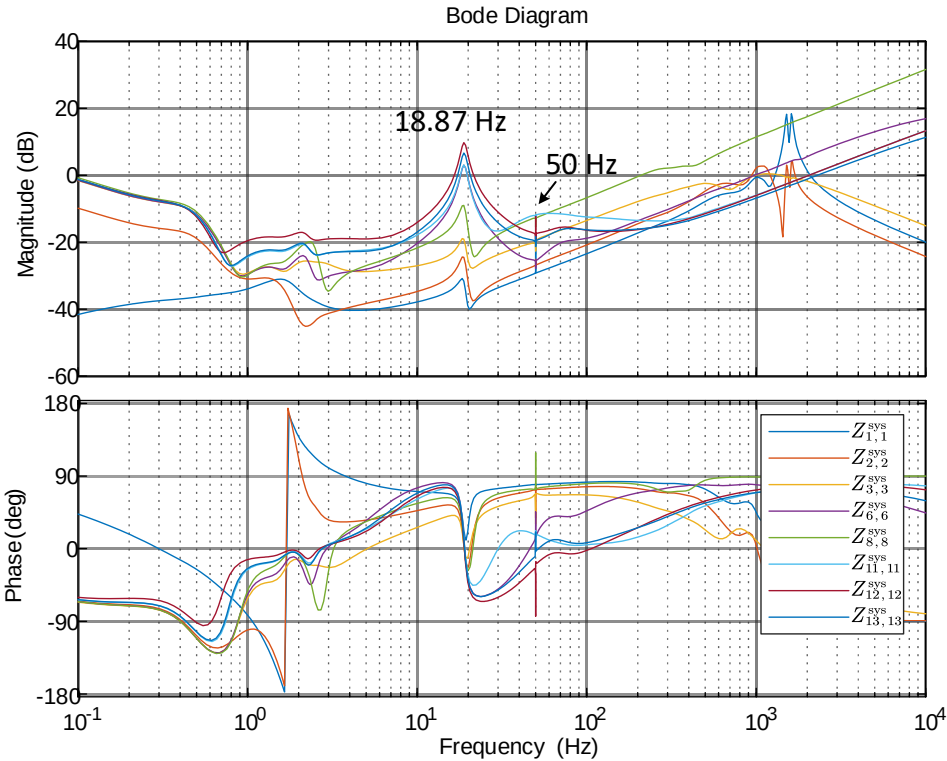
**Modes
& IMR**

Will new bad modes be created after connection? – *Interactions with other IBRs*

Small IMR? – *Strength of point of interconnection*

IMR Application to Identification of Weak Points

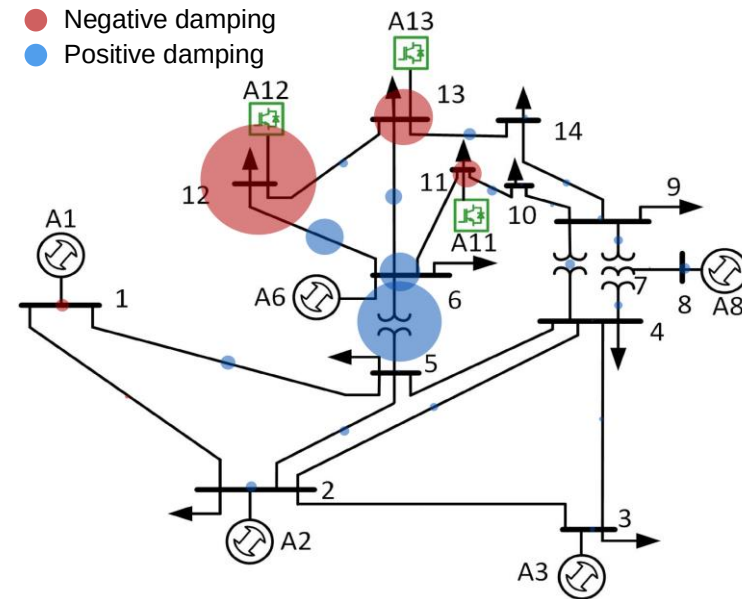
Whole-system Analysis



IMR / AMR analysis



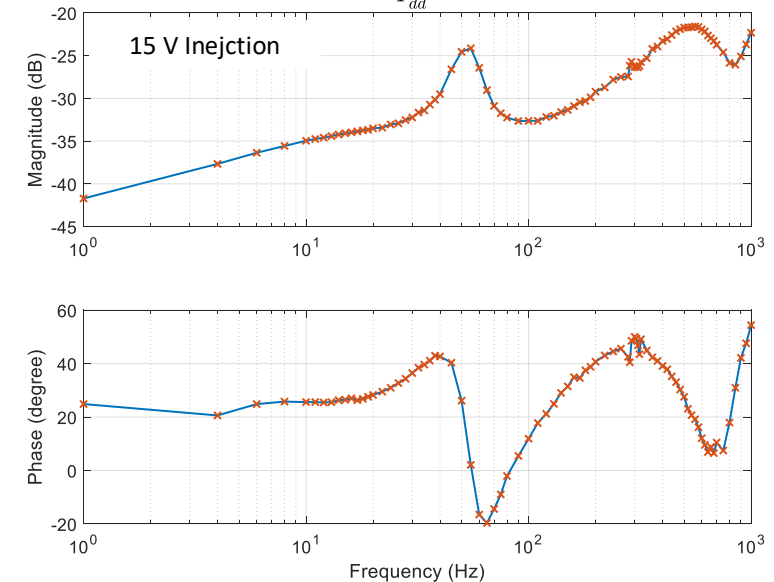
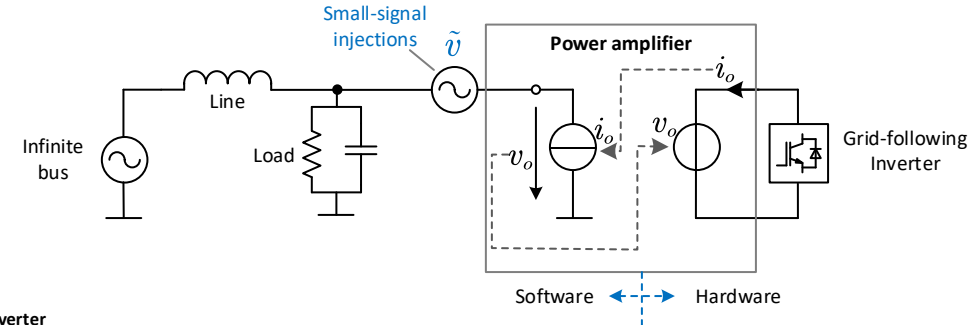
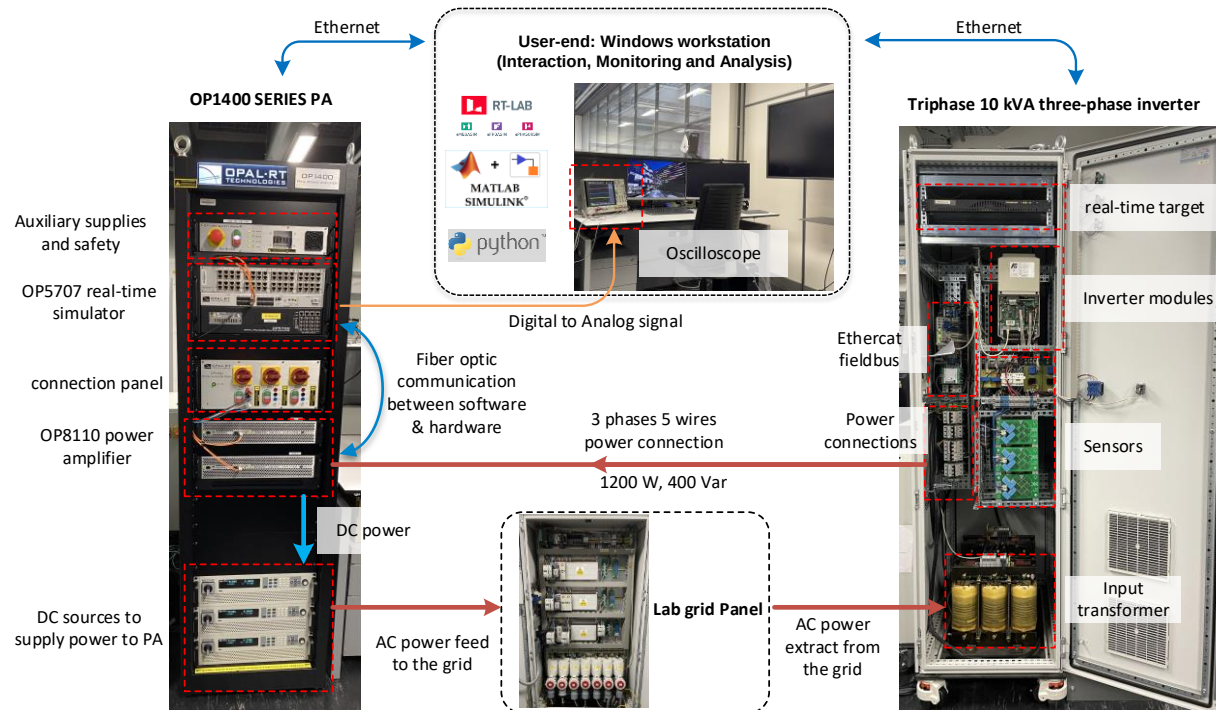
Grey-box approach



Validation of On-line (Real-Time) Monitoring

Power Hardware-in-the-loop (PHIL) platform based on OP1400 series power amplifier used for on-line impedance measurement verification[2].

Maurice Hancock Lab, Imperial College London



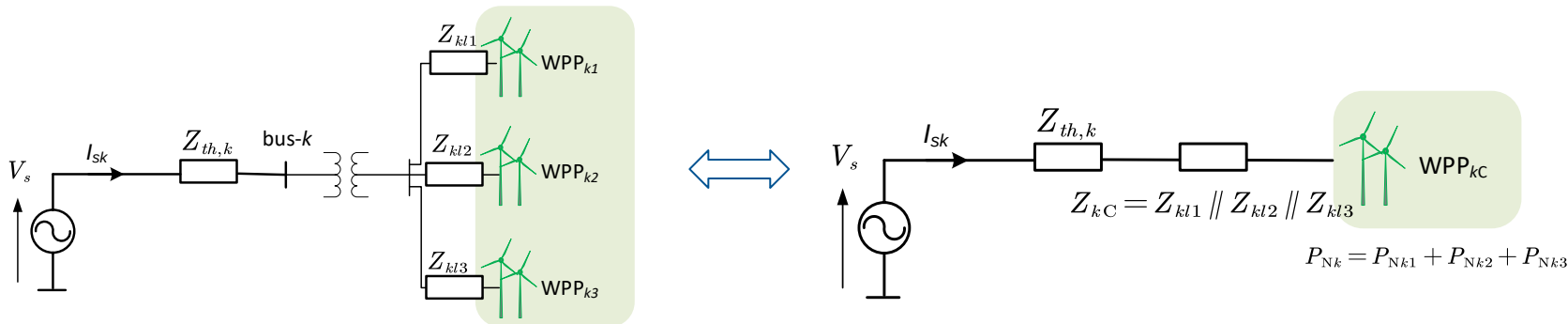
Large-Signal Strength

New Metrics Proposed in Recent Years

- Composite short circuit ratio (CSCR)** [NERC & GE Energy Consulting, 2015]

Create a common (medium voltage) bus and tie all inverter-based resources of interest together at that common bus, then find SCR

$$CSCR = \frac{1}{(Z_{th,k} + Z_{kc})P_{Nk}}$$



- Weighted short-circuit ratio (WSCR)** [ERCOT Inc., 2014]

Familiar weighting principle
but reasoning unexplained

$$WSCR = \frac{\sum SCC_{ki} \times P_{Nki}}{(\sum P_{Nki})^2}$$

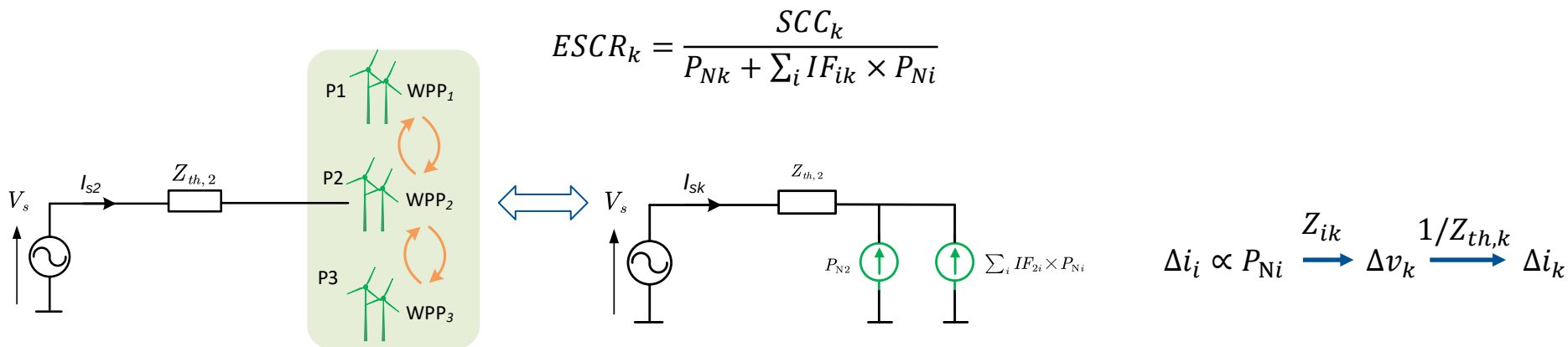
CSCR and WSCR are aggregated indices representing the strength at bus-k when a group of WPPs are going to connect.

They are based on an assumption of strong electrical coupling among WPPs.

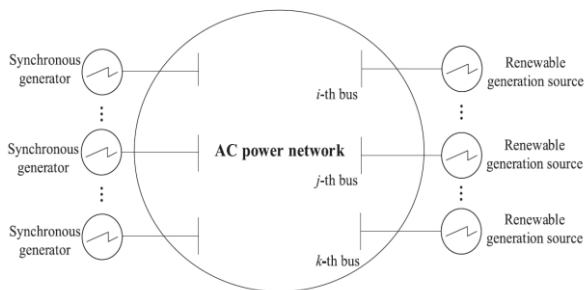
New Metrics Proposed in Recent Years

- Equivalent short-circuit ratio (ESCR)** [CIGRE report, 2016]

Uses Interaction Factor: $IF_{ik} = \frac{\Delta V_i}{\Delta V_k} = \frac{Z_{ik}}{Z_{th,k}} \rightarrow$ transfer impedance



- Site-Dependent SCR (SDSCR)** [North Dakota State University, 2018]



Similar to ESCR but seeks to extend to global area

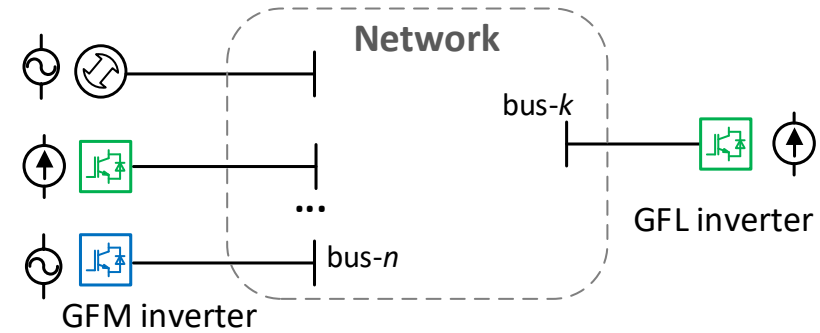
$$\begin{bmatrix} V_G \\ V_R \end{bmatrix} = \begin{bmatrix} Z_{GG} & Z_{GR} \\ Z_{RG} & Z_{RR} \end{bmatrix} \begin{bmatrix} I_G \\ I_R \end{bmatrix} \quad SDSCR_i = \frac{|V_{R,i}|^2}{\left(P_{R,i} + \sum_{j \in \mathbf{R}, j \neq i} P_{R,j} w_{ij} \right) |Z_{RR,ii}|} \quad w_{ij} = \frac{Z_{RR,ij}}{Z_{RR,ii}} \left(\frac{V_{R,i}}{V_{R,j}} \right)^*$$

New Metric: Type-dependent SCR (TDSCR)

Uses equivalent circuit (nodal admittance matrix) for analysis

For grid-following inverters which are current sources, the input and output should be swapped, *i.e.*, input is defined as the current and output is defined as the voltage.

This gives a hybrid matrix H .



$$\begin{bmatrix} Y_{N11} & Y_{N12} & \cdots \\ Y_{N21} & \ddots & \\ \vdots & & Y_{Nkk} & \ddots \\ & & & Y_{Nnn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_k \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} I_1 \\ \vdots \\ I_k \\ \vdots \\ I_n \end{bmatrix}$$

→

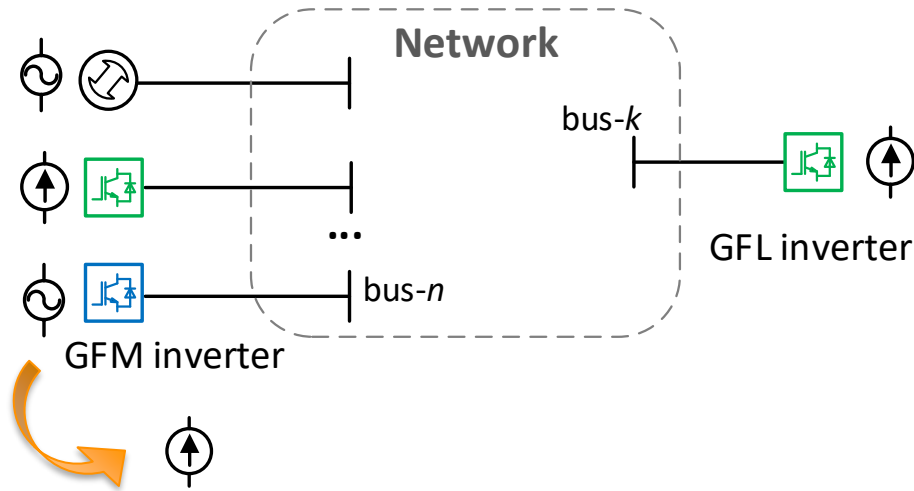
$$\begin{bmatrix} H_{11} & H_{12} & \cdots \\ H_{21} & \ddots & \\ \vdots & & H_{jj} & \ddots \\ & & & H_{kk} & \ddots \\ & & & & H_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_j \\ V_k \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} I_1 \\ \vdots \\ I_j \\ V_k \\ \vdots \\ V_n \end{bmatrix}$$

Hybrid Matrix H

Type-Dependent Short Circuit Ratio

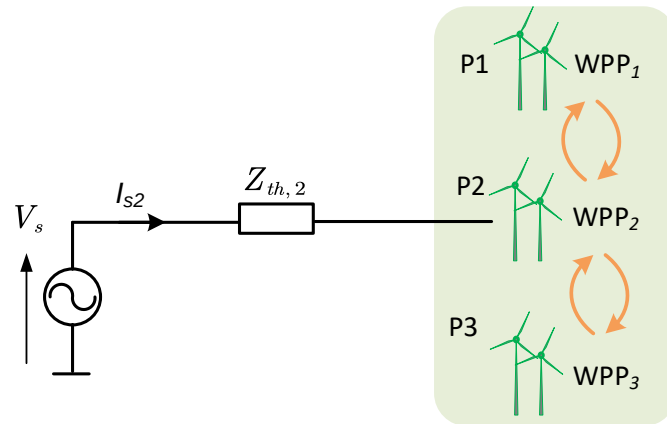
$$TDSCR = \begin{cases} \frac{|H_{kk}|}{P_{Nk}}, & \text{voltage source} \\ \frac{1}{|H_{kk}|P_{Nk}}, & \text{current source} \end{cases}$$

Low Fault Current, and Interactions Among IBRs



During a **fault**, a GFM inverter may mode-change into current source due to its current limitation.

Solution: rewrite the hybrid matrix by changing GFM inverters with current limiter into current sources



For interaction among IBRs:

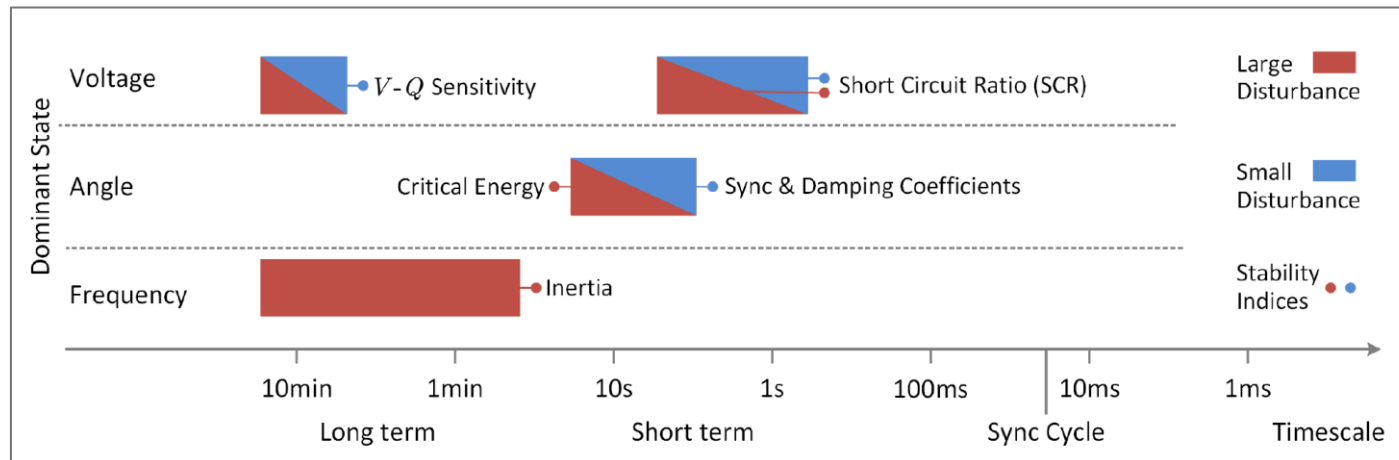
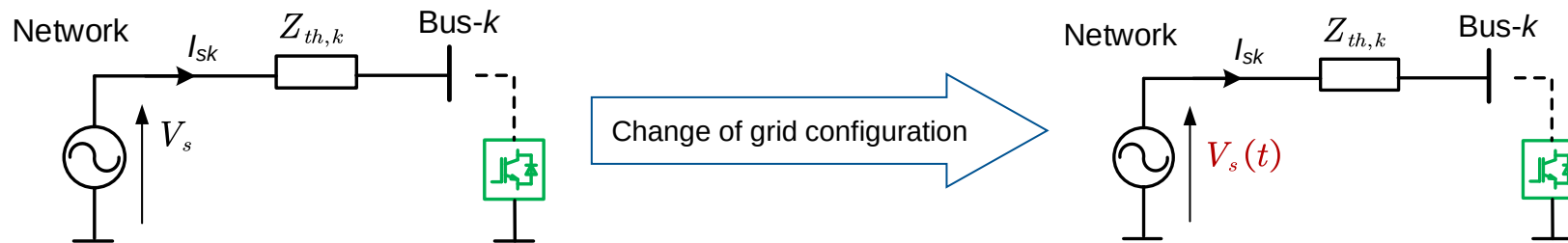
Ideas of ESCR could be borrowed but types of interreacting IBRs need to be considered:

- voltage source - voltage source interaction
- voltage source - current source interaction
- current source - voltage source interaction
- current source - current source interaction

* When two or more IBRs are involved for interaction, H matrix **cannot** be simply operated elementwise.

Further Thinking: Long-term Strength?

SCR is essentially a **short-term** strength metric [4] because a V_s is considered to be at fixed angle. Change of grid configuration cannot be captured by SCR. How might we define a **Long-term** strength metric?



Thank You

