TESLA

Tesla Perspective

ERCOT Grid: AGS-ESR

Functional Specification and

Test Requirements

LAST EDITED
01.08.25

Agenda

- ➢ Tesla's Experience with GFM
- ➢ Tesla's Perspective
    - Test 2: Phase jump
    - Test 3: Small voltage disturbance
    - Test 4, 5 and 6
- ➢ Conclusion

Tesla's Experience

Tesla's **Grid forming** technology has been deployed at scale

2022

Tesla demonstrates largest GFM battery in Australia

110+

Operating off-grid microgrid projects globally

565 MWh

Largest operational GFM resource globally, 158 Megapacks

30+ GWh

Total global deployment

Demonstrated Experience: Utility-Scale & Microgrids

Key GFM Projects

KES—Oahu, HI, USA

185 MW / 565 MWh
Commissioned 2023
GFM & Blackstart

Victoria Big Battery—AUS

300 MW
Commissioned 2021
GFM 2025*

Riverina & Darlington—AUS

150 MW
Commissioned GFM 2023

Hornsdale—AUS

100 MW
Commissioned 2017, expanded 2020
GFM 2022

KIUC – Kauai, HI, USA

13 MW / 52 MWh
Commissioned 2017
GFM 2018

Wallgrove—AUS

50 MW
Commissioned GFM 2021

Redwood Microgrid—CA, USA

2.3 MW / 9 MWh
Commissioned
Reliability in extreme weather

Korrangie—AUS

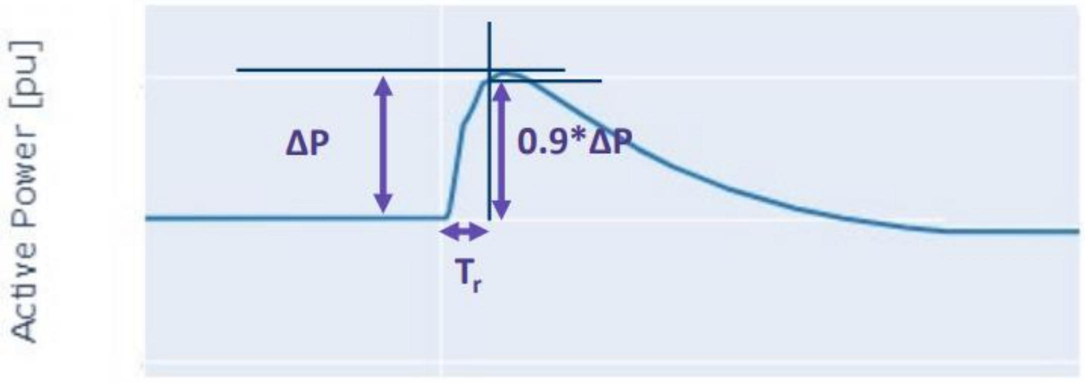
Commissioning expected 2025*

*upcoming GFM projects

Test 2: Phase Angle Jump

Requires increase of 0.2 pu for 10-deg drop @ SCR 3

Performance Criteria
A. Instantaneous active power output of the plant should quickly respond to oppose the angle change. The peak active power change should be at least 0.2 pu (based on rated active power) for each 10-degree voltage phase angle change, in opposing direction. (e.g., A 100 MW rated plant should temporarily decrease active power output from 100 MW to 80 MW, or below, when source voltage angle is increasing 10 degrees; and it should temporarily increase active power from 100 to at least 120 MW, if the current limit allows, when voltage source angle is decreased by 10 degrees.)



Summary:

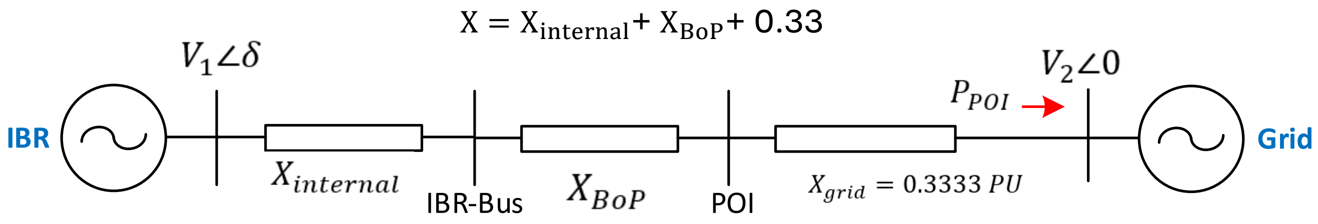
For10-degree angle jump
→ Tr ≤ 1 Cycle

ΔP: Initial change

https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf
https://www.ercot.com/files/docs/2024/10/09/ERCOT%20AGS-ESR%20Oct-11-2024%20IBRWG.pdf

Test 2: Phase Angle Jump

Power change is a function of total impedance and the requirement is not always achievable



Assumptions:

- Initial P = 1 PU
- V_2 and V_1 equal 1 PU and stay constant

$$\Delta P = \left(\frac{\sin(\Delta\ \delta + \delta_0)}{\sin\ \delta_0} - 1 \right), \quad \sin\ \delta_0 = X$$

Requirement boundary :

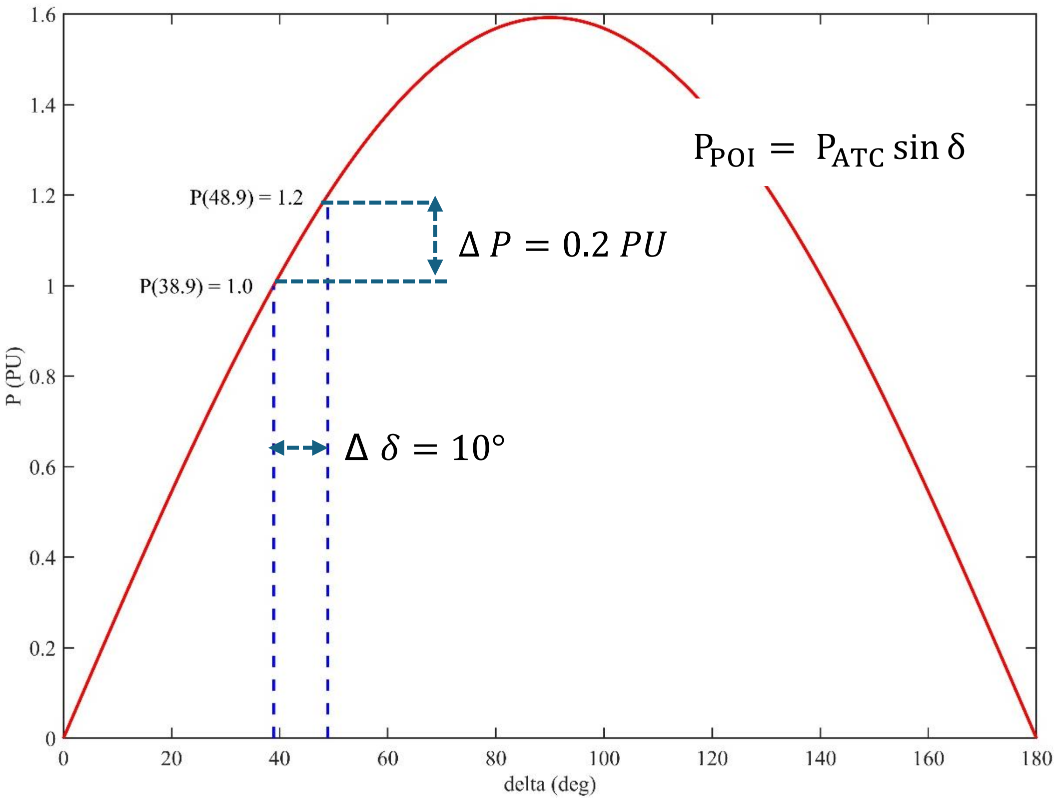
- ΔP at least 0.2 PU for 10-degree angle change

$$\delta_0 \leq 38.9,\ or\ \ X\ \leq 0.63\ PU$$

$$\boxed{X_{internal} + X_{BoP} \leq\ \ 0.29\ PU*}$$

- ΔP at least 0.5 PU for 25-degree angle change

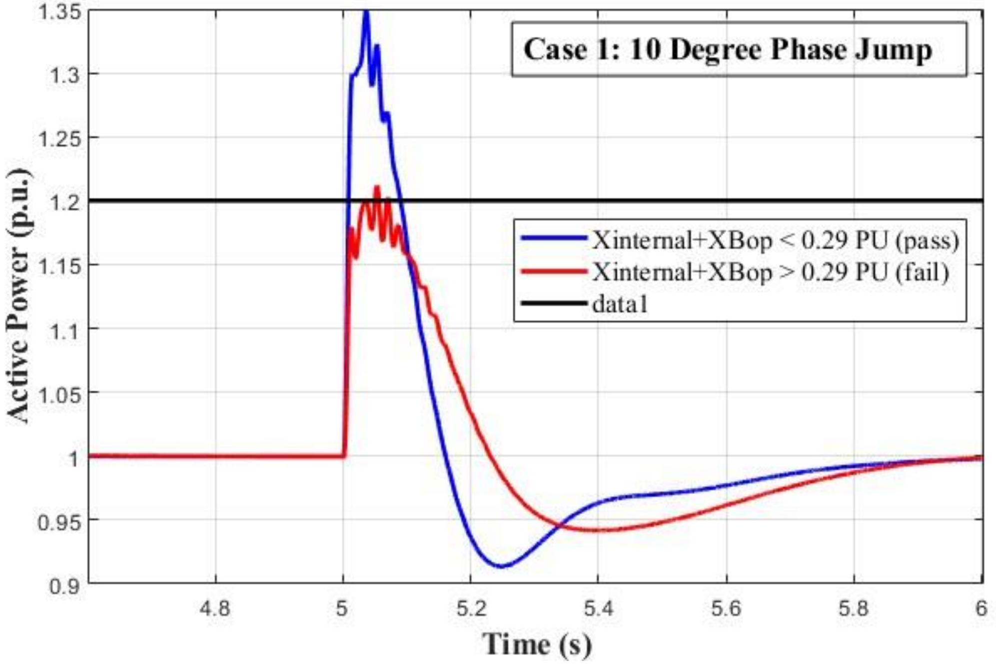
$$\boxed{X_{internal} + X_{BoP} \leq\ \ 0.25\ PU*}$$

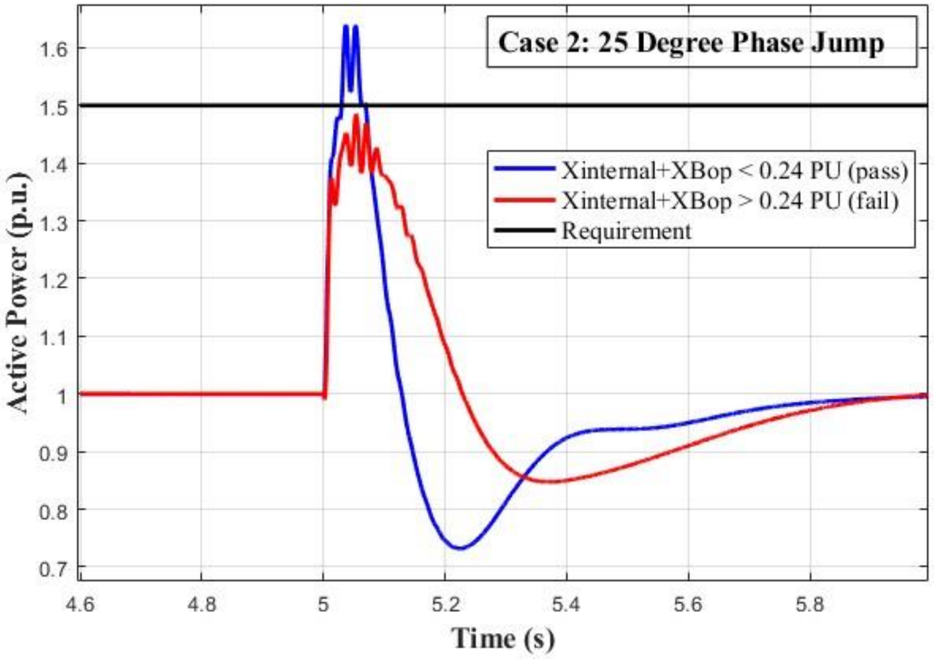


*On POI real power base

Test 2: Phase Angle Jump

Simulation results confirm the boundary condition





Test 2: Phase Angle Jump

Recommendation

Generalized Equation :

$$\Delta P \geq \min\left(0.02\,\Delta\delta, \left((\cos\Delta\delta - 1) + \sin\Delta\delta\,\frac{\sqrt{1-X^2}}{X}\right)\right), for\ \Delta\delta\ \epsilon\ [10°, 25°]$$

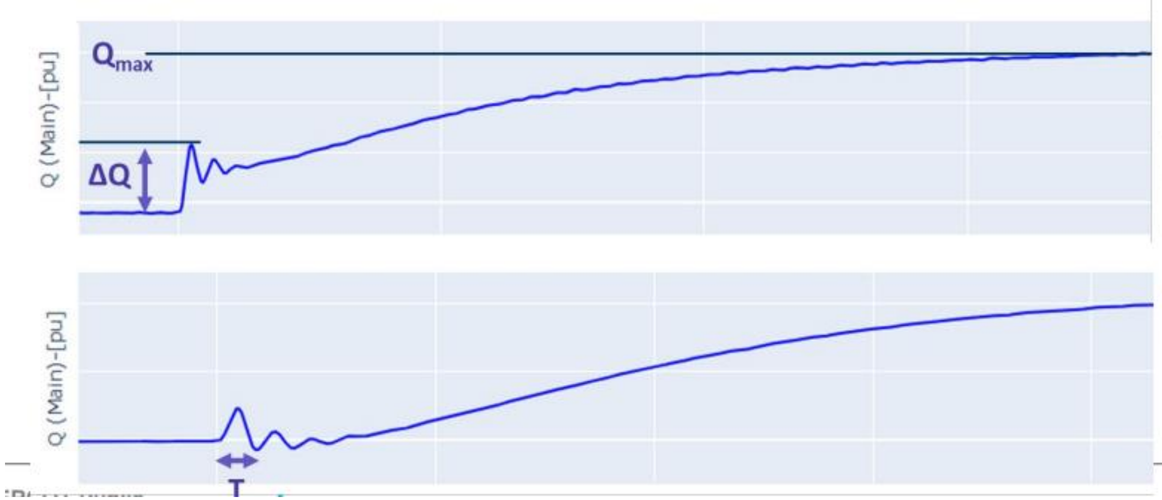
Angle jump	X=30%	X=40%	X=50%	X=60%	X=70%
10	0.53	0.38	0.29	0.22	0.16
25	1.25	0.87	0.64	0.47	0.34

$X = X_{internal} + X_{BoP} + 0.33$

Test 3: Small Voltage Disturbance

Requires reactive power change of 0.03 PU for 3% voltage step change

Performance Criteria
A. Instantaneous reactive power output of the plant should quickly respond to oppose the voltage step change for each of the 3% voltage step changes, with an initial peak reactive power change of at least 0.03 pu on the rated power base (e.g., A 100 MVA rated plant with 0 MVAR initial output should instantaneously increase reactive power output from 0 MVAr to at least 3 MVAr when source voltage magnitude is decreased by 3%.) Note: Reactive power does not return to the pre disturbance level within 6 cycles.
B. Response time to 90% of initial change in instantaneous reactive power should occur within 1 cycle
C. Any oscillation shall be damped.
D. The final reactive power after each 3% step change is expected to reach to the maximum reactive capability of the plant in an attempt to regulate the original voltage set point at 1.0 pu.



Summary:

ΔQ ≥ 0.03 pu

T ≥ 6 Cycles

Tr ≤ 1 Cycle

Tr : the time Q reaches to 0.9* ΔQ

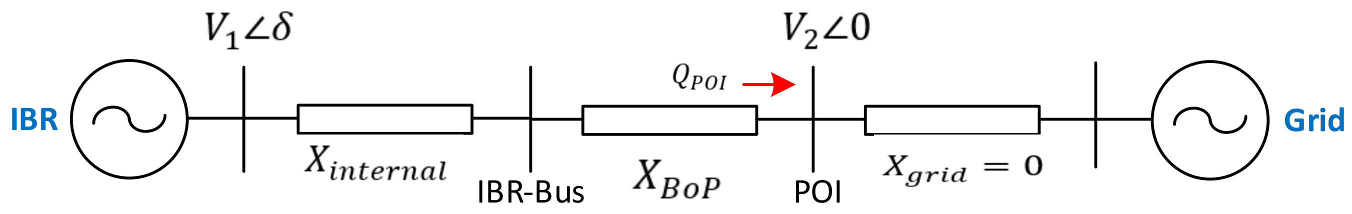
Reactive power reaches to Qmax

https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf
https://www.ercot.com/files/docs/2024/10/09/ERCOT%20AGS-ESR%20Oct-11-2024%20IBRWG.pdf

Test 3: Small Voltage Disturbance

Reactive power change requirement is achievable

$$Q_{\mathrm{POI}} = \frac{V_2}{X}(V_2 \cos\delta - V_1)$$



$$X = X_{internal} + X_{BoP} + X_{grid}$$

Assumptions:

- δ does not change instantaneously
- V_2 and V_1 equal 1 PU stay constant
- δ is small

Boundary Requirement :

- ΔQ of at least 0.03^* PU for 3% voltage change

$$X \leq 0.95\,(\cos\delta\,.\,(2V_2 \pm \Delta V) - V_1)$$

$$\boxed{X \leq 0.92\,PU}$$

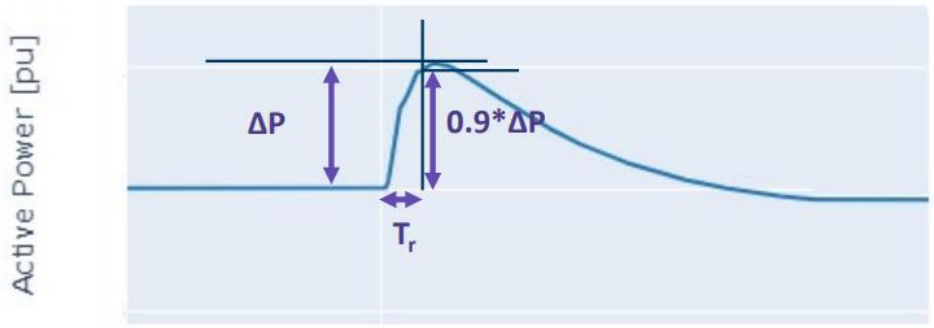
* ΔQ of 0.03 PU on P base is equivalent to 0.03159 PU on S base assuming 0.95 PF

Additional requirements

Rise time requirements

- Phase Angle Jump

B. For the 10-degree voltage phase angle jumps, response time to 90% of initial change in instantaneous active power should occur within one cycle.



Summary:

For10-degree angle jump
→ Tr ≤ 1 Cycle

ΔP: Initial change

Does the one-cycle condition for rise time apply to the case with a 25-degree setting, or is it only relevant to the 10-degree case?

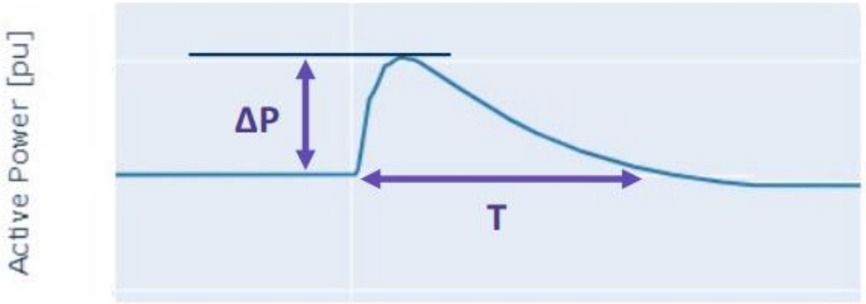
https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf
https://www.ercot.com/files/docs/2024/10/09/ERCOT%20AGS-ESR%20Oct-11-2024%20IBRWG.pdf

Additional requirements

Current limit exceptions

- Phase Angle Jump

Note: If the pre-event dispatch causes the plant to reach the current limit in the inverter when the angle jump is applied, the performance criteria described above (criterion A) may not apply. However, the active power must return to the pre-disturbance level in a stable manner without causing undue degradation of system performance. The active power must be more than or equal to pre disturbance level for at least 3 cycles.



Summary:

For 10-degree angle jump → ΔP ≥ 0.2 pu

For 25-degree angle jump → ΔP ≥ 0.5 pu

T ≥ 3 Cycles

Does the 3-cycles condition apply only when the plant reaches the current limit?

https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf
https://www.ercot.com/files/docs/2024/10/09/ERCOT%20AGS-ESR%20Oct-11-2024%20IBRWG.pdf

Additional requirements

Step change in frequency

- Frequency Change and Inertia Response

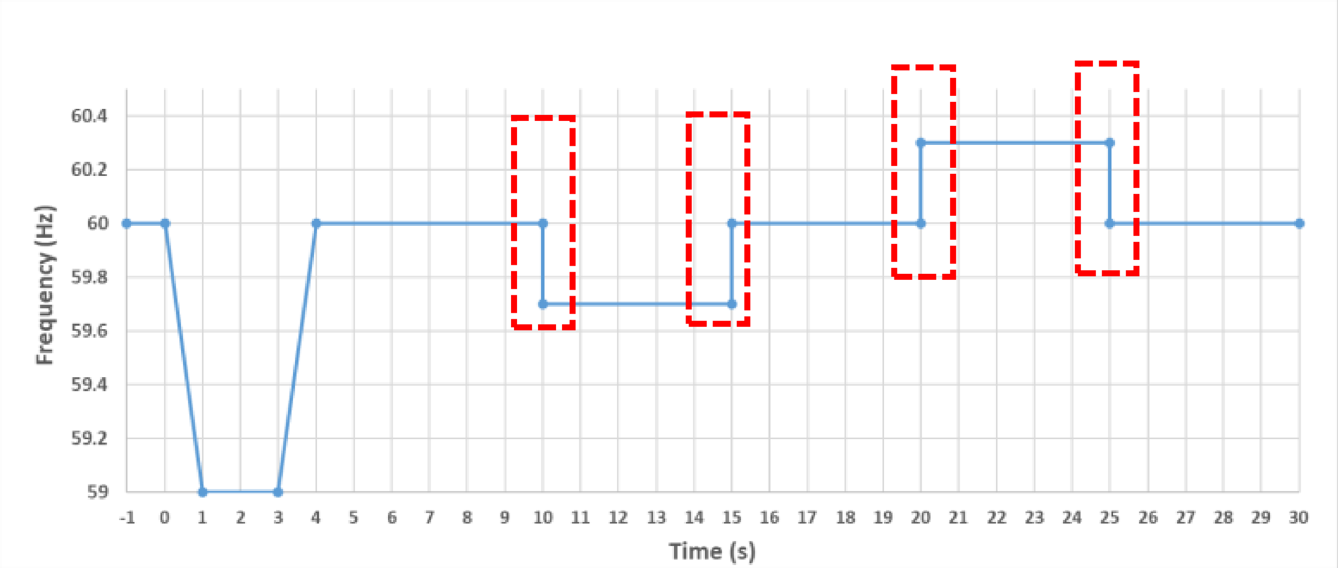


Figure 3. The frequency profile for frequency change and inertia response test

Is it intentional to have a step change in frequency rather than a rate of change of frequency (ROCOF)?

https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf

Additional requirements

Some requirements are subject to interpretation; Recommend using a quantitative approach

- Frequency Change and Inertia Response

Performance Criteria
A. Plant real and reactive power output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels for any significant amount of time.

- System Strength Test

Performance Criteria
Plant real and reactive power output and RMS voltage should be well controlled, and plant shall not trip nor reduce power or voltage (outside of the fault period) for any extended period of time down for all tested SCR range from 10 to 1.2

- Loss of Synchronous Machine Test

Performance Criteria
A. Immediately following the disconnection of voltage source, both plants' output should be well controlled. System frequency and voltage should settle to a stable operating point (within 5 seconds) and not oscillate excessively and damped within 10 seconds or deviate from steady state levels.

https://www.ercot.com/files/docs/2024/09/16/ERCOT%20Advanced%20Grid%20Support%20ESR%20Test%20Requirement_.pdf

Conclusion

- Tesla's analysis and simulations results reveal site-specific dependencies for phase angle test outcomes
    - Recommends adding flexibility to the requirement based on site-specific impedance
- Tesla's analysis revealed reactive power change requirement is achievable for all reasonable sites
- Recommends using quantitative requirements instead of qualitative requirement, which are subject to interpretation

Q&A