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New System Strength Metrics

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Presenter: Dr Yue Zhu (Research Associate)

ESIG 2023 Spring Technical Workshop

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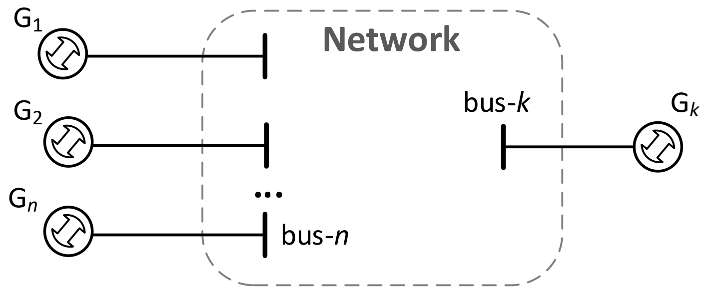
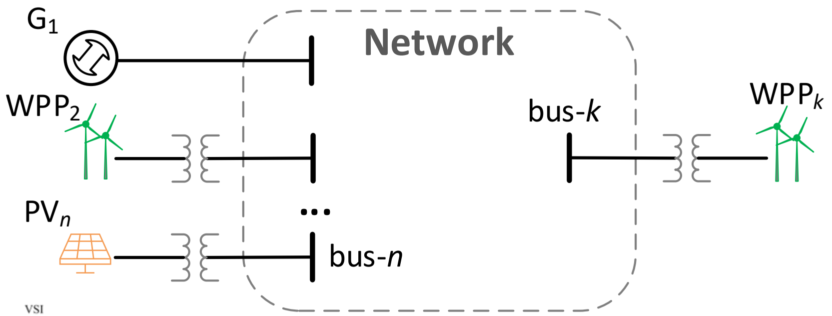
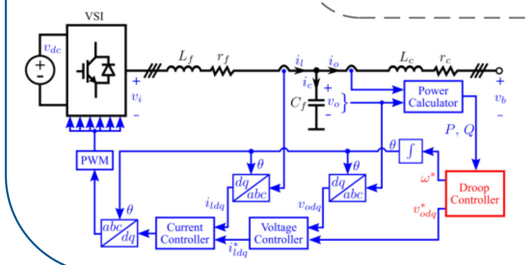
Background

System with Renewables Implemented







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

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

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

Physically defined behavior

Control defined behavior

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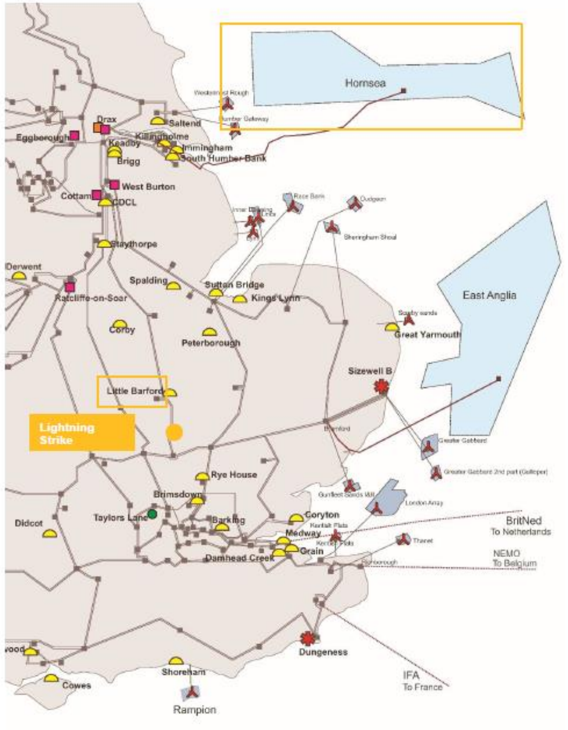
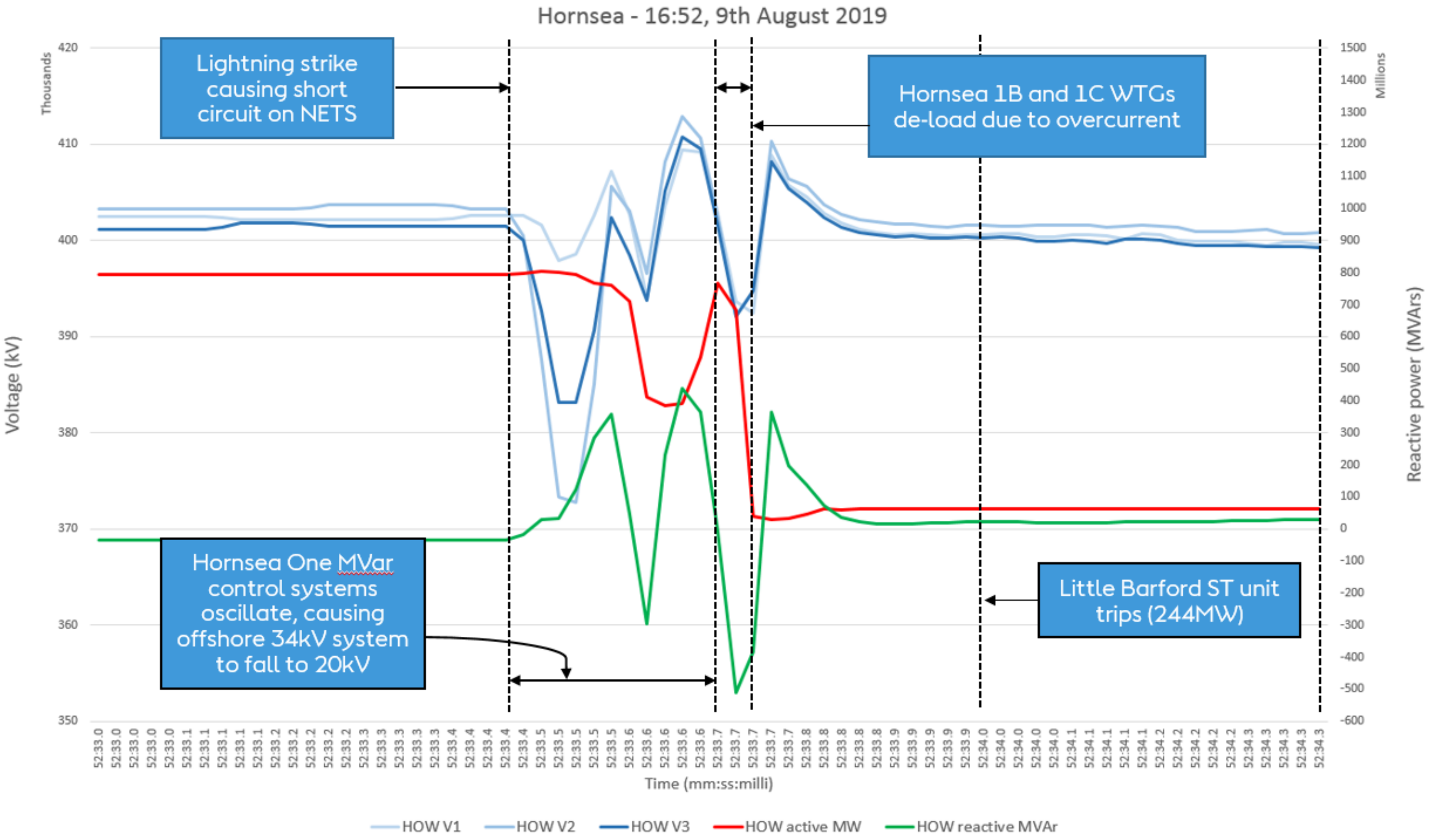
Oscillation at Hornsea Offshore Windfarm: Voltage Instability



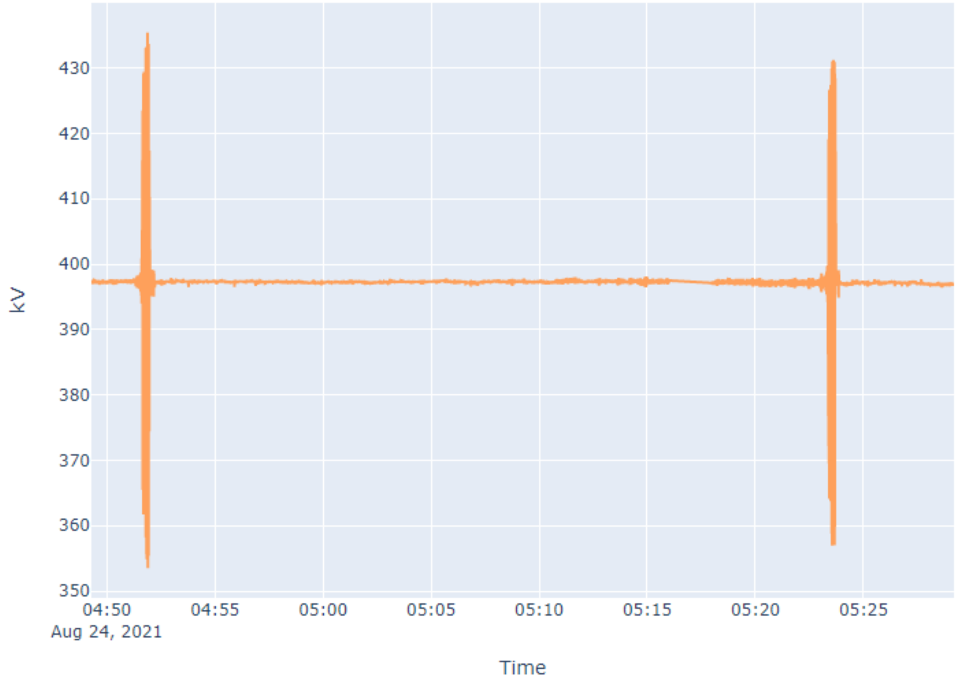


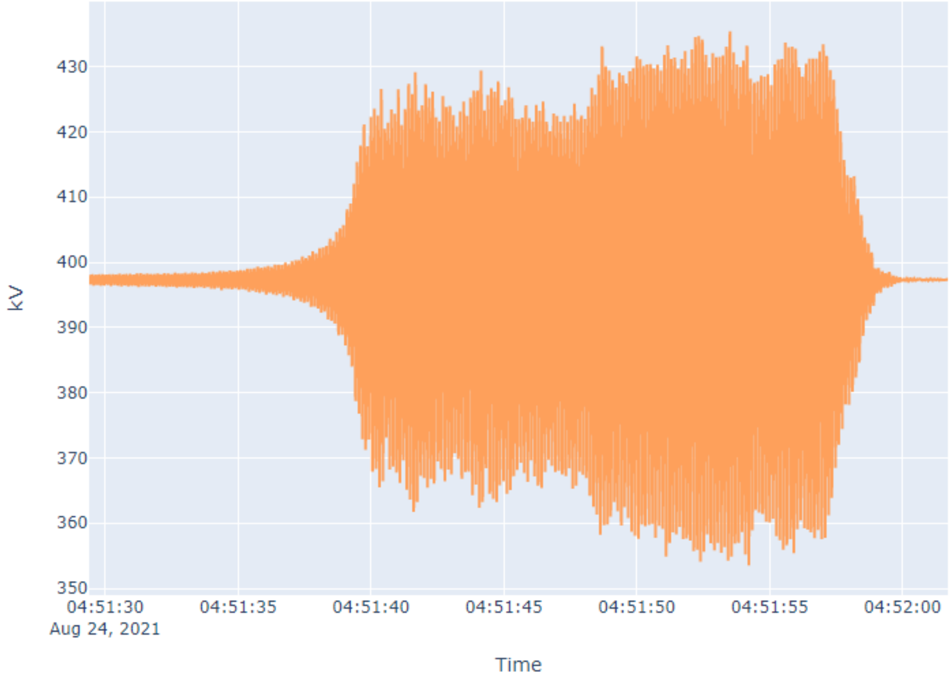
Scotland ‘Double Heart Attack’ with 8 Hz Oscillation

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.

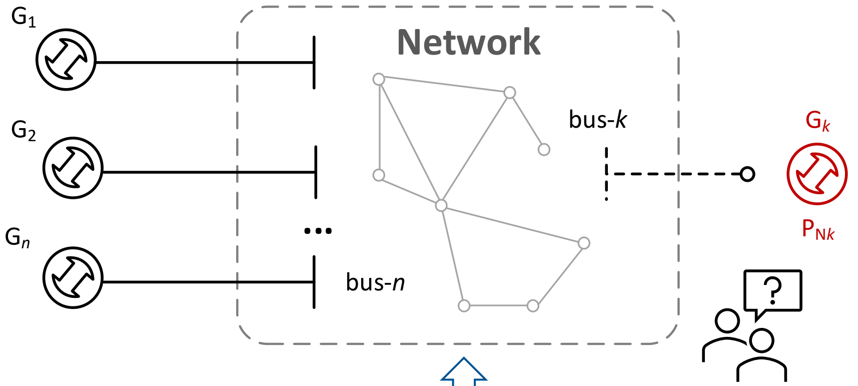




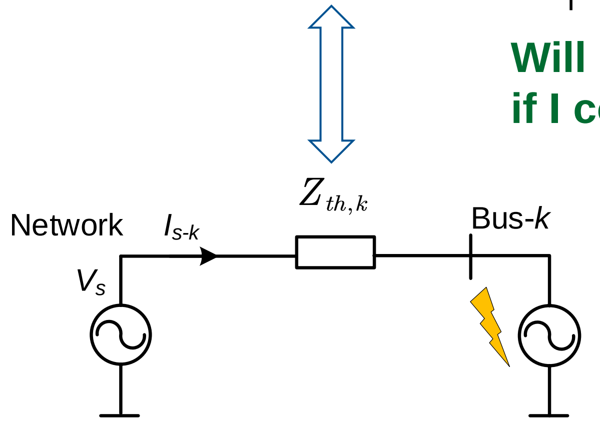
Grid Strength

Strength to Connect: Short Circuit Ratio (SCR)

Grid Strength ⇔ Connectivity



Will it be okay if I connect?



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

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

Short-circuit ratio (SCR): $\mathrm{SCR}_k = \dfrac{\mathrm{SCC}_k}{P_{\mathrm{N}k}} = \dfrac{1}{|Z_{th,k,p.u.}| \cdot P_{\mathrm{N}k,p.u.}}$

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**

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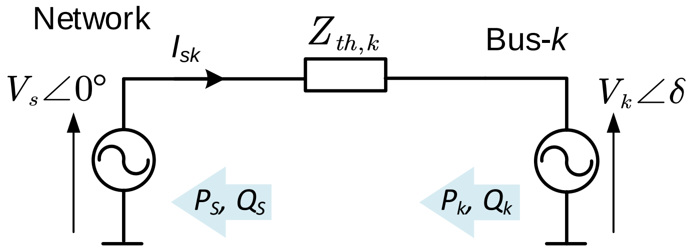
Understanding SCR from a Power or Impedance Perspective

A voltage source trying to deliver it's nominal power

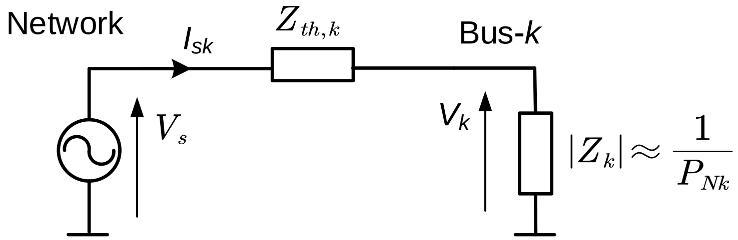


- When $\delta = -90°$, the system reaches the maximum absorbable power

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

Impedance equivalence for operation at rated power

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

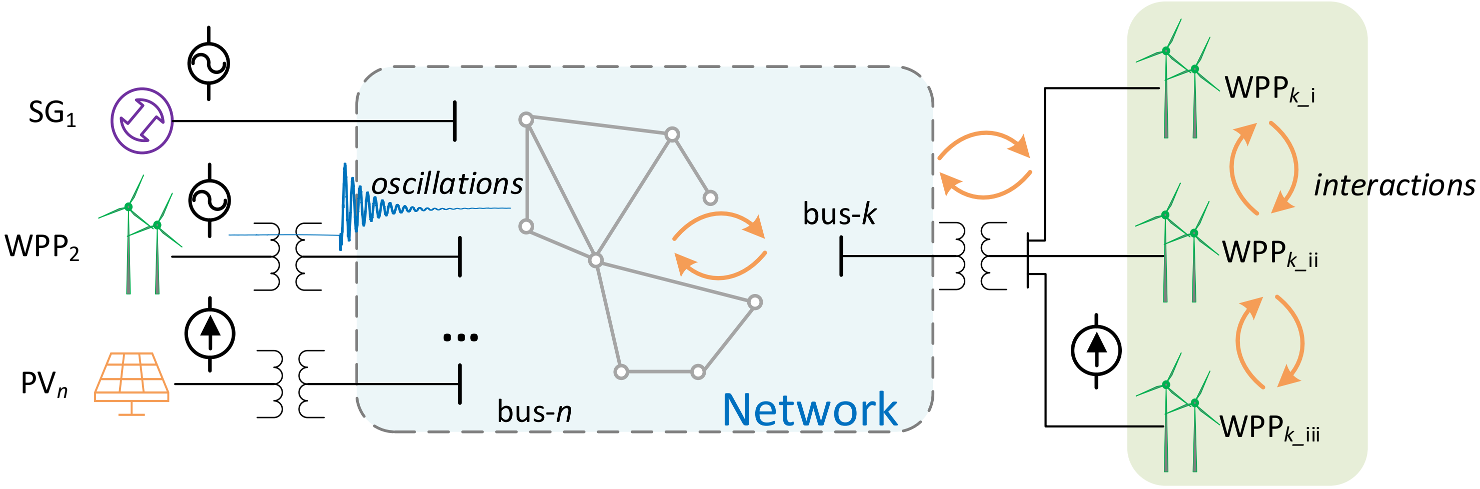


- When $|Z_k| < |Z_{th,k}|$, the voltage at bus-*k* will collapse.

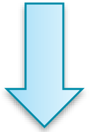
$$|Z_k|_{MIN} = |Z_{th,k}|, \qquad SCR = \frac{|Z_k|}{|Z_k|_{MIN}}$$

	Power	Impedance	Admittance
$SCR = \frac{1}{|Z_{th,k}| \times P_{Nk}}$ ⇔	$\frac{P_{kMAX}}{P_{Nk}}$ ⇔	$\frac{|Z_k|}{|Z_k|_{MIN}}$ ⇔	$\frac{|Y_k|_{MAX}}{|Y_k|}$

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

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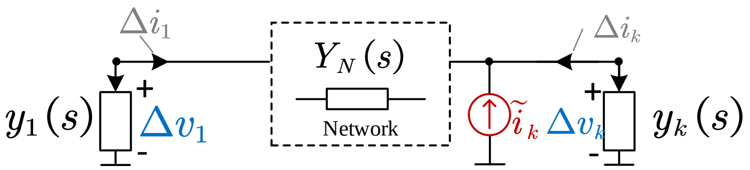
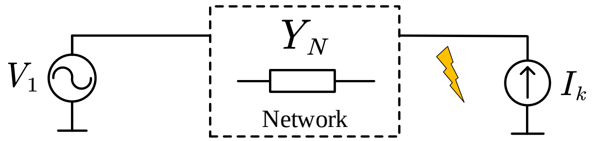
Classification of the New Grid Strength Metrics

	Small-signal Strength	Large-signal Strength
		
Features	• **Small perturbations** around operation point • Frequency-domain analysis • Analysis In **small-signal** scope	• **Large perturbations** • Fundamental frequency analysis, 50 Hz or 60 Hz • A further **extension of SCR**
Targets	• Potential instability caused by inverters, and small-signal interactions among inverters	• Interactions among IBRs • Increased recovery times from voltage dips, • low fault current, • inadequate voltage regulation, • mal operation of protection.
Explorations	• Grid strength impedance metric (GSIM) [University of Strathclyde] • Small-signal generalized short-circuit ratio (gSCR) [Zhejiang University] • Impedance Margin Ratio (IMR)	• 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)

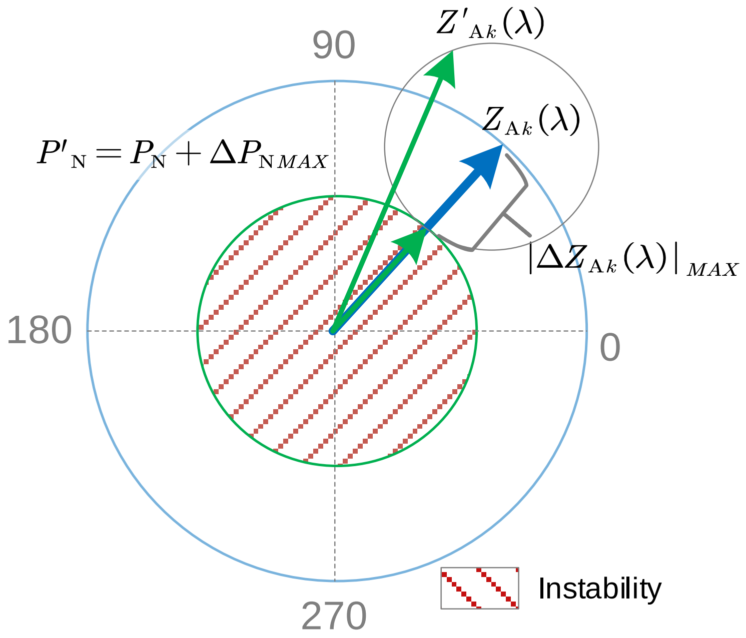
Small-Signal Strength

Impedance Margin Ratio: IMR

$$\boldsymbol{IMR} = \frac{1}{1 - \frac{|\sigma|}{\left|Re\left[\left\langle -\mathrm{Res}_{\lambda}^{*} Y_{kk}^{sys},\ Z_{\mathrm{A}k}(\lambda)\right\rangle\right]\right|}}$$

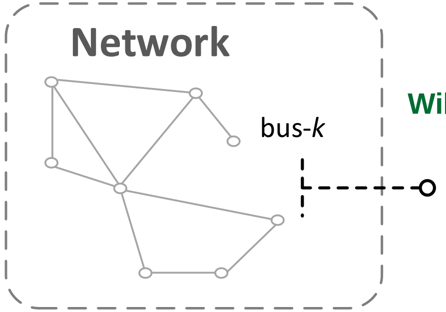
We also have Admittance Margin Ratio (AMR), which is equivalent to IMR with same values

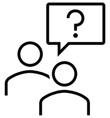
IMR refers to the ratio between the maximum allowable nominal power (for which mode λ remain in LHP) and the nominal power. Small-signal strength at bus-*k* is determined by its minimum IMR.



- 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





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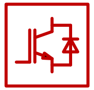


From measurement, or analysis (for white-box model), or simulation

From measurement, or data provided by vendors based on control design

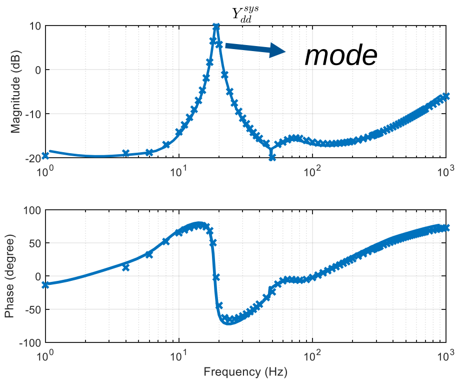
GSIM Method

Network impedance spectrum seen from bus-*k* $Z_{th,k}(j\omega)$,

IBR impedance spectrum $Z_{Ak}(j\omega)$, measured, or provided by the vendors

Assembly of Spectrum

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



$$Y_{kk}^{\mathrm{sys}}(s) = \sum_{i=1}^{m} \frac{R_{ki}}{s - \lambda_i},$$

Poles → *Residues*

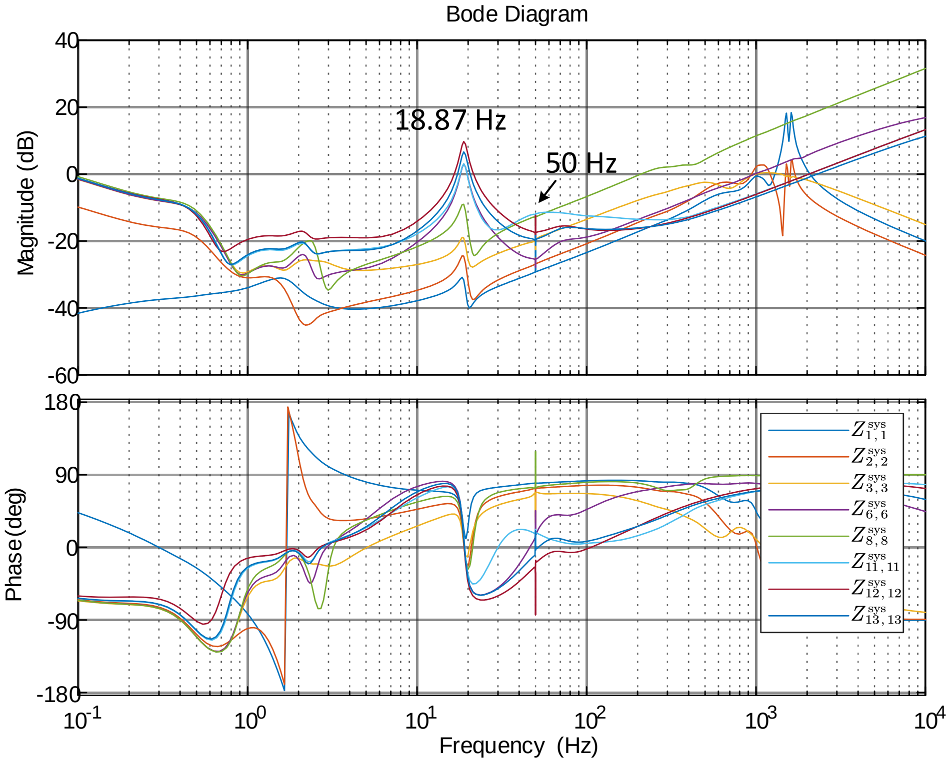
Modes & IMR

- Will new bad modes be created after connection? – *Interactions with other IBRs*
- Small IMR? – *Strength of point of interconnection*

[3] "Future power networks." [Online]. Available: https://github.com/Future-Power-Networks/Publications

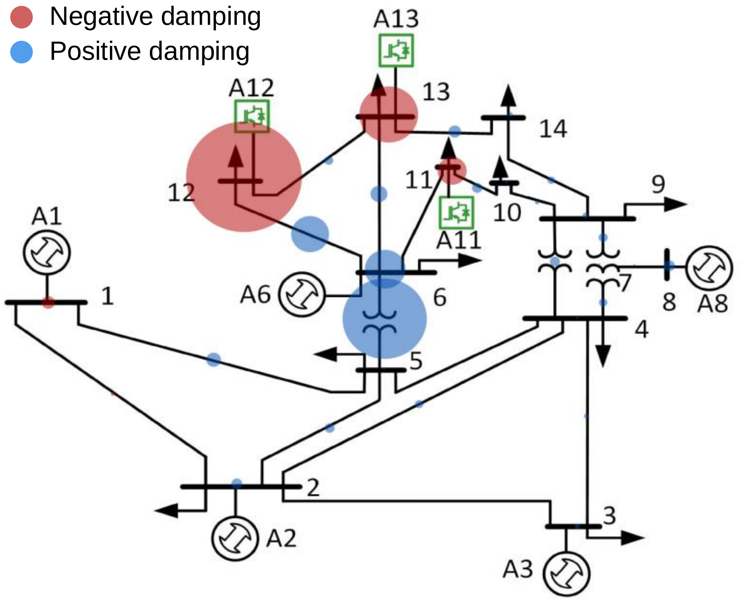
IMR Application to Identification of Weak Points

Whole-system Analysis



IMR / AMR analysis

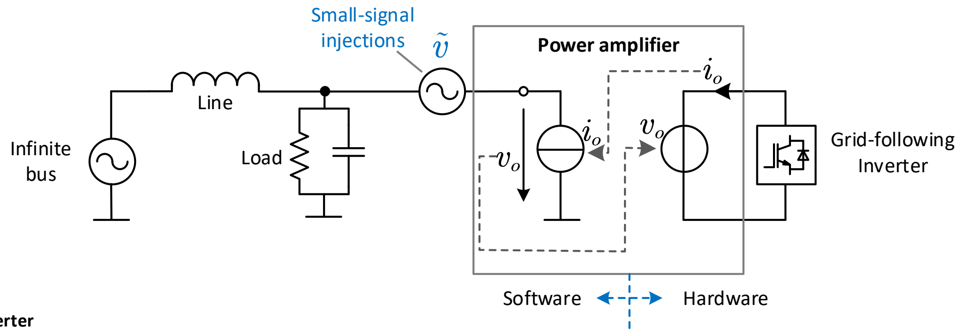
Grey-box approach

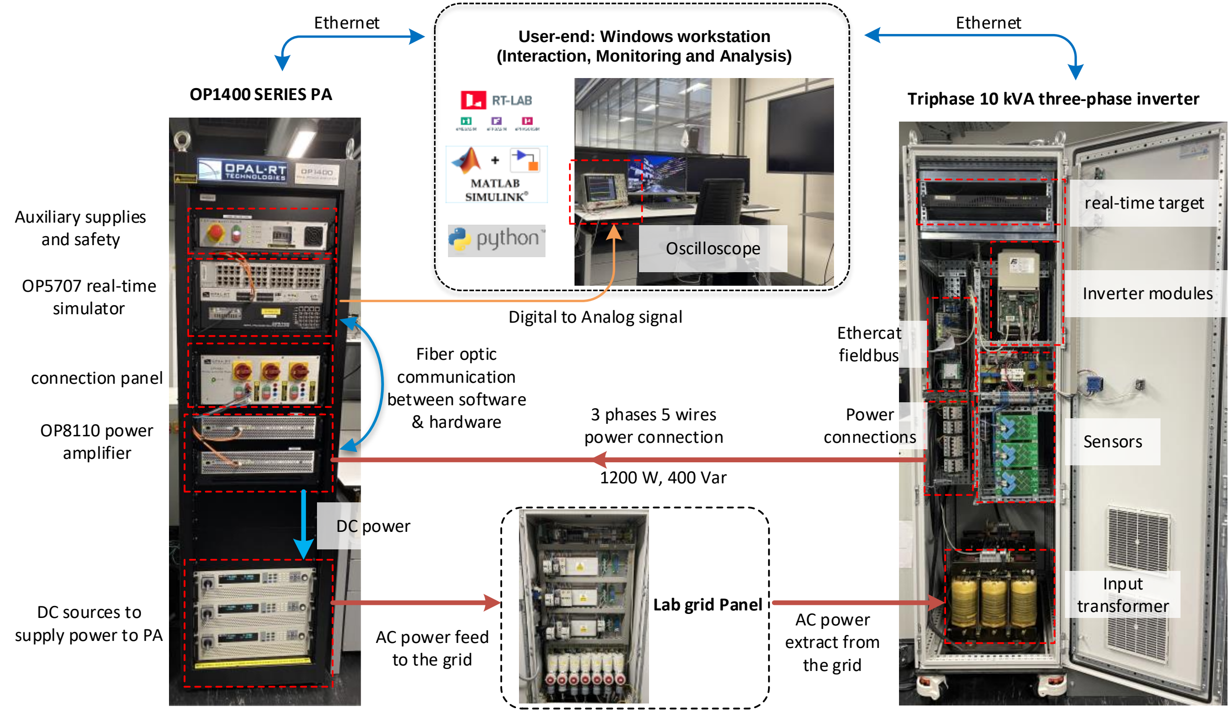


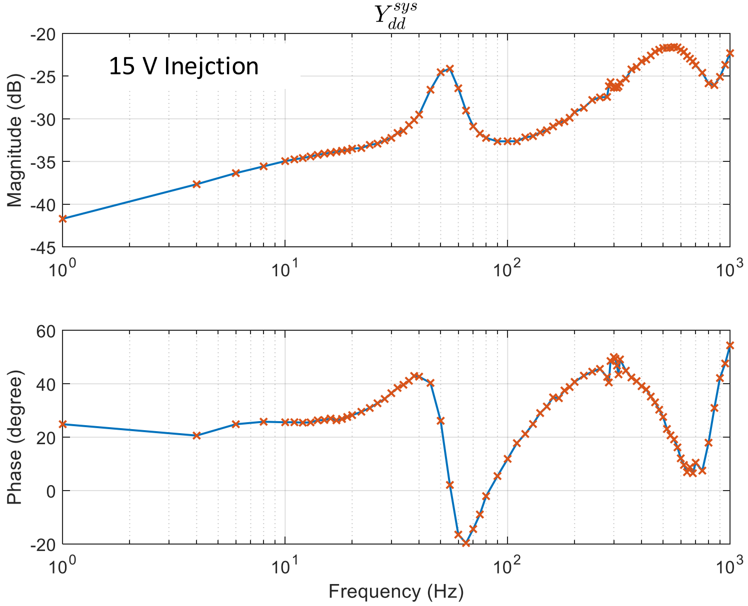
Validation of On-line (Real-Time) Monitoring

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







[2] Y. Zhu, Y. Zhang and T. C. Green, "Injection Amplitude Guidance for Impedance Measurement in Power Systems," in IEEE Trans on Power Electronics, doi: 10.1109/TPEL.2023.3256182.

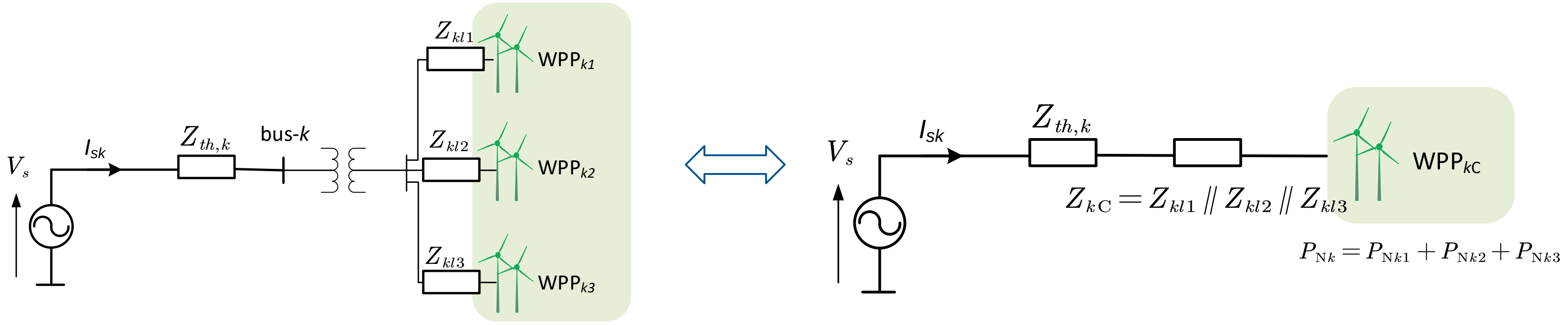
Large-Signal Strength

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.

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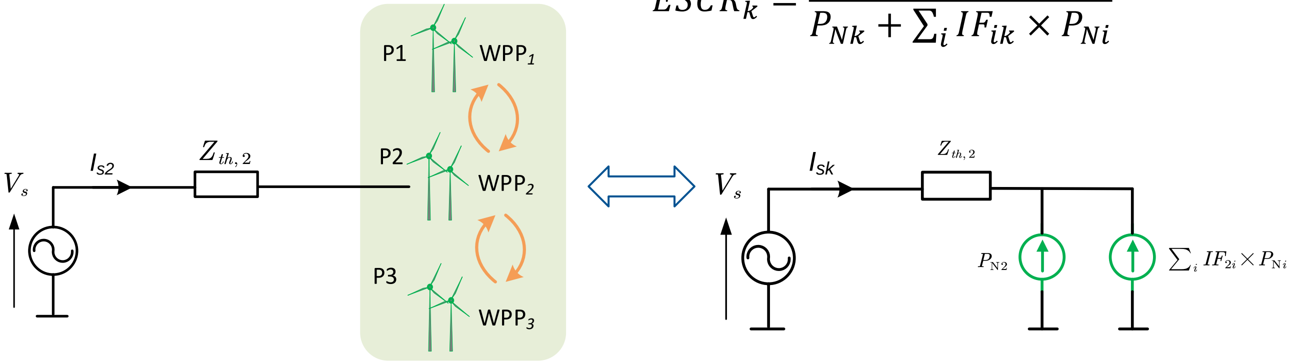
New Metrics Proposed in Recent Years

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

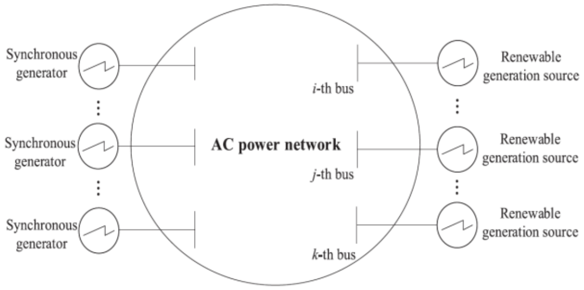
Uses Interaction Factor: $IF_{ik} = \frac{\Delta V_i}{\Delta V_k} = \frac{Z_{ik}}{Z_{th,k}}$ ⇢ transfer impedance

$$ESCR_k = \frac{SCC_k}{P_{Nk} + \sum_i IF_{ik} \times P_{Ni}}$$



$$\Delta i_i \propto P_{Ni} \xrightarrow{Z_{ik}} \Delta v_k \xrightarrow{1/Z_{th,k}} \Delta i_k$$

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



Similar to ESCR but seeks to extend to global area

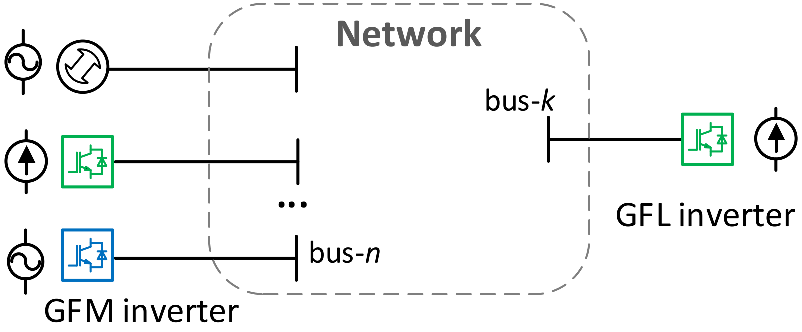
$$\begin{bmatrix} V_G \\ V_R \end{bmatrix} = \begin{bmatrix} Z_{GG} & Z_{GR} \\ Z_{RG} & Z_{RR} \end{bmatrix} \begin{bmatrix} I_G \\ I_R \end{bmatrix} \quad SDSCR_i = \frac{|V_{R,i}|^2}{\left(P_{R,i} + \sum_{j \in \mathbf{R}, j \neq i} P_{R,j} w_{ij}\right) |Z_{RR,ii}|} \quad w_{ij} = \frac{Z_{RR,ij}}{Z_{RR,ii}}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

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*.



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

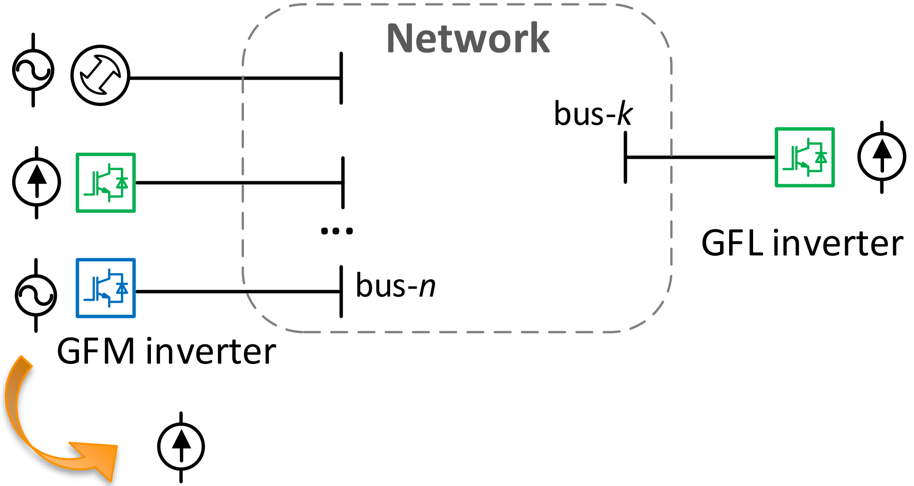
$$\begin{bmatrix} H_{11} & H_{12} & \cdots & & & \\ H_{21} & \ddots & & & & \\ \vdots & & H_{jj} & & & \\ & & & H_{kk} & & \\ & & & & \ddots & \\ & & & & & H_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_j \\ I_k \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} I_1 \\ \vdots \\ I_j \\ V_k \\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

Hybrid Matrix *H*

Type-Dependent Short Circuit Ratio

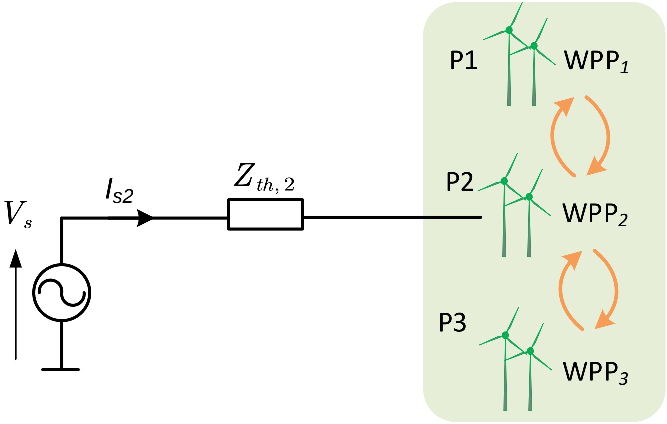
$$TDSCR = \begin{cases} \dfrac{|H_{kk}|}{P_{Nk}}, \textit{voltage source} \\ \dfrac{1}{|H_{kk}|P_{Nk}}, \textit{current source} \end{cases}$$

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.

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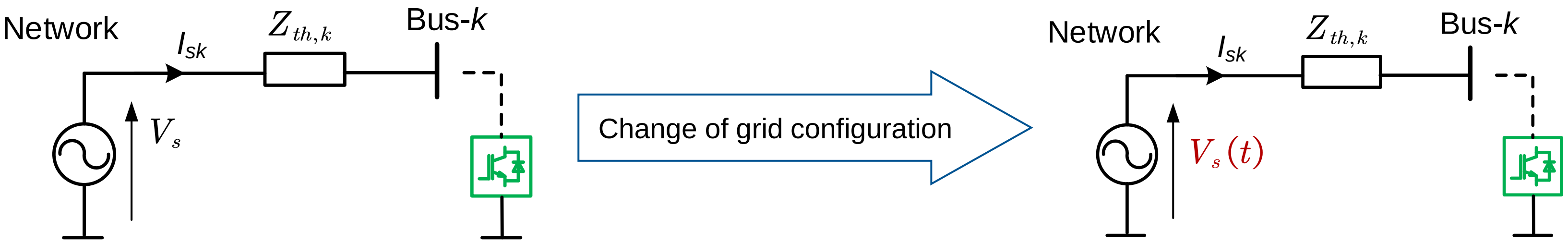
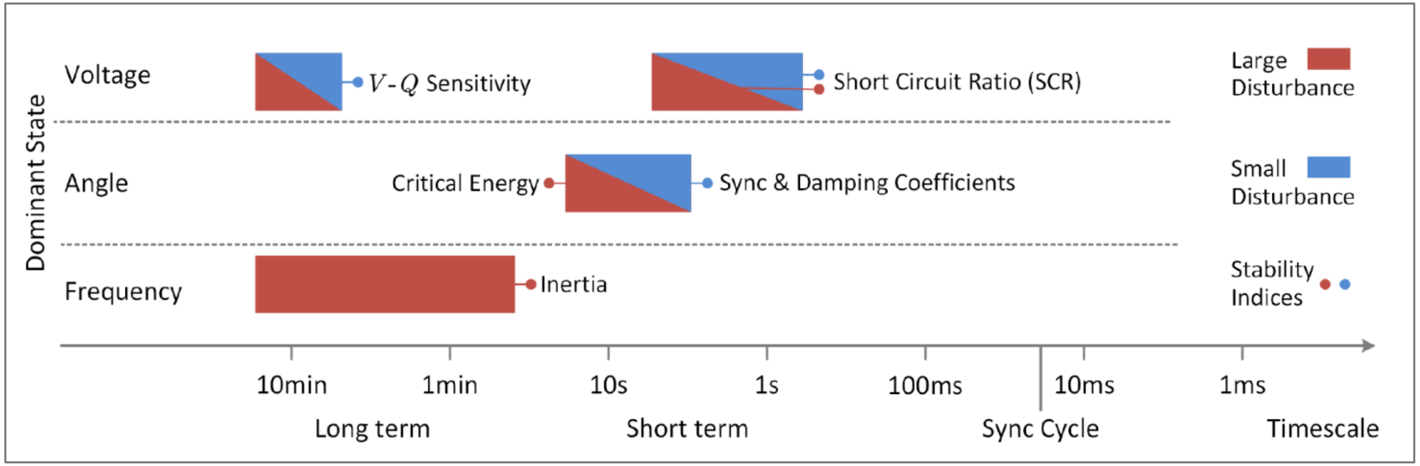
Further Thinking: Long-term Strength?

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?





[4] Y. Gu and T. C. Green, "Power System Stability With a High Penetration of Inverter-Based Resources," in Proceedings of the IEEE, 2022, doi: 10.1109/JPROC.2022.3179826.

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Thank You