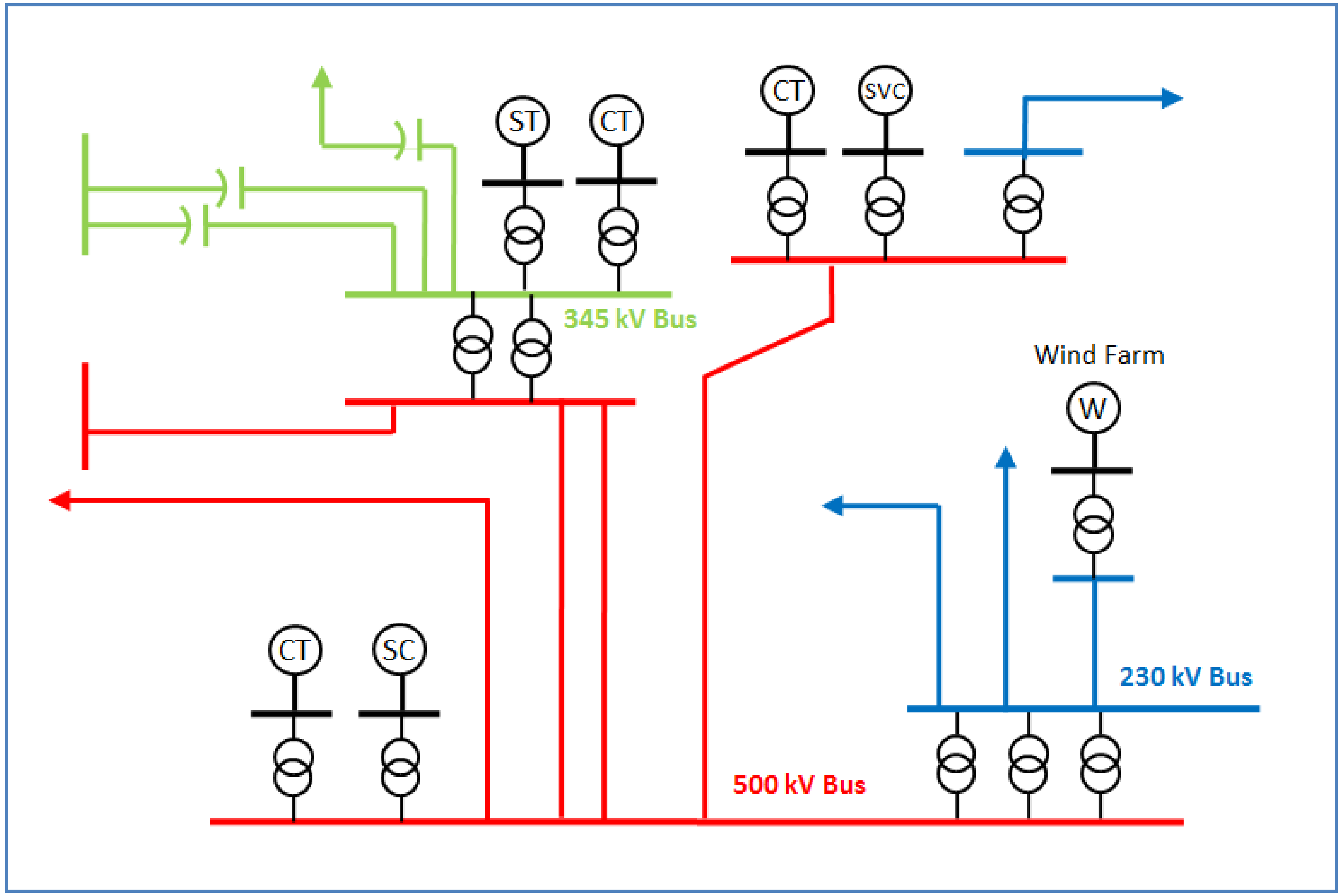
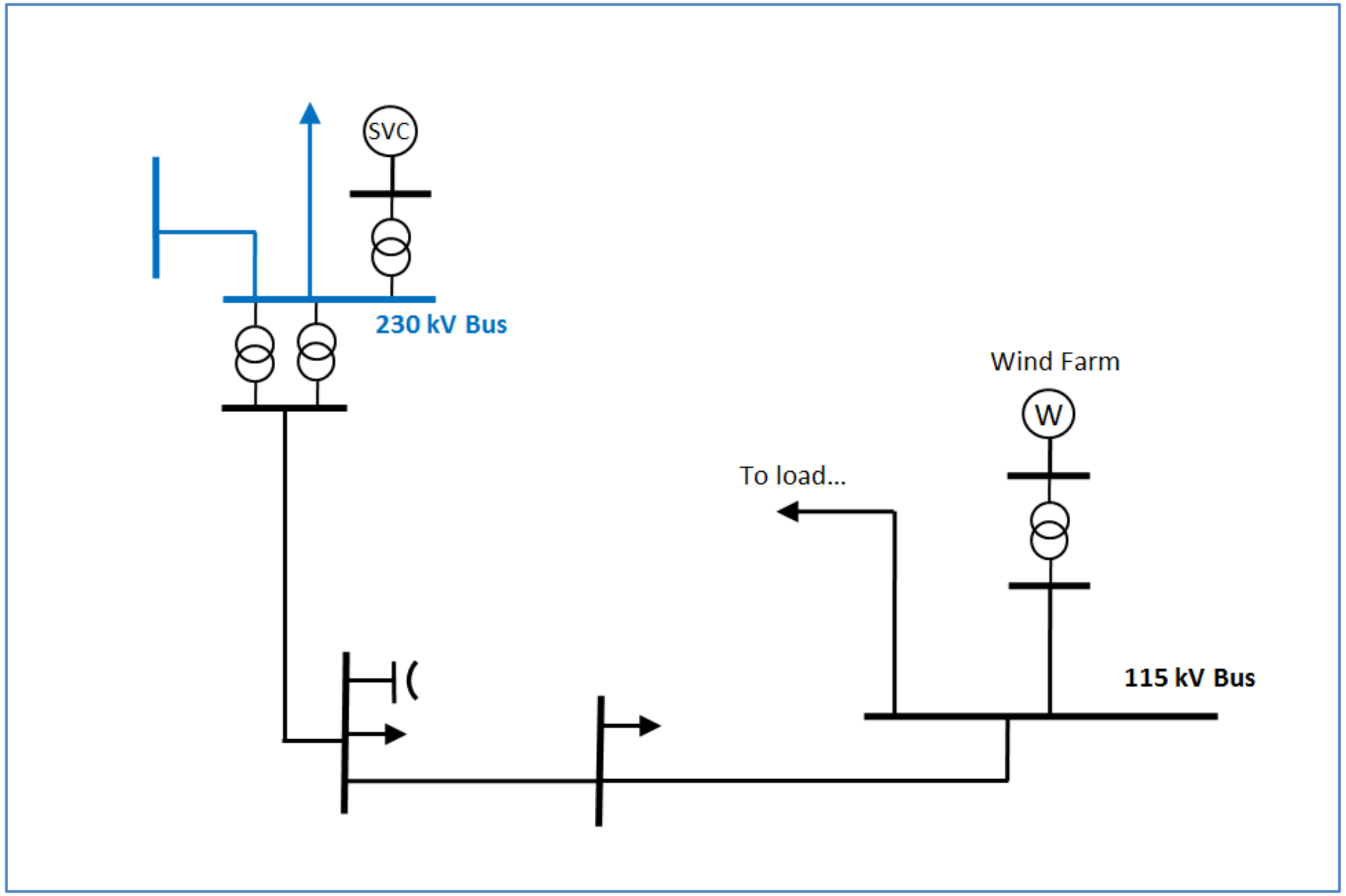
Weak Grid Concepts and System Strength Metrics

Topic Change

What is a *strong* system?



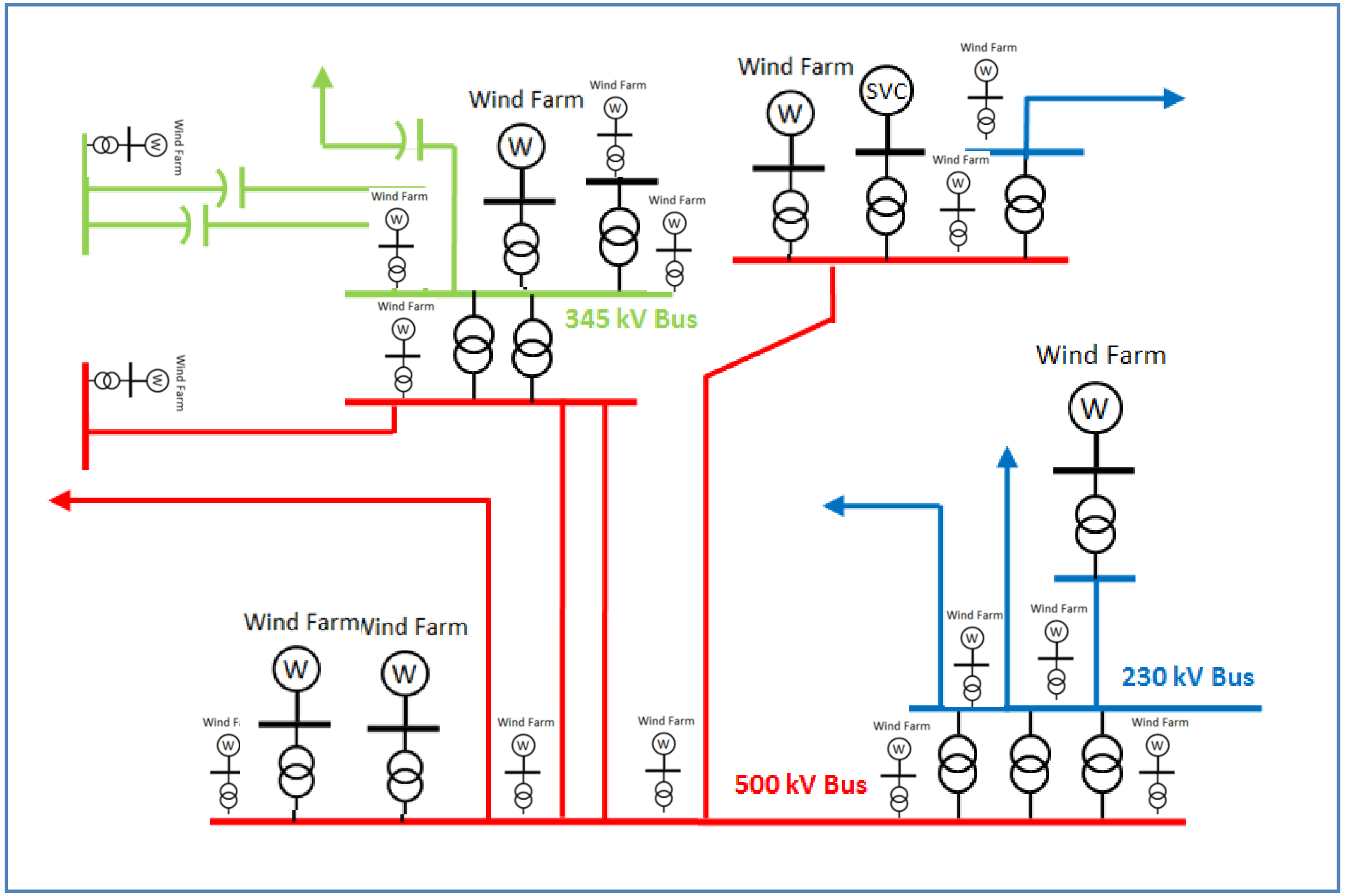
What is a *weak* system?



Is the network *relatively* weak or strong?

- The size of the wind farm ***relative*** to the strength of the system is a useful metric… *(Figure courtesy NREL/GE)*

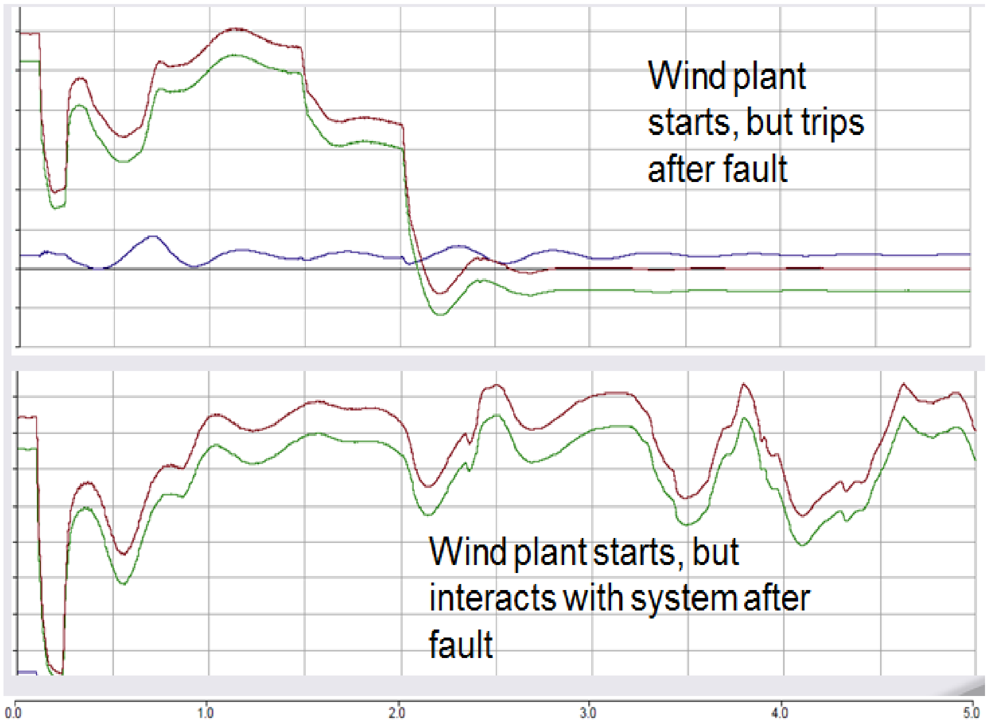
What is a *weak* system in Texas?



Technical Issues in Weak Grids

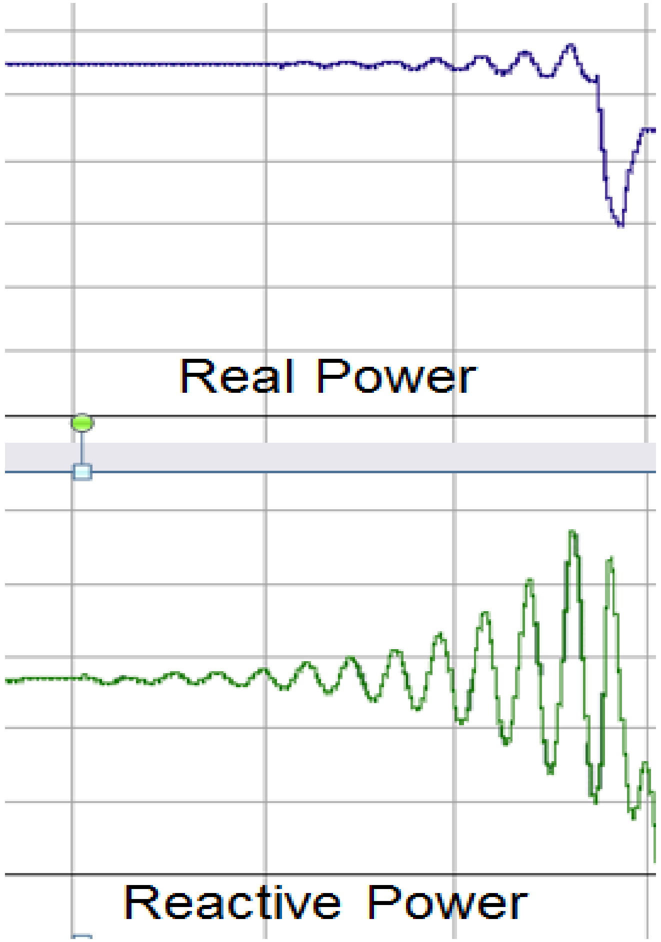
- Failure to ride through disturbances
  - Plant may trip following a network disturbance, leading to wider system issues, such as under-frequency or loss of voltage support.
  - Weak systems make ride-through more difficult

- Control interactions
  - The weaker the interconnection, the more likely controls will be to influence each other and interact negatively with each other or with the system.

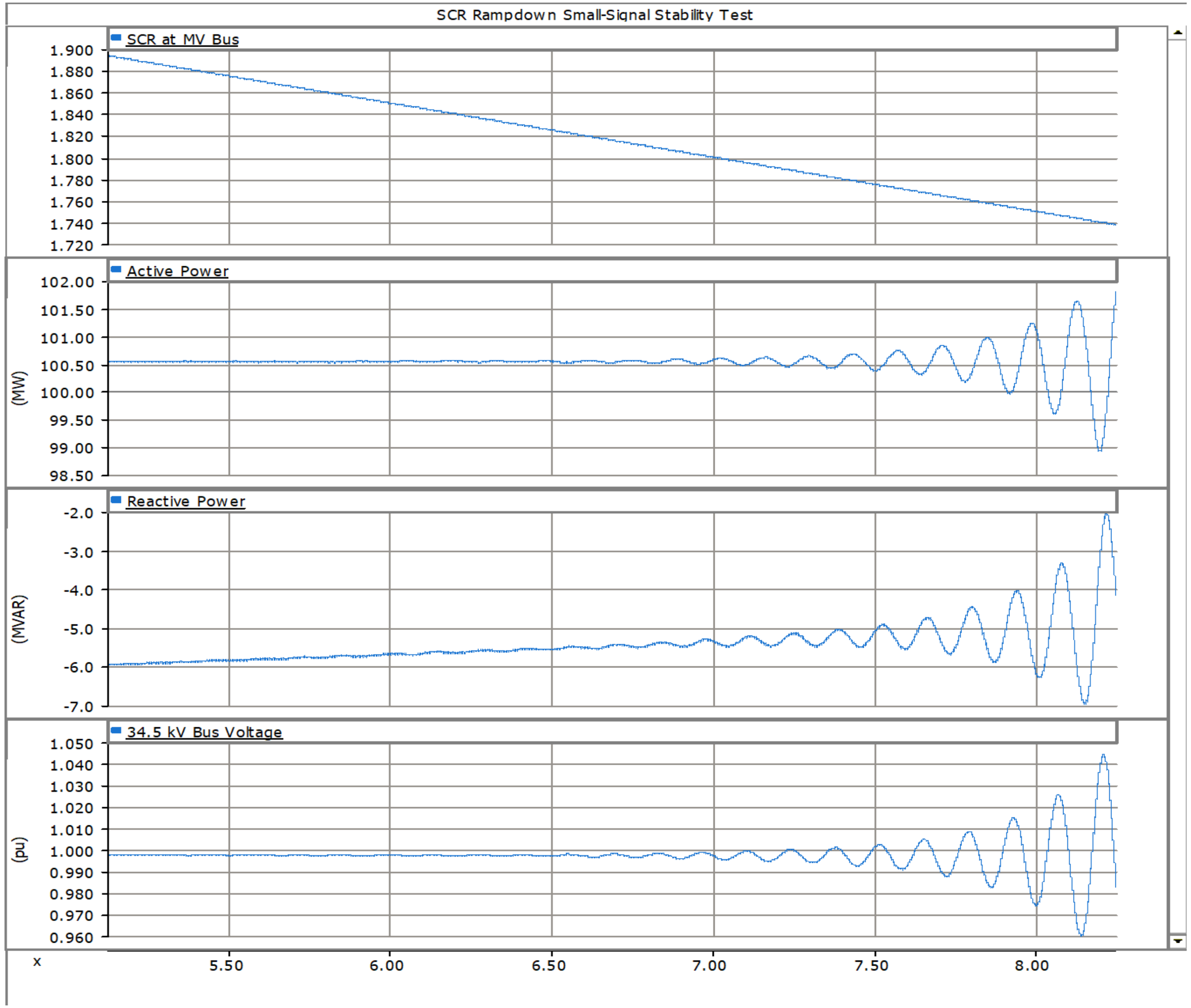


Technical Issues in Weak Grids

- Control instability
  - If the network is weak enough, controls may enter unstable region with no external influence needed (small signal instability)
- Example
  - Wind farm located in Western Canada on a long radial connection, SCR approx. 1.2

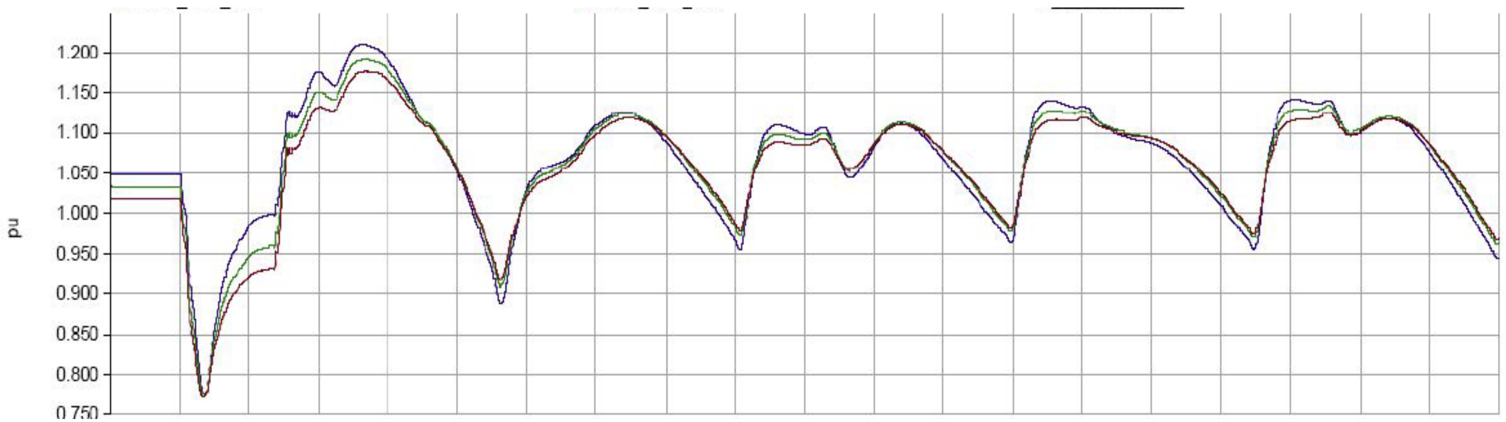


Small Signal Control Instability

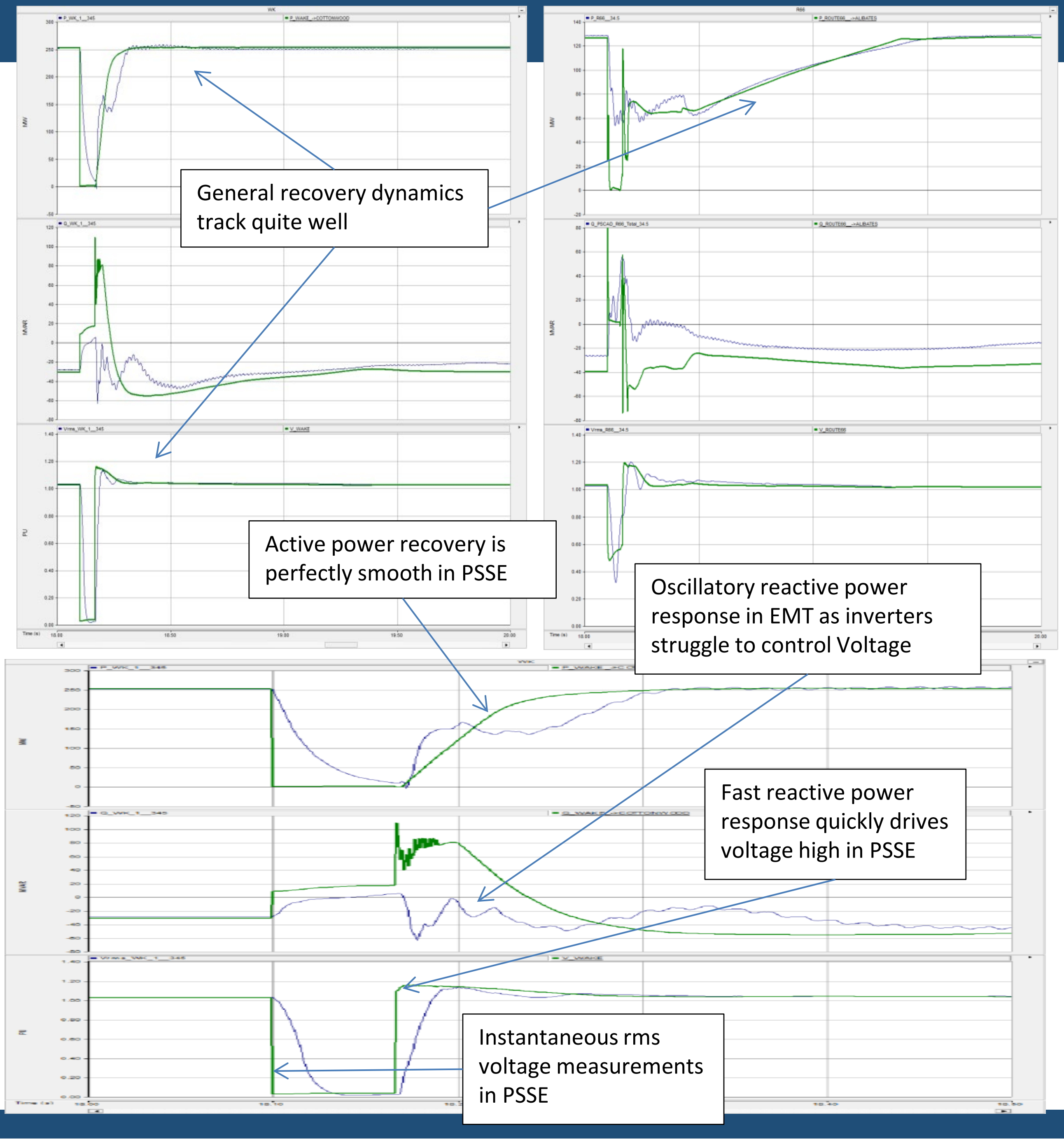


Technical Issues in Weak Grids

- Cycling between turbine control modes
  - Turbine controls may have special control modes to handle fault ride through (eg. reduce active power, tightly control terminal voltage, gently ramp active power back up to rated values)
  - If system is weak, control modes may be invoked multiple times as turbine attempts recovery, introducing severe transients into the system.



Transient Stability Limitations: Texas example:



SCR Definition

- The relative strength of the ac system, the IBR/FACT/HVDC is connecting to, is often parameterized by an index called the short circuit ratio or SCR.

$$\textbf{Short Circuit Ratio (SCR)} = \frac{\textbf{Short Circuit MVA (SCMVA)}}{\textbf{Rated Power (Prated)}}$$

Representation of an AC Grid for testing

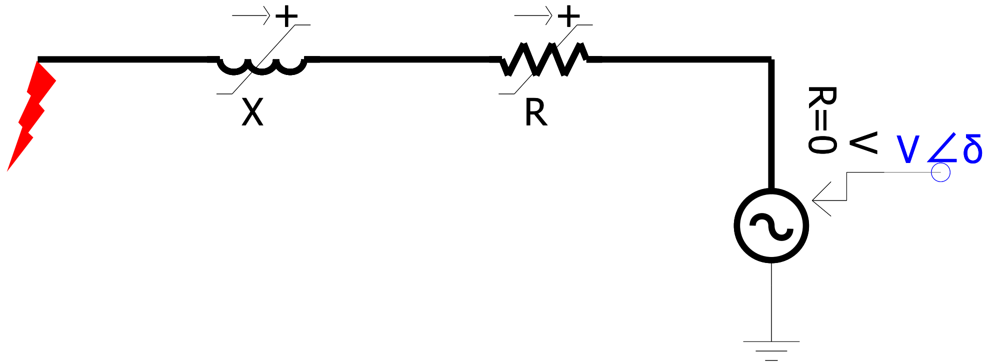
To represent an AC grid in a simulation tool, following parameters are required;

1. **R** (Resistance of the grid)
2. **X** (Reactance of the grid)
3. **V** (Voltage magnitude behind the impedance)
4. **δ** (Voltage angle behind the impedance)

The objective is to calculate above parameters backwards from available SCR information (i.e. SCR and X/R)

SCR & X/R

Assume;
V=1, δ=0



Calculation of Impedance

- $SCMVA = SCR \cdot Prated$
- $Isc = \frac{SCMVA}{V_{pre\_fault}}$
- $Z = \frac{V}{Isc}$
- $R = \frac{Z}{\sqrt{1+k^2}}$
- $X = k \cdot R$

Per unitize on Sbase = Prated →

- $SCMVA = SCR \cdot 1$
- $Isc = \frac{SCR}{1}$
- $Z = \frac{1}{SCR}$
- $R = \frac{1}{SCR} \cdot \frac{1}{\sqrt{1+k^2}}$
- $X = \frac{1}{SCR} \cdot \frac{k}{\sqrt{1+k^2}}$

Note: $k = X/R$

Power Transfer Limit

The power transfer across an impedance can be written as;

$$P(\delta) := \frac{V1^2}{|Z|} \cdot \cos(\arg(Z)) - \frac{V1 \cdot V2}{|Z|} \cdot \cos(\arg(Z) + \delta)$$

Assume;
X/R=∞ (i.e. R = 0)

Fully Inductive

$$P(\delta) := \frac{V1 \cdot V2}{X} \cdot \sin(\delta)$$

$When\ R = 0 \rightarrow X = \frac{1}{SCR}$

$$P(\delta) := SCR \cdot \sin(\delta)$$

$$MAX(P) := SCR$$

Assume;
X/R=0 (i.e. X = 0)

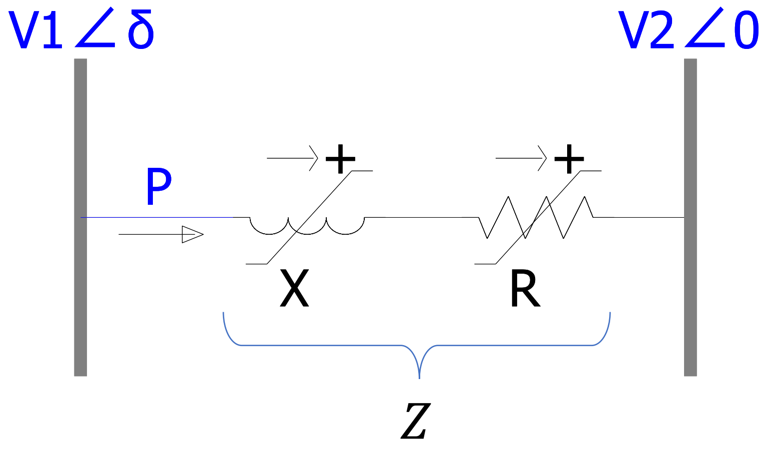
Fully Resistive

$$P(\delta) := \frac{V1^2}{R} - \frac{V1 \cdot V2}{R} \cdot \cos(\delta)$$

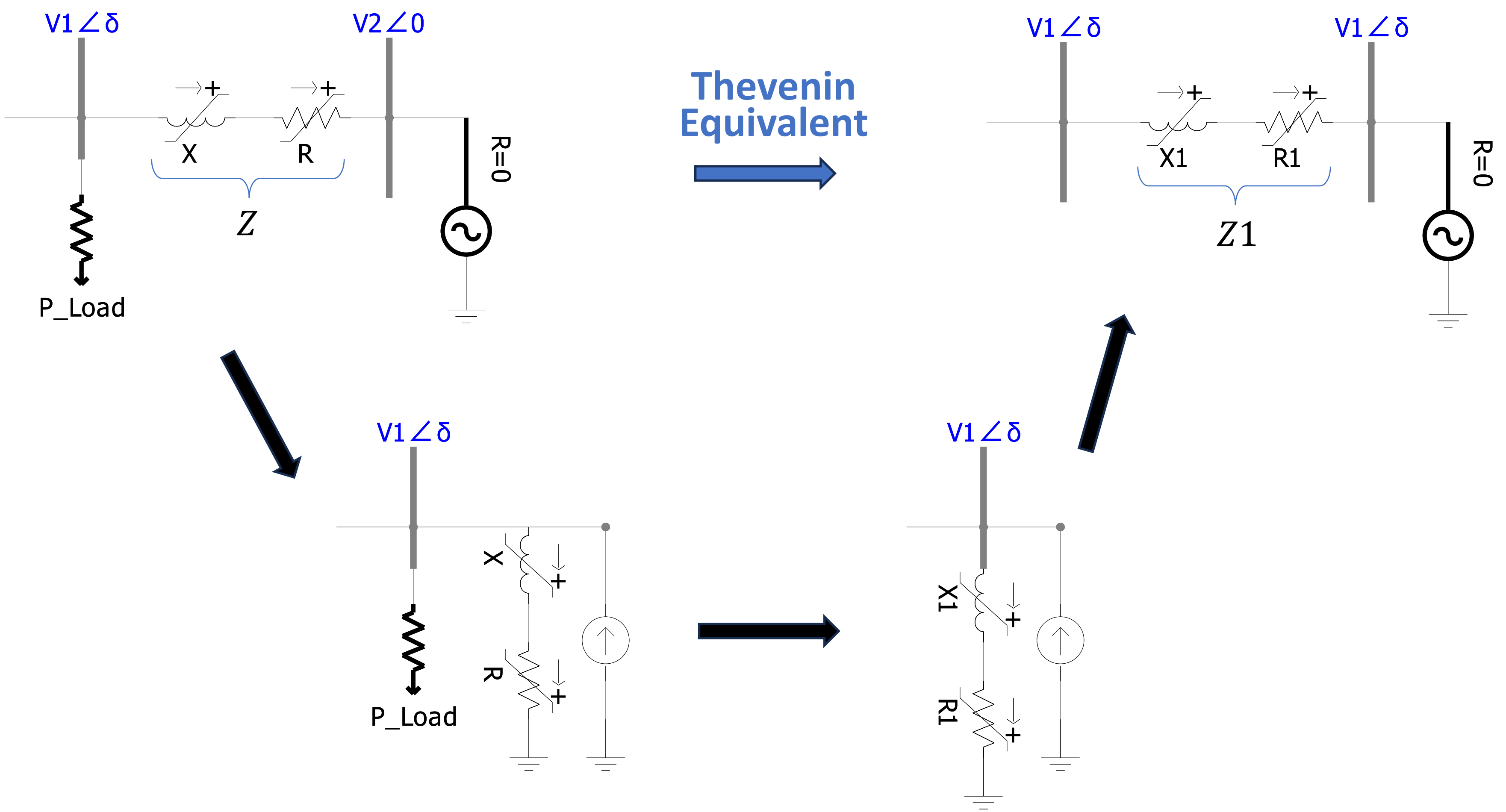
$When\ X = 0 \rightarrow R = \frac{1}{SCR}$

$$P(\delta) := SCR \cdot (1 - \cos(\delta))$$

$$MAX(P) := SCR \cdot 2$$



Representation of AC Grids of SCR < 1

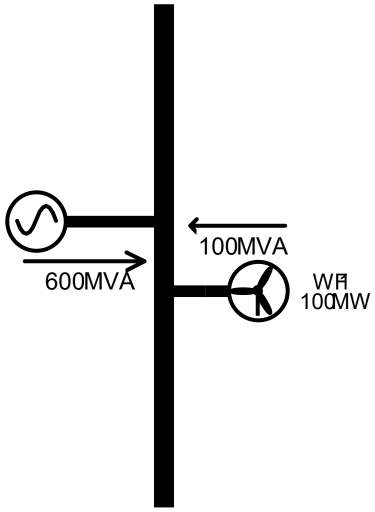


Sample SCRs...

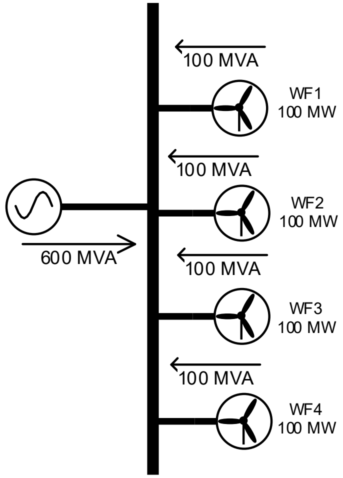
SCR Value	Concerns?
Less than 1.5	- Power electronics can't maintain control… wind plant will not run at full power. - Conventional study tools (Transient stability) may not run.
Less than 2.5	- Potential for control problems… Wind plant may trip inappropriately, or interact badly with the external network - Conventional study tools may not be accurate
Higher than 2.5	- Wind plant will likely perform predictably

SCR Metric - Limitations

- Can be misleading if there are multiple wind plants sharing system strength (Credit Cigre/AEMO)



$$\frac{600}{100} = \mathrm{SCR} = 6$$



$$\text{WF1 SCR} = \frac{600+100+100+100}{100} = 9\ ???$$

Metrics – Effective SCR (ESCR)

- ESCR accounts for the impedance increasing effect of capacitive filters (usually used in HVDC)

$$ESCR_{POI} = \frac{SCMVA_{POI} - MVAR_{Filter}}{MW_{VER}}$$

- First parallel resonance shifts the fundamental frequency impedance, so shunt capacitance can weaken the system.

Effect of shunt capacitance on Z60

Metrics – Weighted SCR (WSCR)

- Allows consideration of nearby resources which share SCMVA
- Neglects electrical separation
- May misrepresent group strength if there are outliers

$$WSCR = \frac{\text{Weighted} \quad S_{SCMVA}}{\sum_{i}^{N} P_{RMWi}} = \frac{(\sum_{i}^{N} S_{SCMVAi} * P_{RMWi})/\sum_{i}^{N} P_{RMWi}}{\sum_{i}^{N} P_{RMWi}} = \frac{\sum_{i}^{N} S_{SCMVAi} * P_{RMWi}}{(\sum_{i}^{N} P_{RMWi})^2}$$

Where does WSCR work?

Workshop: Calculate SCR and WSCR for each group

Small problem plant

	A	B	A*B	
	MW	SCMVA		SCR
	25	25	625	1
	100	1000	100000	10
	200	3000	600000	15
	400	4000	1600000	10
	200	3000	600000	15
	400	2000	800000	5
	200	1000	200000	5
	1525	14025	3900625	
WSCR	1.677237			

Larger problem plant

	A	B	A*B	
	MW	SCMVA		SCR
	100	100	10000	1
	100	1000	100000	10
	200	3000	600000	15
	400	4000	1600000	10
	200	3000	600000	15
	400	2000	800000	5
	200	1000	200000	5
	1600	14100	3910000	
WSCR	1.527344	0.910631		

Reduction in problem plant MW

	A	B	A*B	
	MW	SCMVA		SCR
	5	25	125	5
	100	1000	100000	10
	200	3000	600000	15
	400	4000	1600000	10
	200	3000	600000	15
	400	2000	800000	5
	200	1000	200000	5
	1505	14025	3900125	
WSCR	1.72189	1.026623		

Increase in problem plant SCMVA

	A	B	A*B	
	MW	SCMVA		SCR
	25	125	3125	5
	100	1000	100000	10
	200	3000	600000	15
	400	4000	1600000	10
	200	3000	600000	15
	400	2000	800000	5
	200	1000	200000	5
	1525	14125	3903125	
WSCR	1.678312	1.000641		

increase in power at strong bus

	A	B	A*B	
	MW	SCMVA		SCR
	25	25	625	1
	100	1000	100000	10
	200	3000	600000	15
	450	4000	1800000	8.888889
	200	3000	600000	15
	400	2000	800000	5
	200	1000	200000	5
	1575	14025	4100625	
WSCR	1.653061	0.985586		

increase in power at weak bus

	A	B	A*B	
	MW	SCMVA		SCR
	25	25	625	1
	100	1000	100000	10
	200	3000	600000	15
	400	4000	1600000	10
	200	3000	600000	15
	400	2000	800000	5
	250	1000	250000	4
	1575	14025	3950625	
WSCR	1.592593	0.949533		

WSCR Pros and Cons

Goals of metric:

- represent sharing of conventional system strength
- represent electrical coupling between devices

Problems with WSCR:

- doesn't necessarily show local plant concerns
- more sensitive to active power changes than to increases in SCMVA, unless strongly coupled electrically.
- doesn't account for non-active power electronic devices like STATCOMs
- Doesn't account for capacity, only dispatched power
- Requires relatively close grouping of resources to have any meaning.

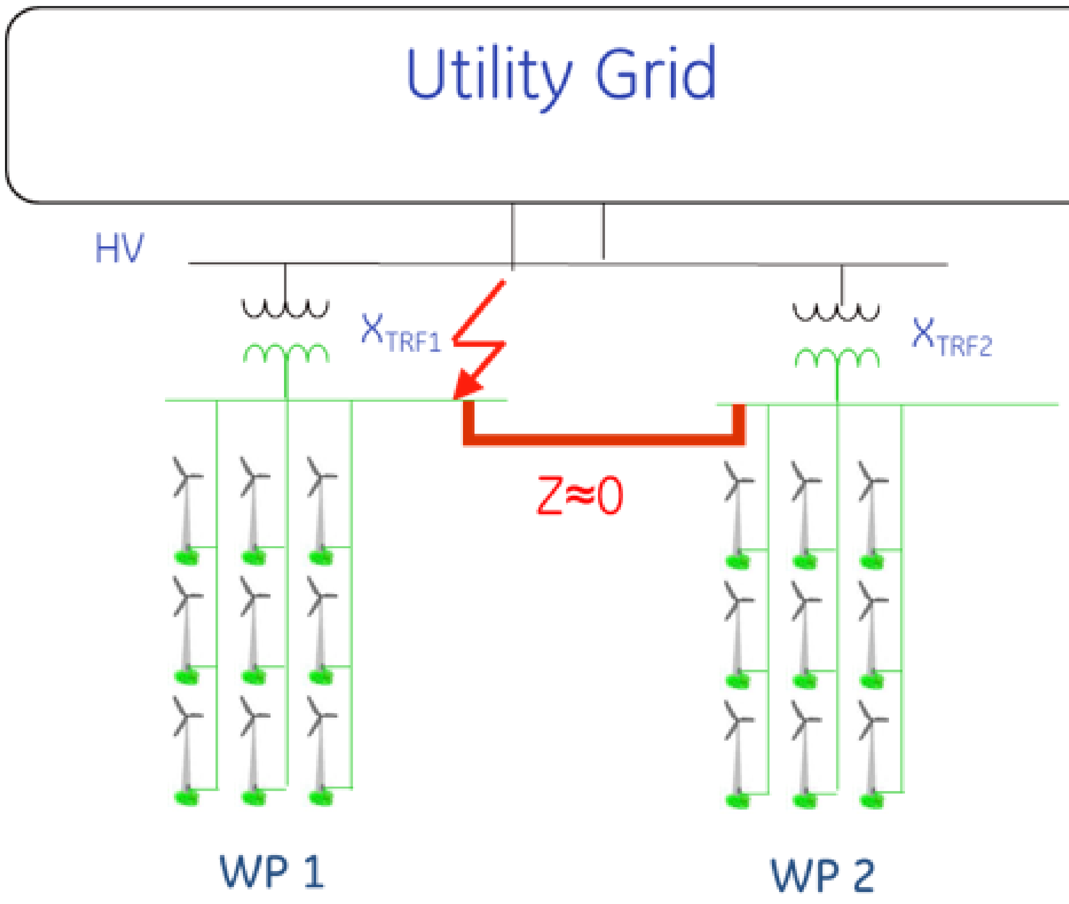
Good things about WSCR:

- Weights improvements to weak buses over strong buses.

Metrics – Composite SCR

- MV buses of wind farms in the cluster are shorted together and fault level is calculated in the simulation tool at the shorted bus.
- Similar limitations to WSCR

$$CSCR = \frac{S_{MV}}{(WP1_{RAT} + WP2_{RAT} + WP3_{RAT})}$$



Metrics – SCR with Interaction Factors (SCRIF), or Equiv. SCR

- Similar to “Multi-Infeed ESCR” (MIESCR)
- Allows consideration of other plants for evaluation of system strength for a single interconnection
- Allows consideration of FACTS (like STATCOM)
- Does not provide a common metric for a group of resources
- Requires more substantial calculation

$$SCRIF_i = \frac{S_i}{P_i + \sum_j \left(IF_{ji} * P_j\right)} \qquad IF_{ij} = \frac{\Delta V_i}{\Delta V_j}$$

Metrics – MVA vs. MW (eg. WSCR-MVA)

- Care should be taken with all simple metrics with de-rated wind capacity.
- You can use MVA rating of equipment, rather than Power
- Allows consideration of partial power generation
- Allows consideration of FACTS (like STATCOM)
- Similar limitations to WSCR
- *The reality is usually somewhere in between MW and MVA*

Comparison of SCR based metrics:

Table 2.1: Comparison of SCR Methods							
Metric		**Simple calculation using short circuit program**	**Accounts for nearby inverter based equipment**	**Provides common metric across a larger group of VER**	**Accounts for weak electrical coupling between plants within larger group**	**Considers non-active power inverter capacity***	**Able to consider individual sub-plants within larger group**
SCR	Short Circuit Ratio	★★	X	X	X	X	X
CSCR	Composite SCR	★	★★	★★	X	X	X
WSCR-MW	Weighted SCR using MW	★	★★	★★	★	X	X
WSCR-MVA	Weighted SCR using MVA	★	★★	★★	★	★★	X
SCRIF	Multi-Infeed SCR	X	★★	X	★★	★★	★★

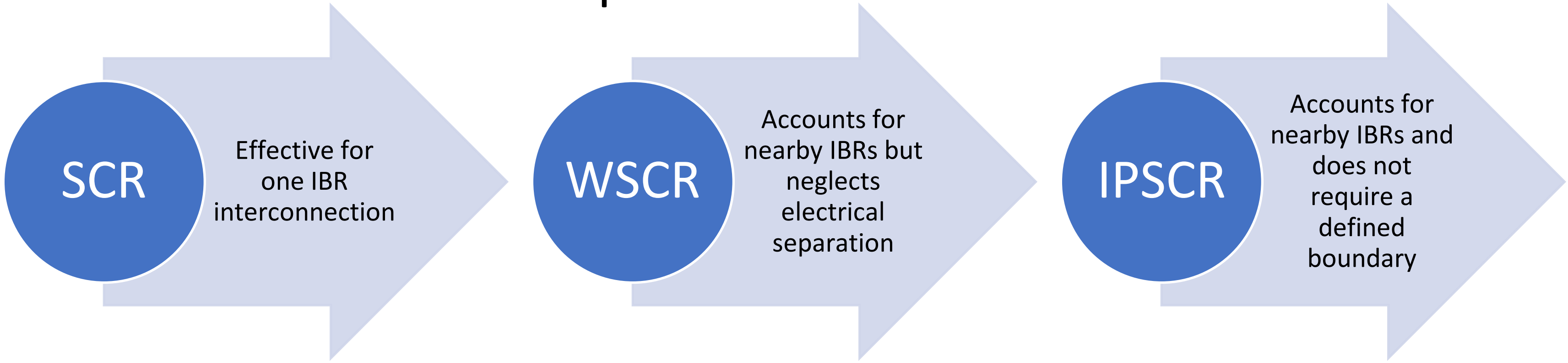
IPSCR

- Inverter Penetration SCR (IPSCR) [1]

$$IPSCR = \frac{SCMVA_{Case\ B}}{SCMVA_{Case\ C}}$$

IBR penetration ↑ **IPSCR** ↓

- Evaluates how much system strength comes from IBRs
  - Case B = case with all IBRs turned off
  - Case C = case with all conventional generation turned off and IBR Xsource tuned until it contributes 1 p.u. SCMVA

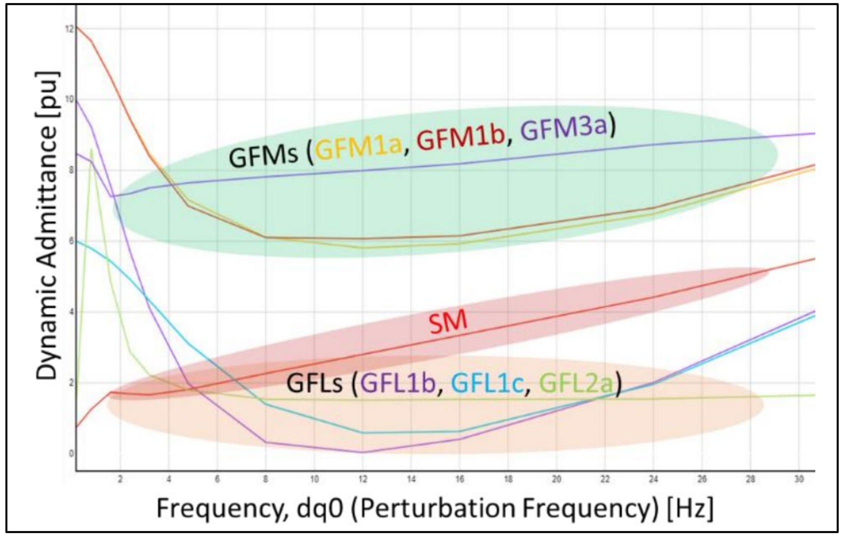


Can IPSCR be refined further?

[1] L. Unruh and A. Isaacs (2021), ‘Description of Inverter Penetration (IPSCR) Metric for Quantifying System Strength in Large Networks’

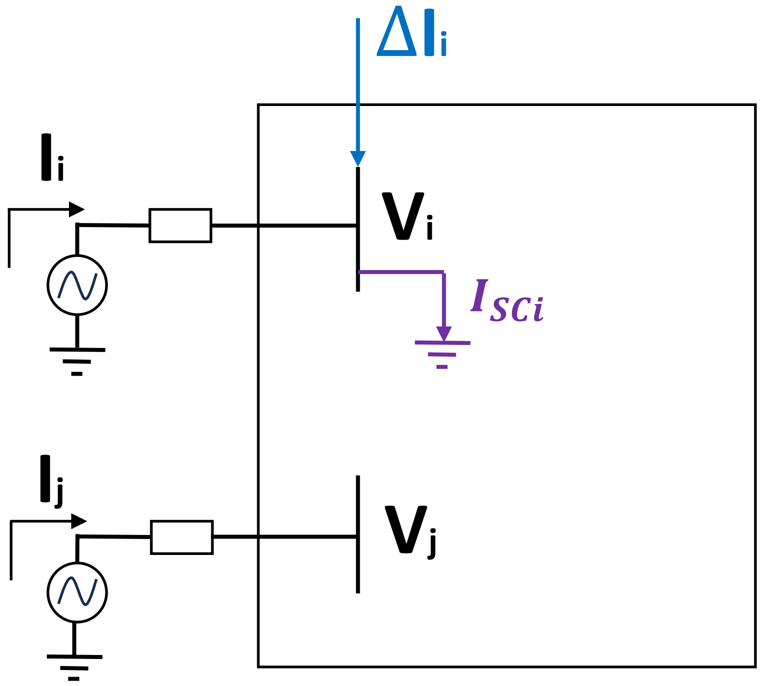
Generation Resource Characterization

- Industry has been exploring how to characterize GFM technology using impedance scans
- Entities are suggesting or requiring impedance scans for GFM technology
- Provides perspective on how technology will behave
- GFM technology routinely shows superior behaviour when compared to GFL and SM
- How do we tie resource characterization into our metric? We make it impedance based



Source: M. Richwine et al., Power System Stability Analysis & Planning Using Impedance-Based Methods, 2023

Modifying SCRIF



$$\begin{bmatrix}\Delta V_i \\ \Delta V_j\end{bmatrix} = \begin{bmatrix}Z_{ii} & Z_{ij} \\ Z_{ji} & Z_{jj}\end{bmatrix}\begin{bmatrix}\Delta I_i \\ \Delta I_j\end{bmatrix}$$

Calculate interaction factor:

$$\begin{bmatrix}\Delta V_i \\ \Delta V_j\end{bmatrix} = \begin{bmatrix}Z_{ii} & Z_{ij} \\ Z_{ji} & Z_{jj}\end{bmatrix}\begin{bmatrix}\Delta I_i \\ 0\end{bmatrix}$$

$$\Delta V_i = Z_{ii}\Delta I_i$$

$$\Delta V_j = Z_{ji}\Delta I_i$$

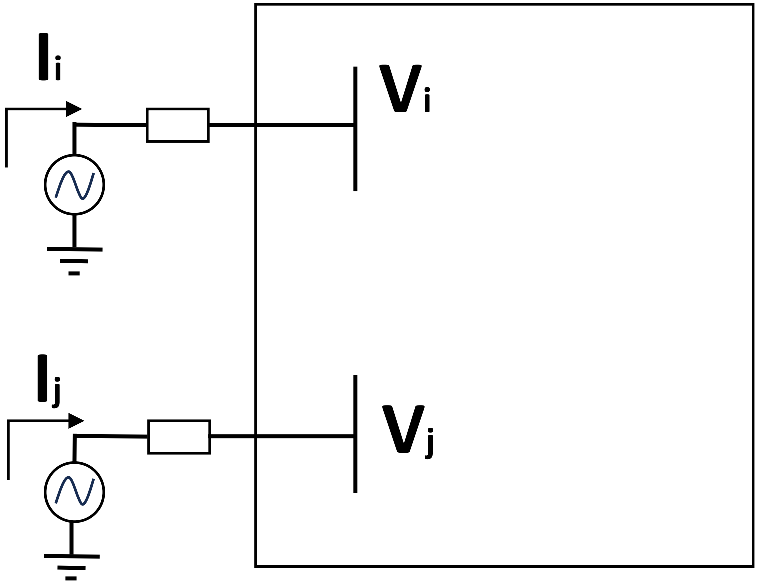
$$\longrightarrow \quad \frac{\Delta V_j}{\Delta V_i} = \frac{Z_{ji}}{Z_{ii}}$$

Calculate SCMVA:

$$\begin{bmatrix}\Delta V_i \\ \Delta V_j\end{bmatrix} = \begin{bmatrix}Z_{ii} & Z_{ij} \\ Z_{ji} & Z_{jj}\end{bmatrix}\begin{bmatrix}I_{SCi} \\ 0\end{bmatrix}$$

$$\Delta V_i = Z_{ii} I_{SCi} \longrightarrow I_{SCi} = \frac{\Delta V_i}{Z_{ii}} \longrightarrow SCMVA_i = \frac{\Delta V_i^{\,2}}{Z_{ii}}$$

Modifying SCRIF



Developing Impedance-Based SCR Metric:

$$SCRIF = \frac{SCMVA_i}{P_i + \sum_{j=1, j\neq i}^{n} (P_j * IF_{ji})}$$

$$IF_{ji} = \frac{\Delta V_j}{\Delta V_i} = \frac{Z_{ji}}{Z_{ii}}$$

$$SCMVA_i = \frac{{\Delta V_i}^2}{Z_{ii}}$$

$$SCRIF = \frac{\frac{{\Delta V_i}^2}{Z_{ii}}}{\sum_{j=1}^{n} \left(P_j * \frac{Z_{ji}}{Z_{ii}} \right)}$$

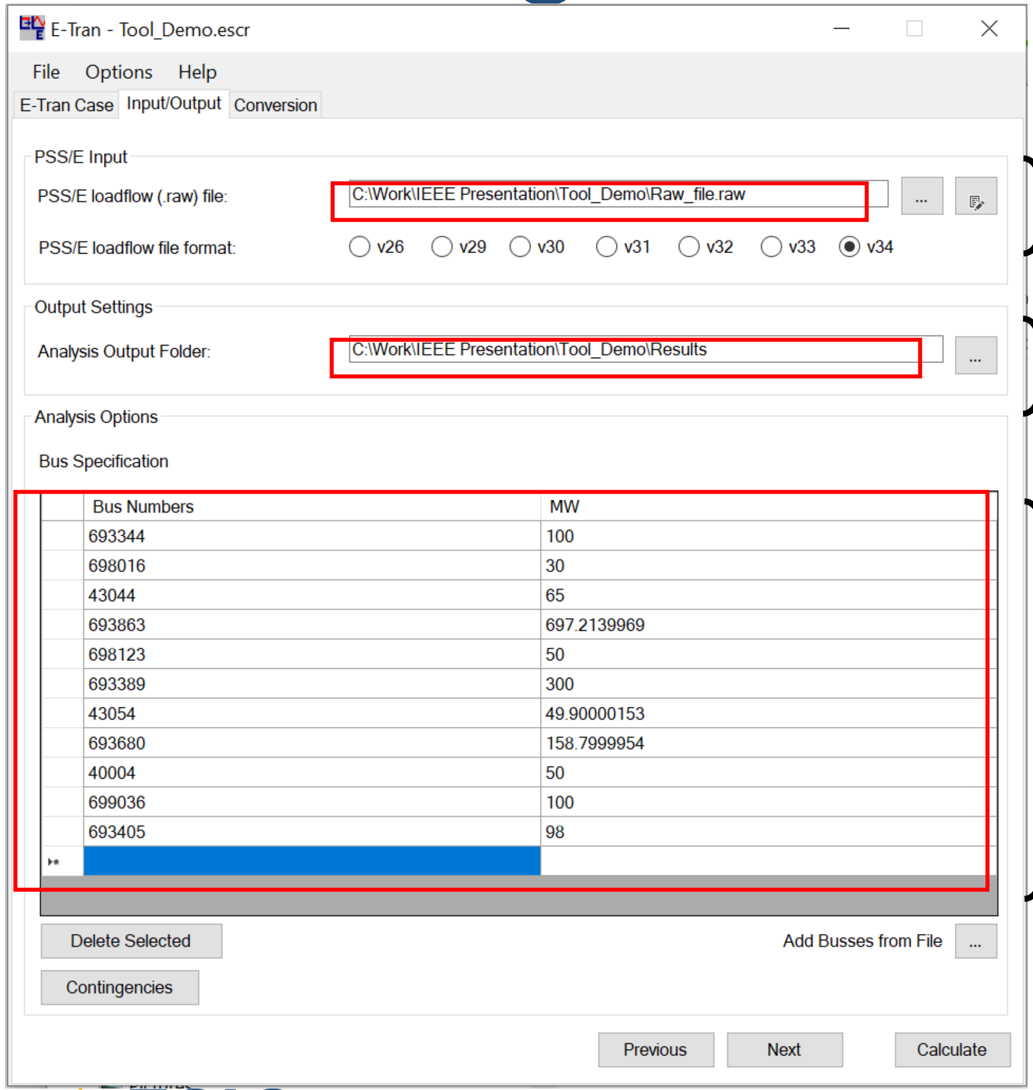
$$NSCR = \frac{{\Delta V_i}^2}{\sum_{j=1}^{n} (P_j * Z_{ji})}$$

Expanding to entire system

- The NSCR calculation can readily be expanded to large systems

Construct full system admittance matrix → Modify to develop contingency specific matrices → Reduce matrices based on POIs of interest → Invert admittance matrix to get impedance matrix → Calculate interaction factors → Compute NSCR values

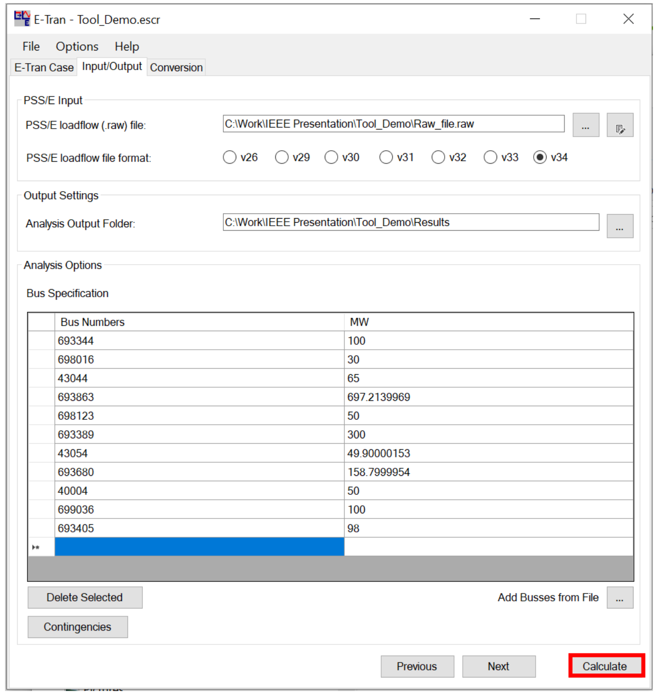
Building a tool…

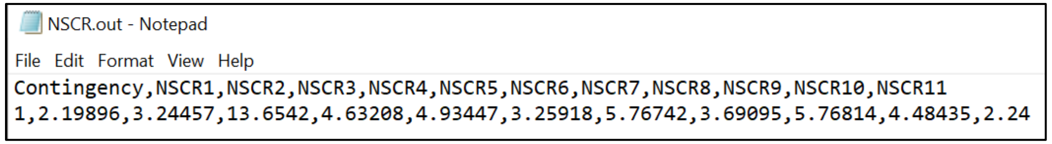


Raw file with correct Zsource

Folder to output results to

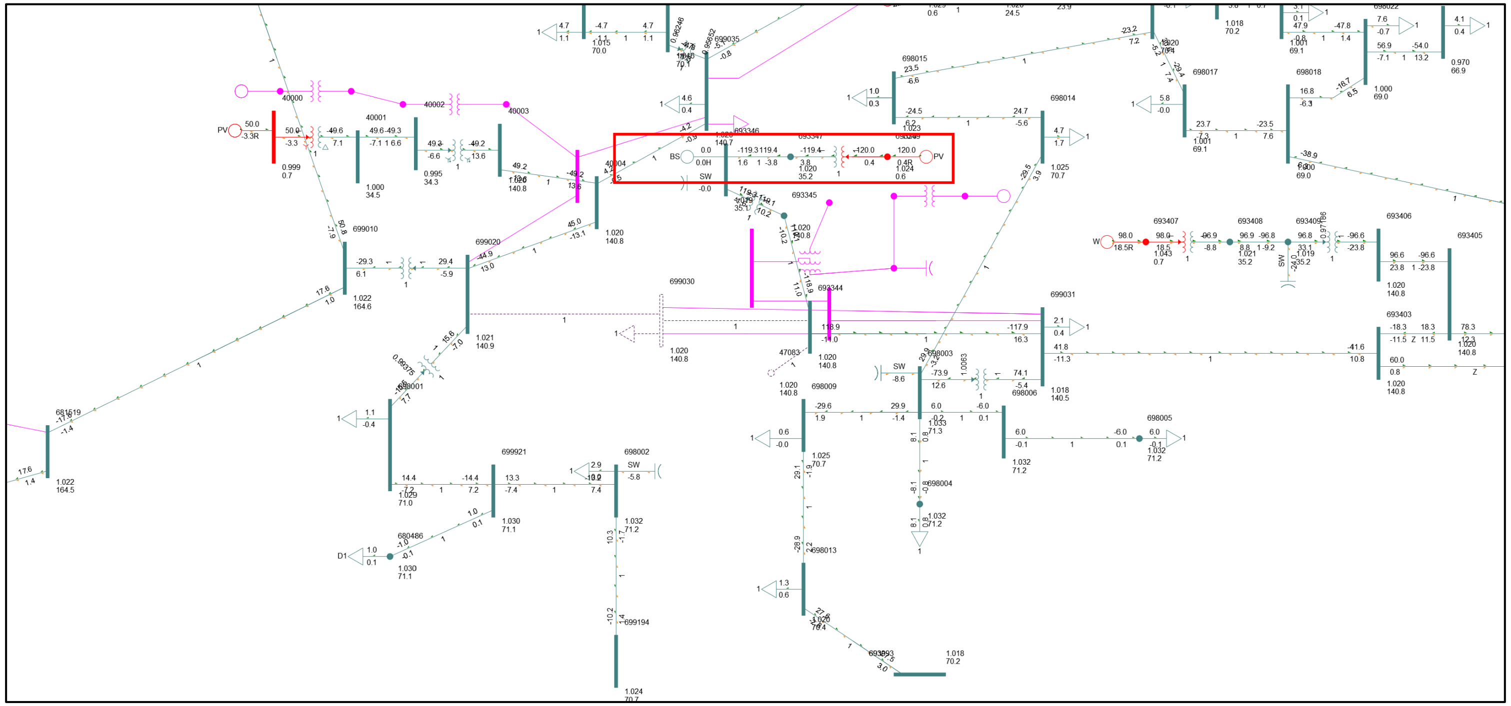
POI buses of interest and corresponding MW injections





Calibrating the tool

- We can use known system instabilities to set “bad” NSCR numbers



- PV plant was found to have:
  - Stability @ 100 MW
  - Marginal stability @ 120 MW
  - Instability @ 140 MW

Setting unstable NSCR values

```
Contingency,NSCR1,NSCR2,NSCR3,NSCR4,NSCR5,NSCR6,NSCR7,NSCR8,NSCR9,NSCR10,NSCR11
1,2.19896,3.24457,13.6542,4.63208,4.93447,3.25918,5.76742,3.69095,5.76814,4.48435,2.24
```

100 MW

```
Contingency,NSCR1,NSCR2,NSCR3,NSCR4,NSCR5,NSCR6,NSCR7,NSCR8,NSCR9,NSCR10,NSCR11
1,2.02501,3.17621,13.5431,4.60871,4.90736,3.23487,5.71591,3.66555,5.73015,4.44036,2.10722
```

120 MW

```
Contingency,NSCR1,NSCR2,NSCR3,NSCR4,NSCR5,NSCR6,NSCR7,NSCR8,NSCR9,NSCR10,NSCR11
1,1.87673,3.11084,13.4345,4.58567,4.88065,3.21101,5.66569,3.64057,5.69279,4.39756,1.9895
```

140 MW

Plant Dispatch	EMT Result	NSCR
100 MW	stable	2.1989
120 MW	marginally stable	2.0250
140 MW	unstable	1.8767

SCR-based metrics

- Key Takeaways
  - While lower SCR typically increases the likelihood of potential issues with inverter-based resources, these methods should be used as a screening tool for simple “radial” systems only.
  - Weak grid issues are system- and equipment-specific and it is difficult to define a “minimum system strength” criteria that can be applied uniformly.
  - What is “weak” for one manufacturer may not be a problem for another. What was “weak” for one manufacturer two years ago may no longer be difficult to achieve. The addition of a new piece of equipment may (through poor controls, for example) suddenly destabilize otherwise very well controlled existing equipment.

Appropriate use of SCR-based metrics

- Use metrics to gain a high-level understanding of relative impact of the interconnecting plant
- If there is any concern, involve planners, developers, and manufacturers to identify potential risks
- Use that understanding, *combined with specific knowledge of the equipment and transmission system*, decide whether further study is required.

- Note: it is very difficult to use SCR to set planning guidelines and thresholds

Mitigation Alternatives

- If a small SCR suggests there may be problems, mitigation is directly suggested by the formula…
- How do we fix a weak system problem?

$$SCR_{POI} = \frac{SCMVA_{POI}}{MW_{VER}}$$

Mitigation alternatives

- *SMALLER GENERATORS!*
- Selective curtailment or RAS
- More transmission
- Larger transformers
- Series capacitors (careful)
- Control tuning
- Synchronous Condensers
- FACTS (SVC or STATCOM?)
- **GFM Batteries!!**