New Methods for Measuring Voltage Stability Limits Utilizing HELM™ Tools

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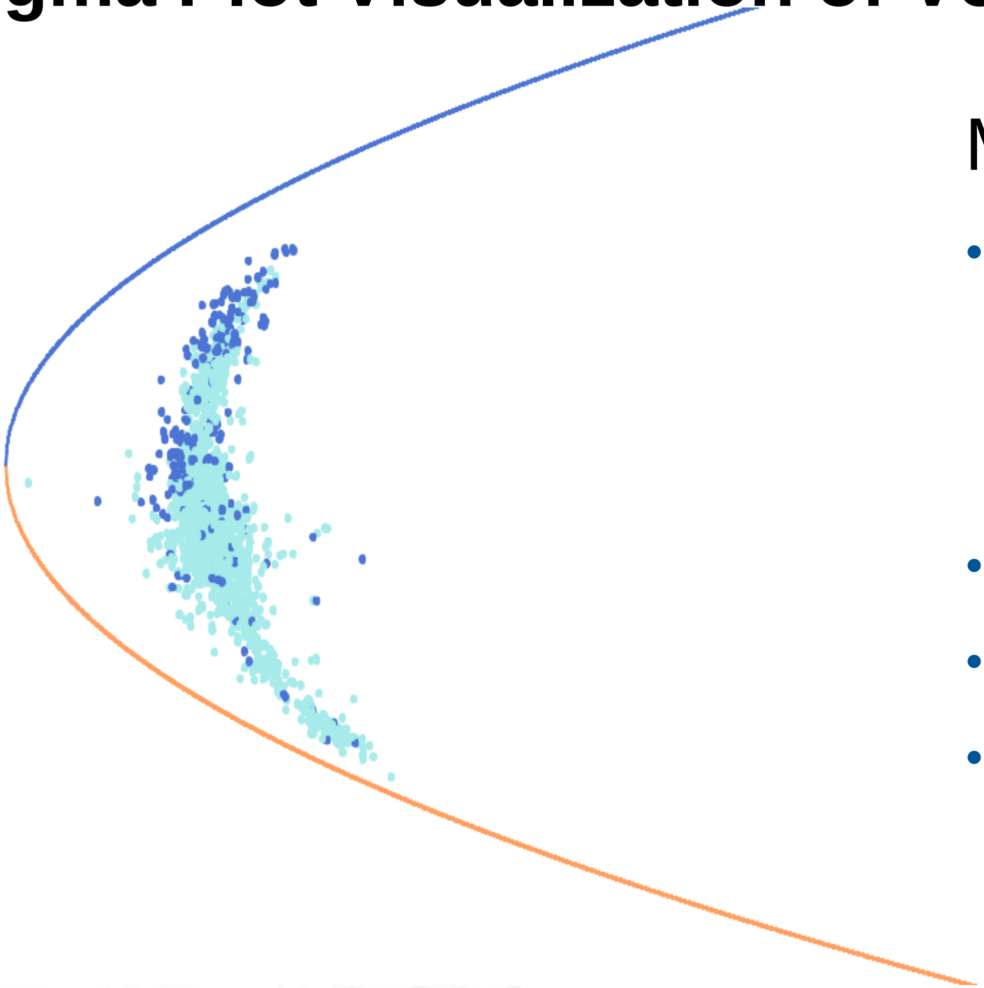
Today's Topic –
Sigma Plot Visualization of Voltage Stability



My goals:

- Share a new approach
  - Based on HELM™
  - Node-by-node visualization of your grid
- Share two examples
- Discuss applications
- Get you to think about uncovering new applications of this tool

What would you do with an easy approach to visualizing voltage stability?

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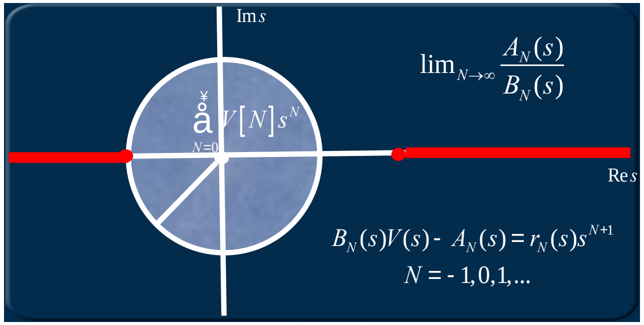
Context

- Battelle/Gridquant Collaboration
- HELM™ - Holomorphic Embedding Loadflow Method by Gridquant
- A deterministic solution to the load flow equation
  - No need for seed
  - Works in stressed conditions, up to collapse (and beyond)
  - See distance to collapse
  - Visualize voltage stability
  - Determine paths to a desired state – limit violation solver, restoration tool (HELM-Agora)

In order to apply HELM, Gridquant uncovered some interesting properties of the sigma plot

HELM™ Math

- Useful references - www.gridquant.com/technology
  - 2012 IEEE paper by Trias
  - Two bus model proof
  - Patents

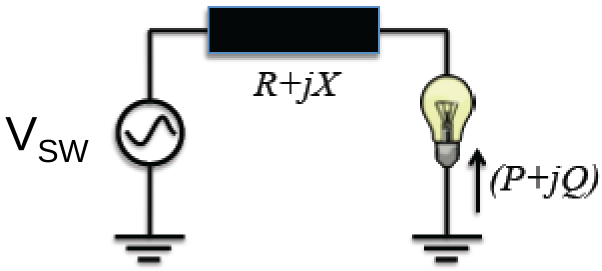


- HELM process narrative
  - Embed the non-linear, constant power contribution $S \rightarrow sS$
  - Cast into algebraic curve, represent as power series up to singularity radius, compute coefficients deterministically using power series and its reciprocal, perform analytic continuation using an algebraic approximant (Pade)
  - Stahl's Theorem (1997) permits a unique analytic continuation to s=1

Holomorphic Embedding and Analytic Continuation deliver a deterministic solution

The Sigma Plot – The Two-Bus Model

- Nonlinear model at each PQ bus
- Two bus model: V_{sw}, $Z=R+jX$, $S=P+jQ$
- Load flow equation in the form of



Sign convention: P,Q positive when injecting *into the node*

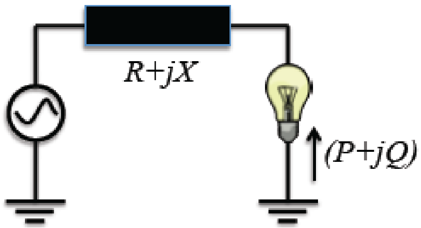
$$\frac{V - V_{sw}}{Z} = \frac{S^*}{V^*} \implies \frac{V}{V_{sw}} = 1 + \frac{ZS^*}{\|V_{sw}\|^2 \frac{V^*}{V_{sw}^*}}$$

Defining $U \equiv {}^{V}/_{V_{sw}}$ and $\sigma \equiv {}^{ZS^*}/_{\|V_{sw}\|^2}$. $(\sigma = \sigma_R + j\sigma_I)$.

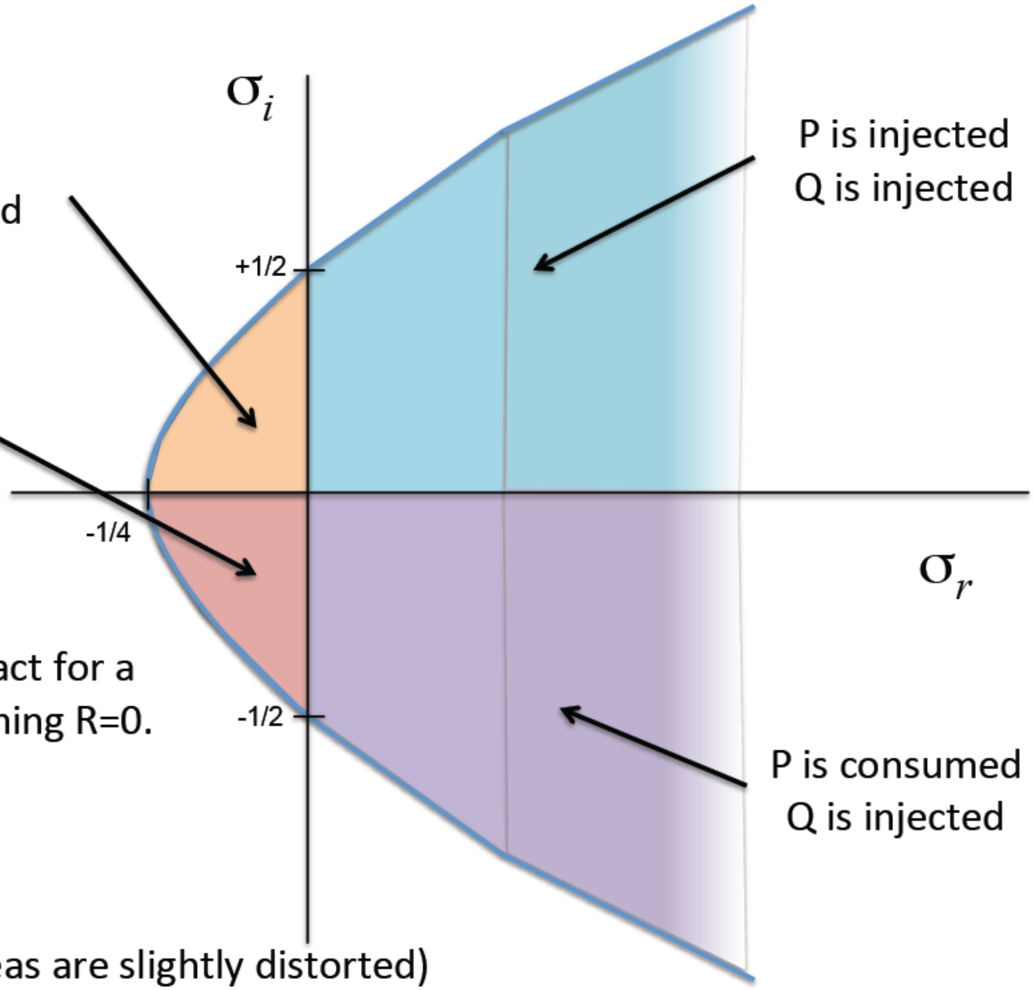
$$U = 1 + \frac{\sigma}{U^*} = \frac{1}{2} \pm \sqrt{\frac{1}{4} + \sigma_R - \sigma_I^2 + j\sigma_I}$$

We now have a stability boundary defined by a collection of sigma values that make the radicand zero

The Sigma Plot – What does it tell you?



Sign convention: P,Q positive when injecting *into the node*



Remember this is only exact for a two-bus model and assuming R=0.

$$\sigma_r = XQ + RP \simeq XQ$$

$$\sigma_i = XP - RQ \simeq XP$$

(if R is not zero, these areas are slightly distorted)

But is this visualization useful for N buses?

The Sigma Plot – The N-bus model

- The HELM™ approach is applied to the load flow equation for N nodes. Voltages become holomorphic functions of the complex variable s

$$\sum_j Y_{ij} V_j(s) + Y_i^{sh} V_i(s) = \frac{s\, S_i^*}{V_i^*(s^*)}$$

- Holomorphic embedding calculates the voltages as a power series, evaluated by analytic continuation (variation on a Pade approximant) to define a new set of functions:

$$V_i(s) = 1 + \frac{s\, \sigma_i(s)}{V_i^*(s^*)}$$ (recall $U = 1 + \frac{\sigma}{U^*}$ for two bus model)

- Analogous to a local, nonlinear, dimensionless Thevenin equivalent

HELM permits determination of sigma without initial voltages. In fact, sigma can be determined when voltage cannot.

The Sigma Plot – Case 1 - Base

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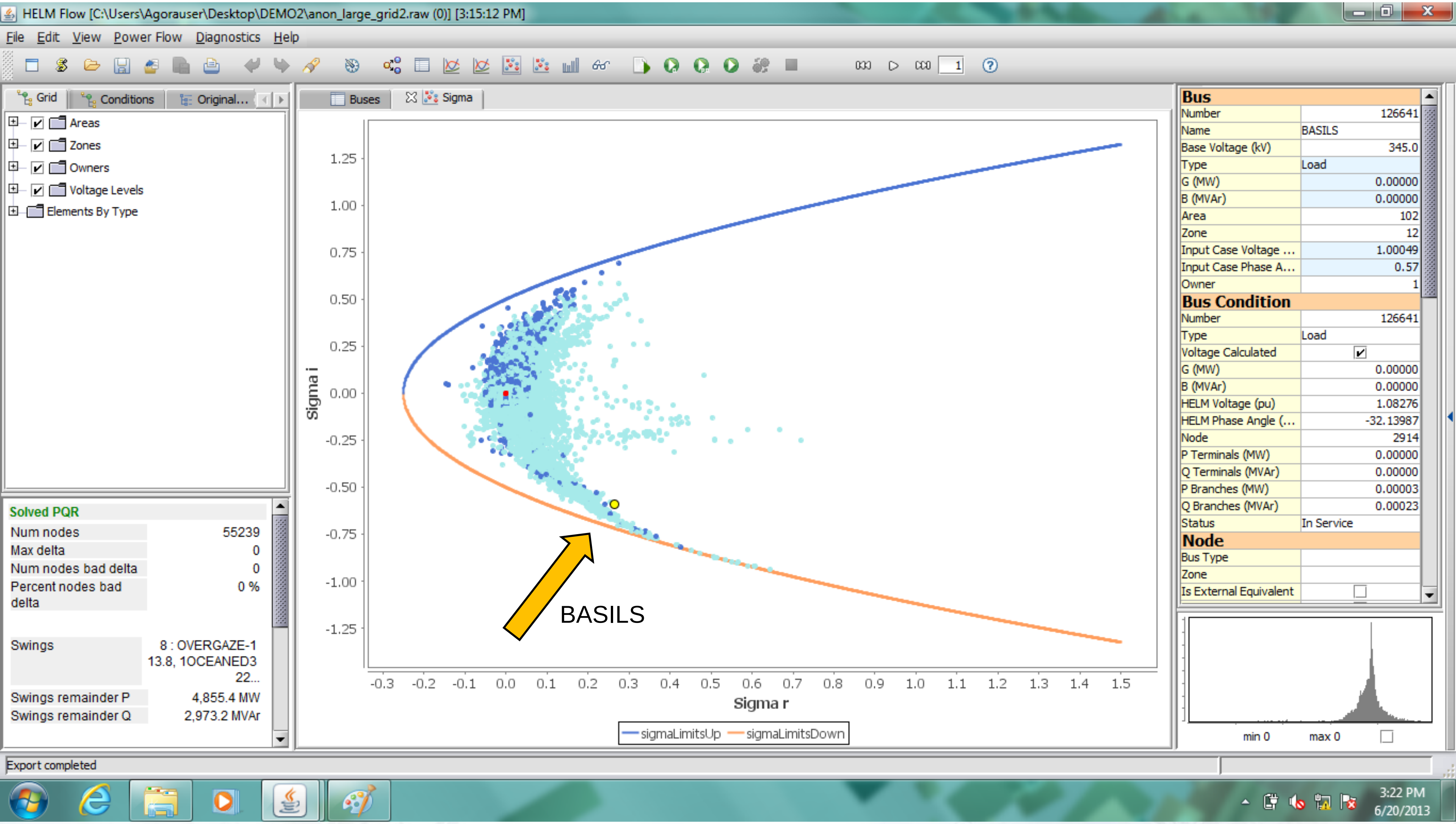
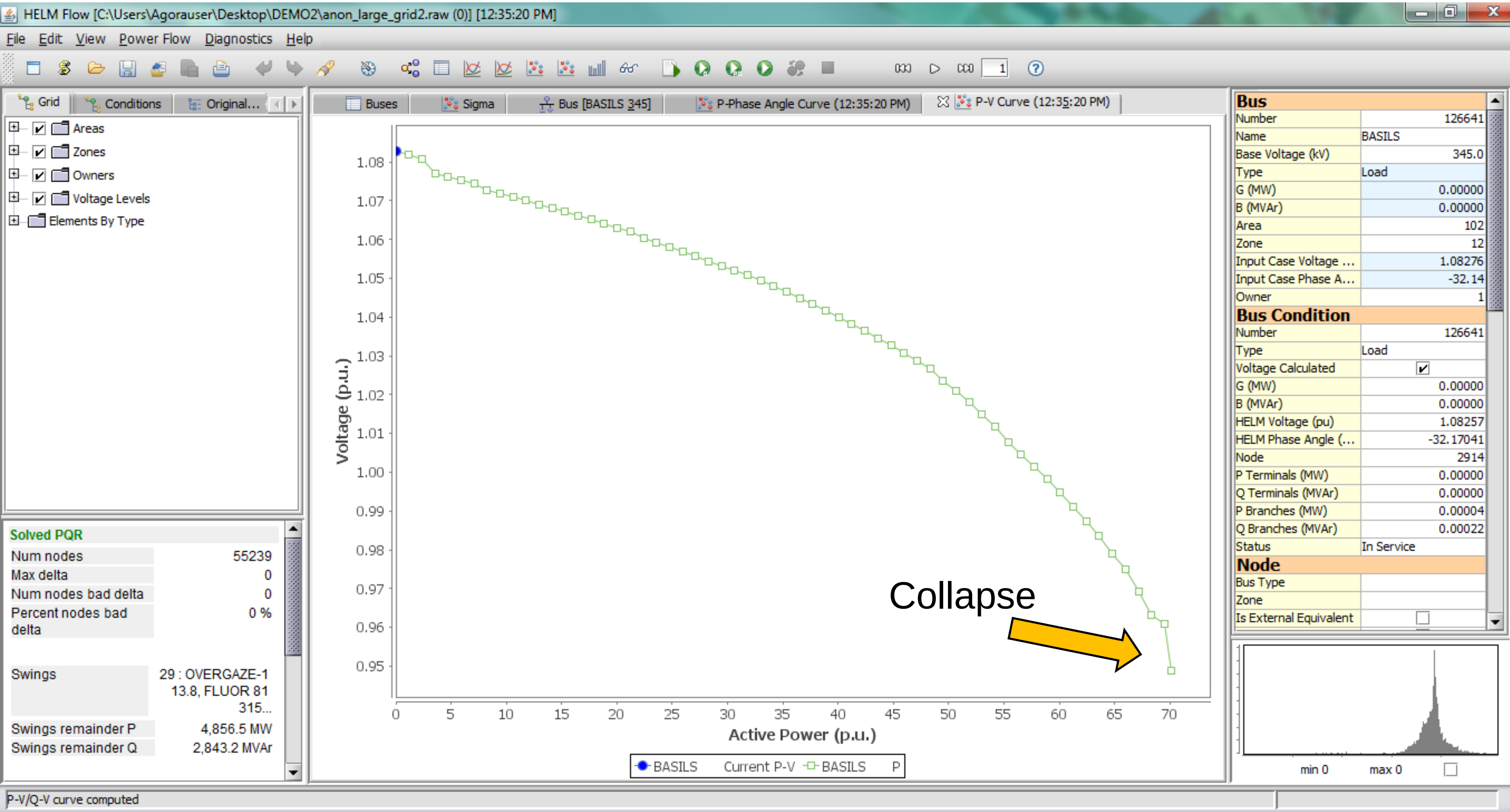


Anonymized model – 55239 nodes

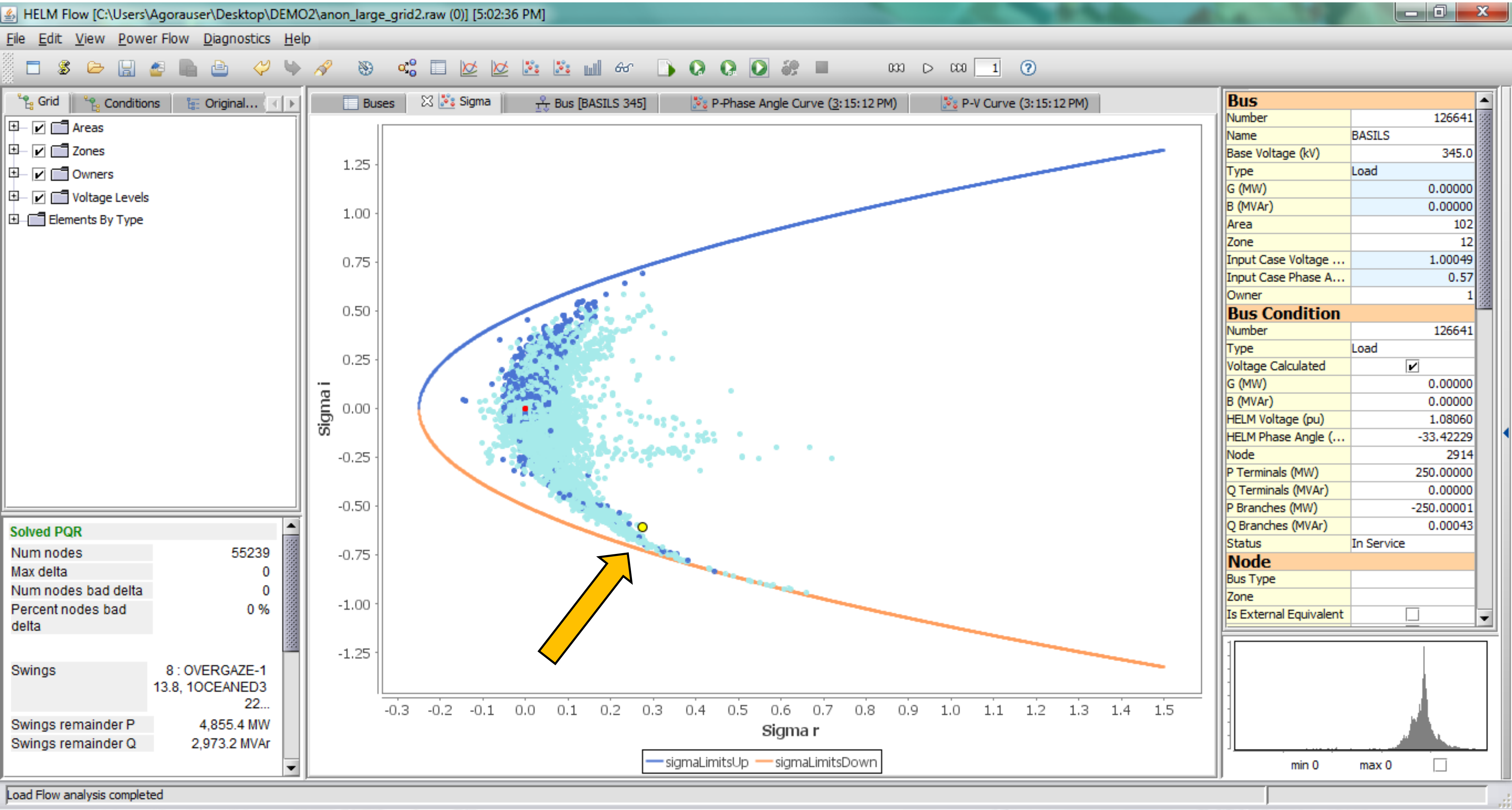
Examining the "BASILS" node under increased load

The Sigma Plot – Case 1 – PV Curve



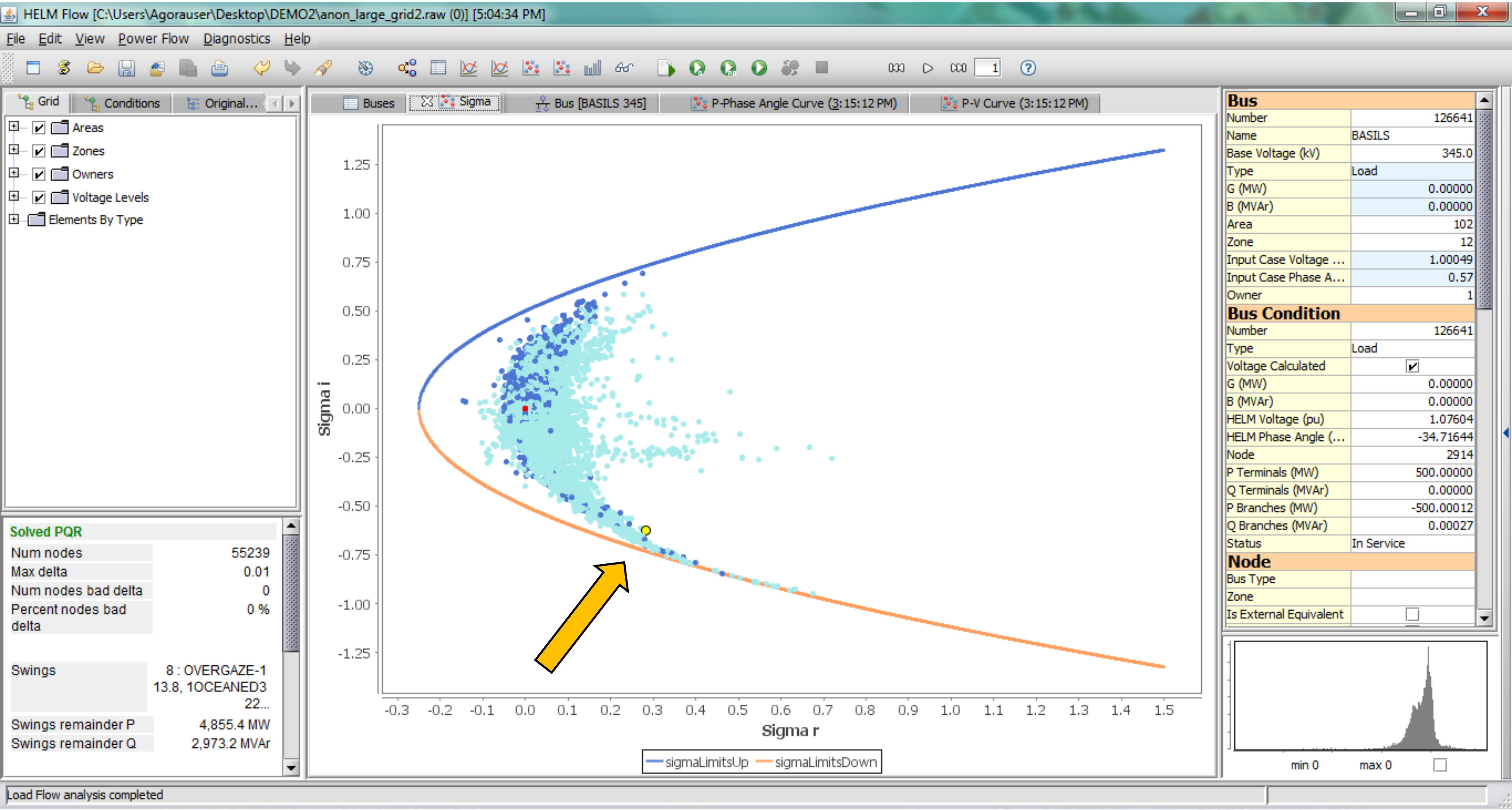
PV Curve for "BASILS" showing distance to collapse
(Scale: 10 = 1,000MW)

The Sigma Plot – Case 1 – P=250MW



We start changing load on the bus

The Sigma Plot – Case 1 – P=500MW



A small increase shows motion in BASILS, but also many nodes in the vicinity

The Sigma Plot – Case 1 – P=2,500MW

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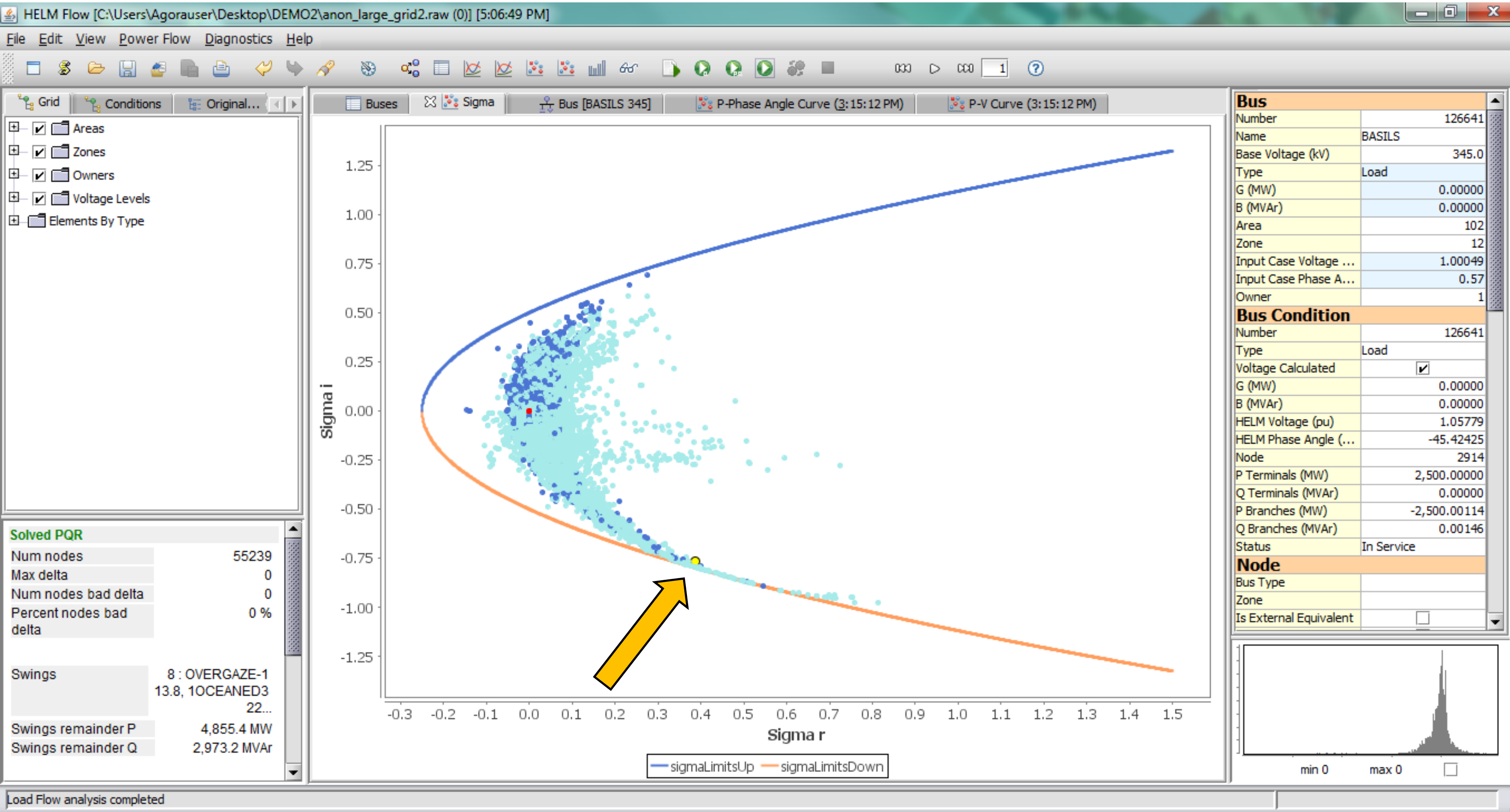

Motion towards the collapse parabola

The Sigma Plot – Case 1 – P=6,500MW

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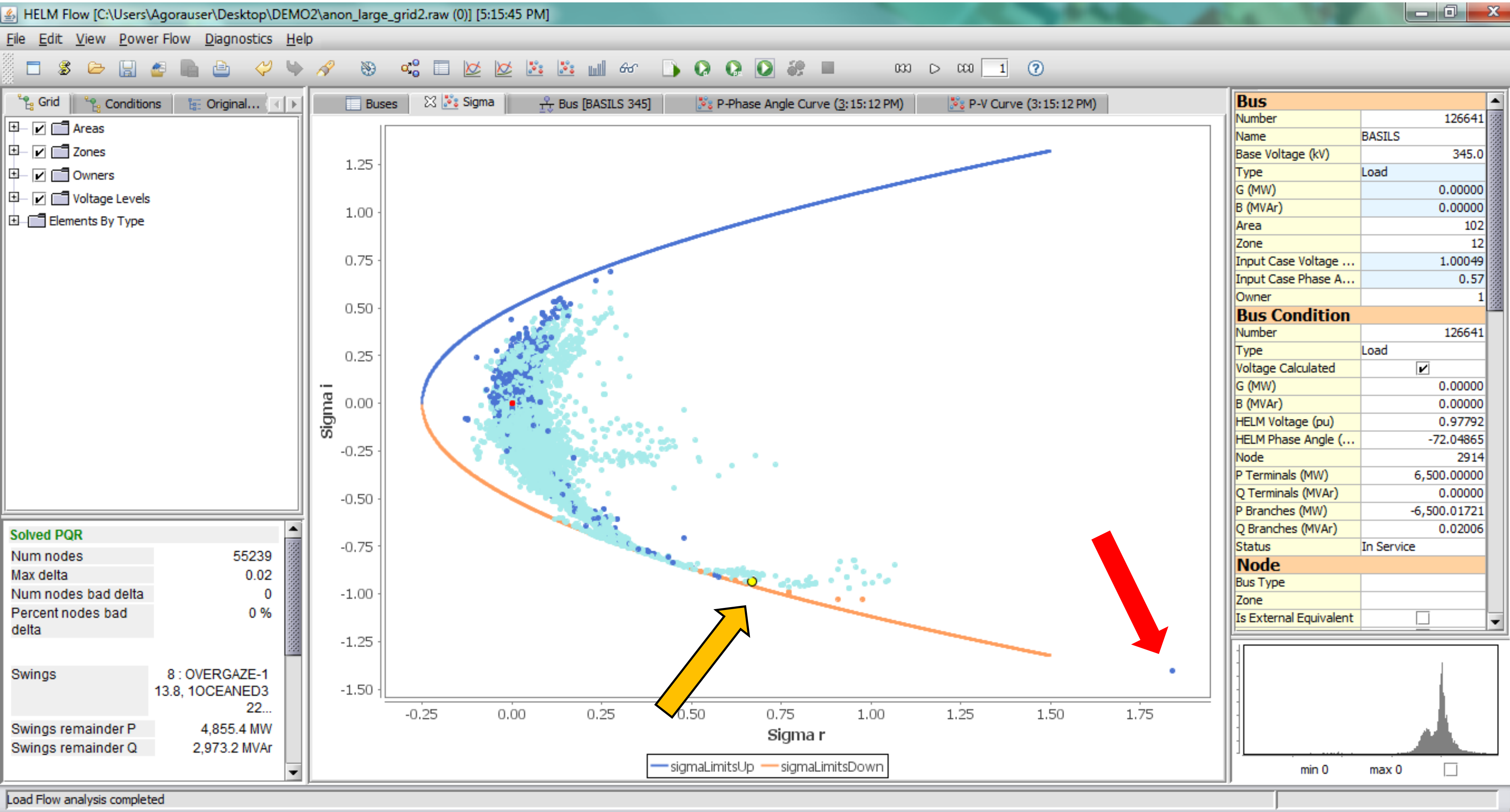
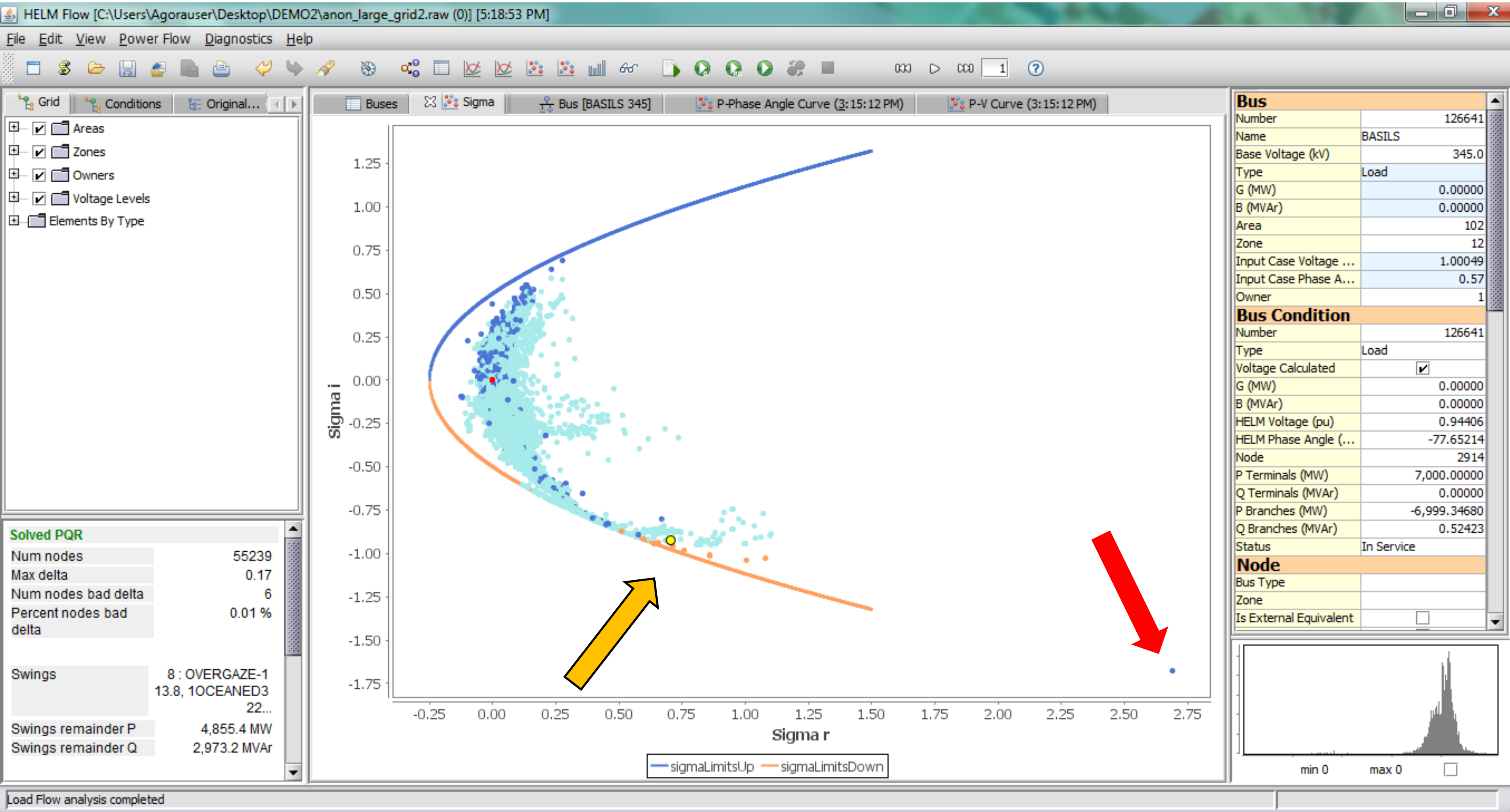


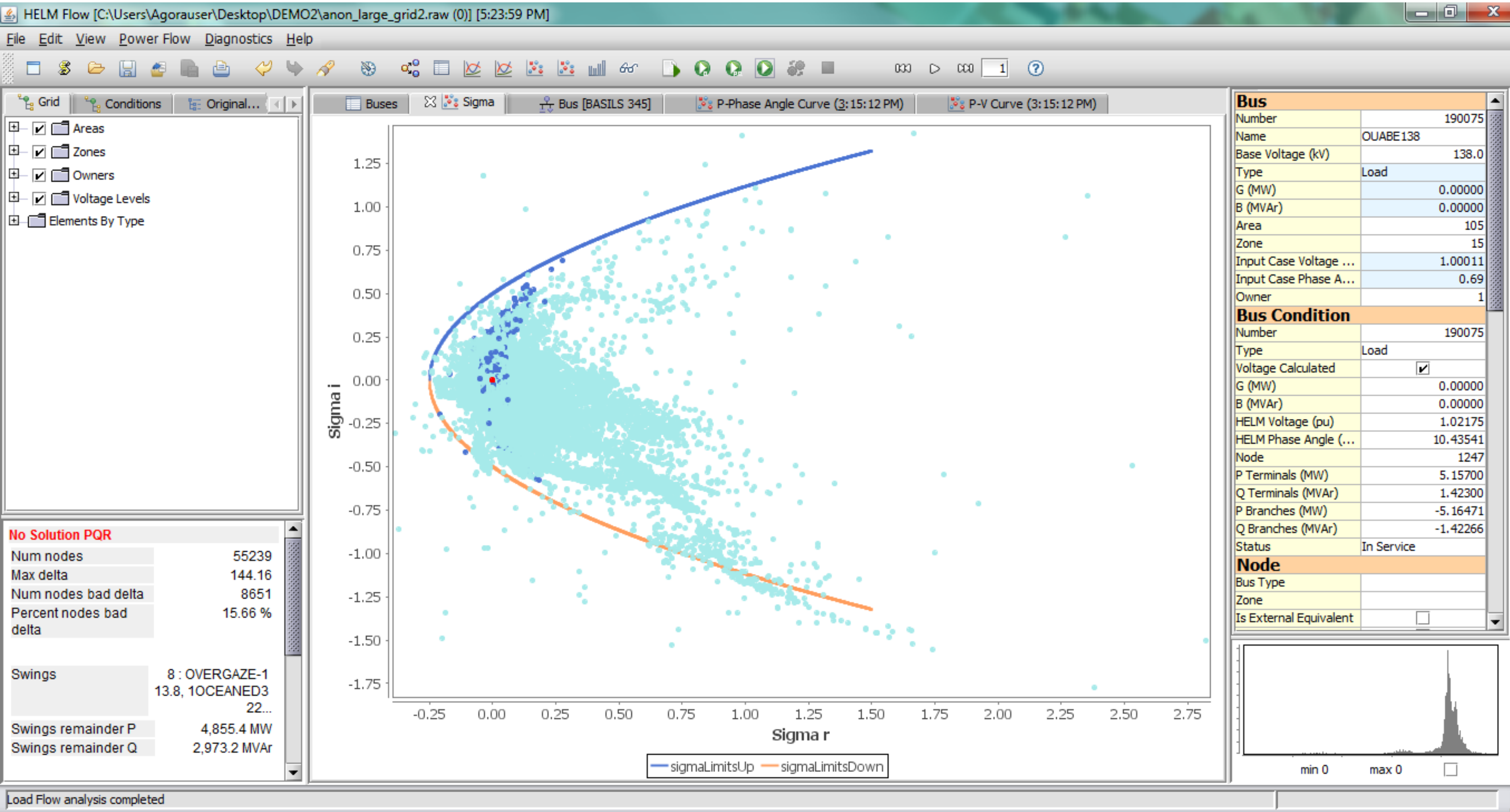
BASILS appears no closer to the parabola, but we have a new outlier

The Sigma Plot – Case 1 – P=7,000MW



The rogue node is getting worse

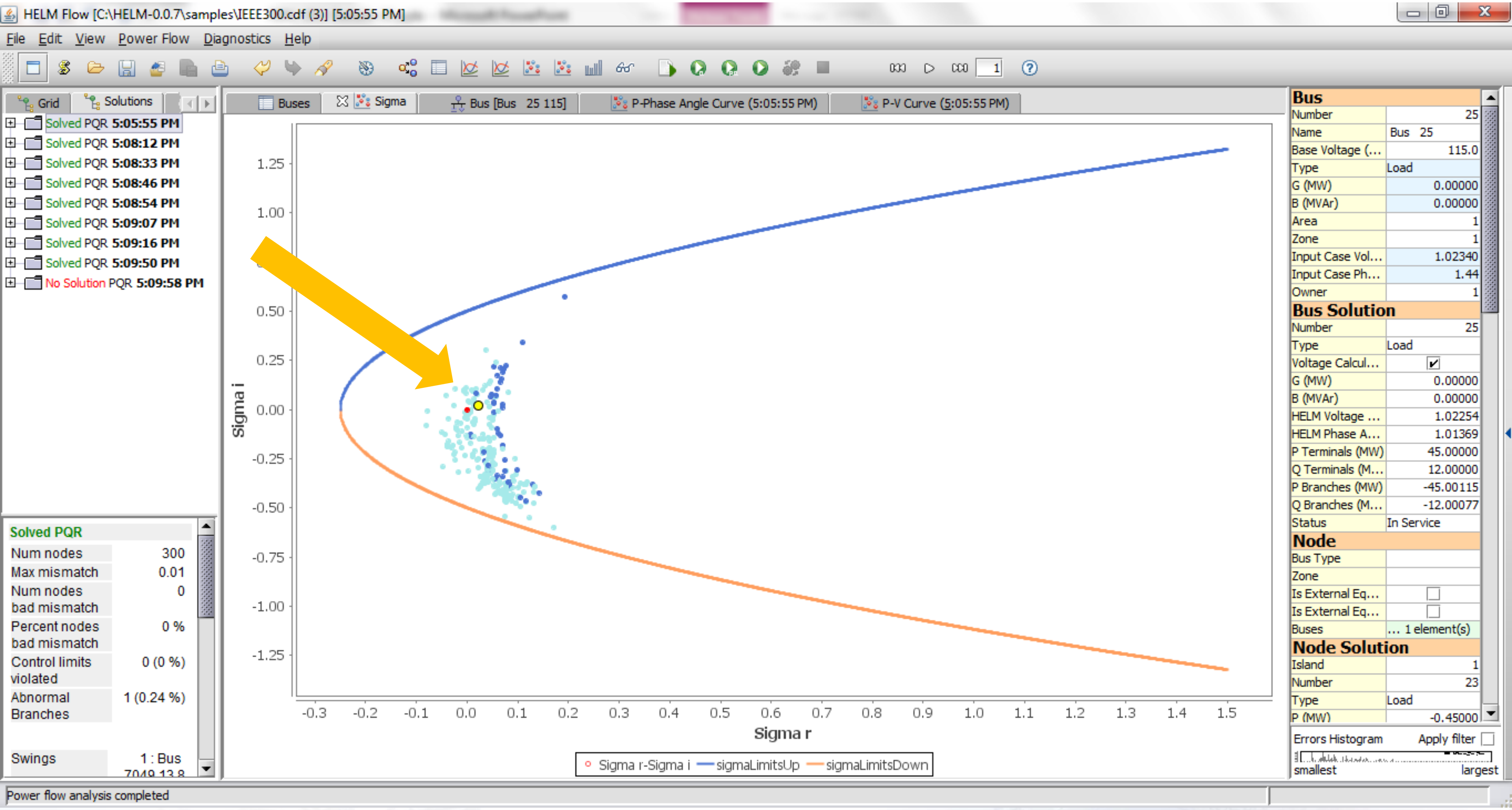
The Sigma Plot – Case 1 – P=7,500MW



Voltage collapse – as predicted by the PV curve

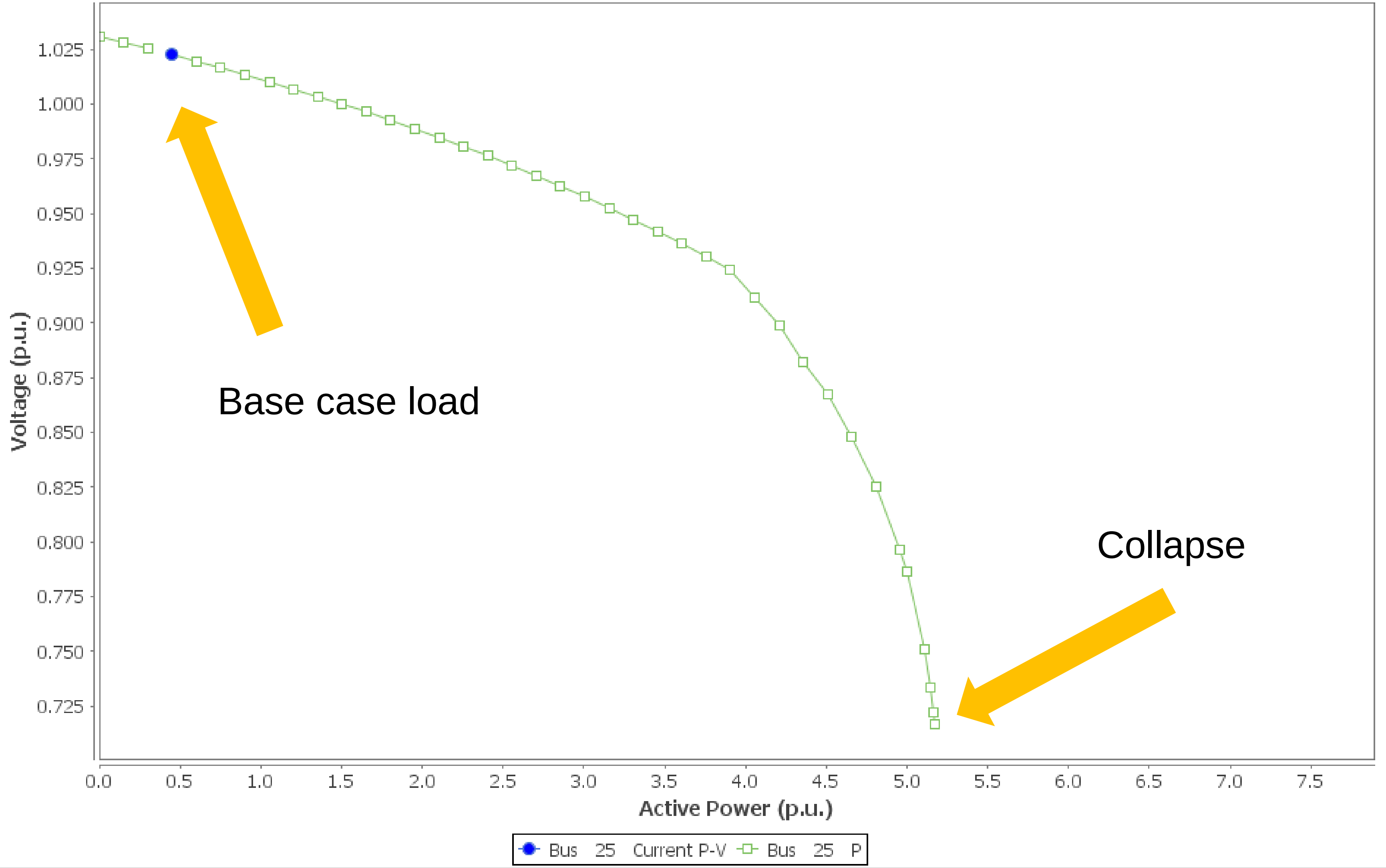
Yet there is information to be gained from sigma

The Sigma Plot – Case 2 – IEEE300



IEEE300 Base Case
We'll focus on Bus 25

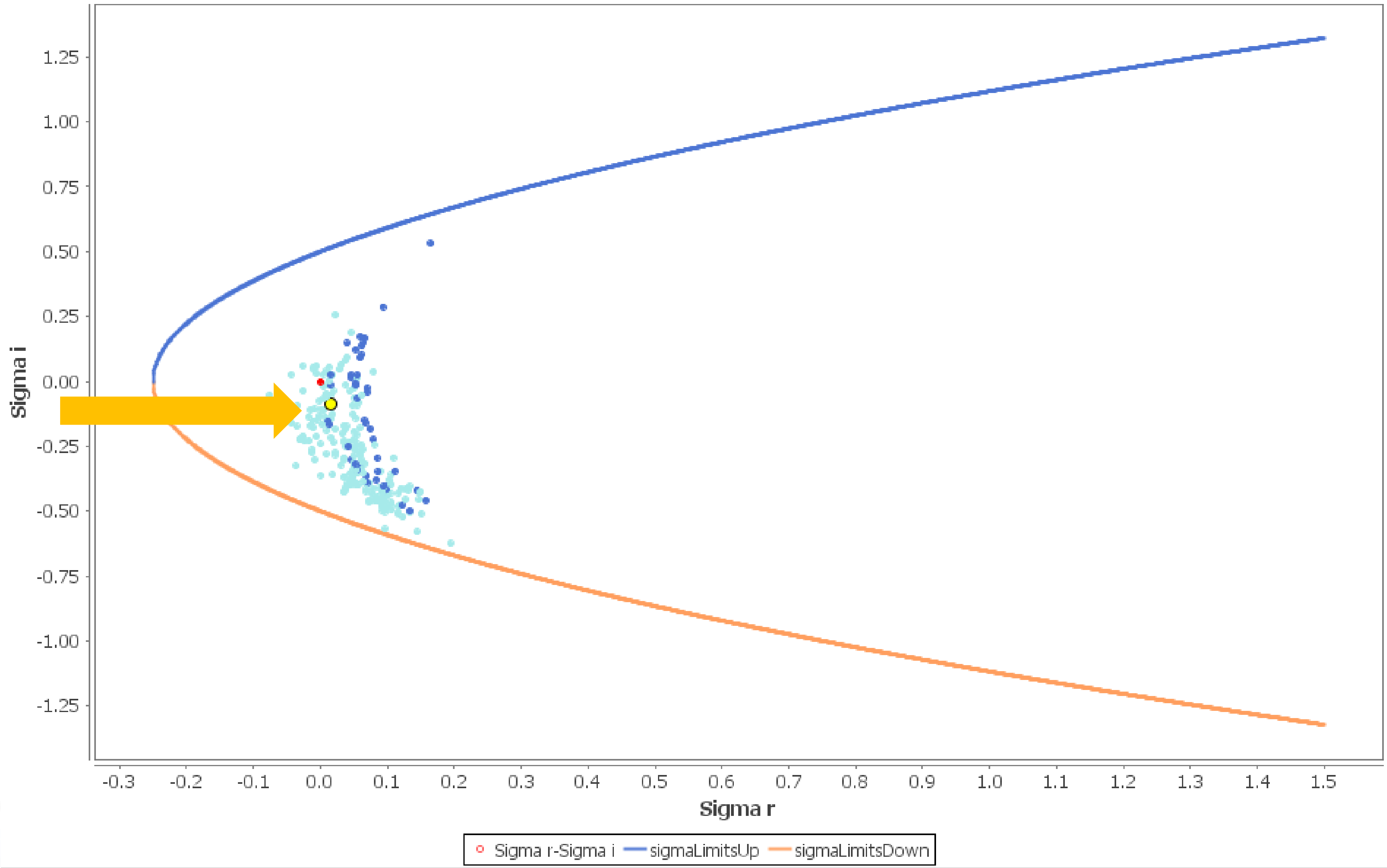
The Sigma Plot – Case 2 – IEEE300



PV Curve for Bus 25 – blue dot is base case

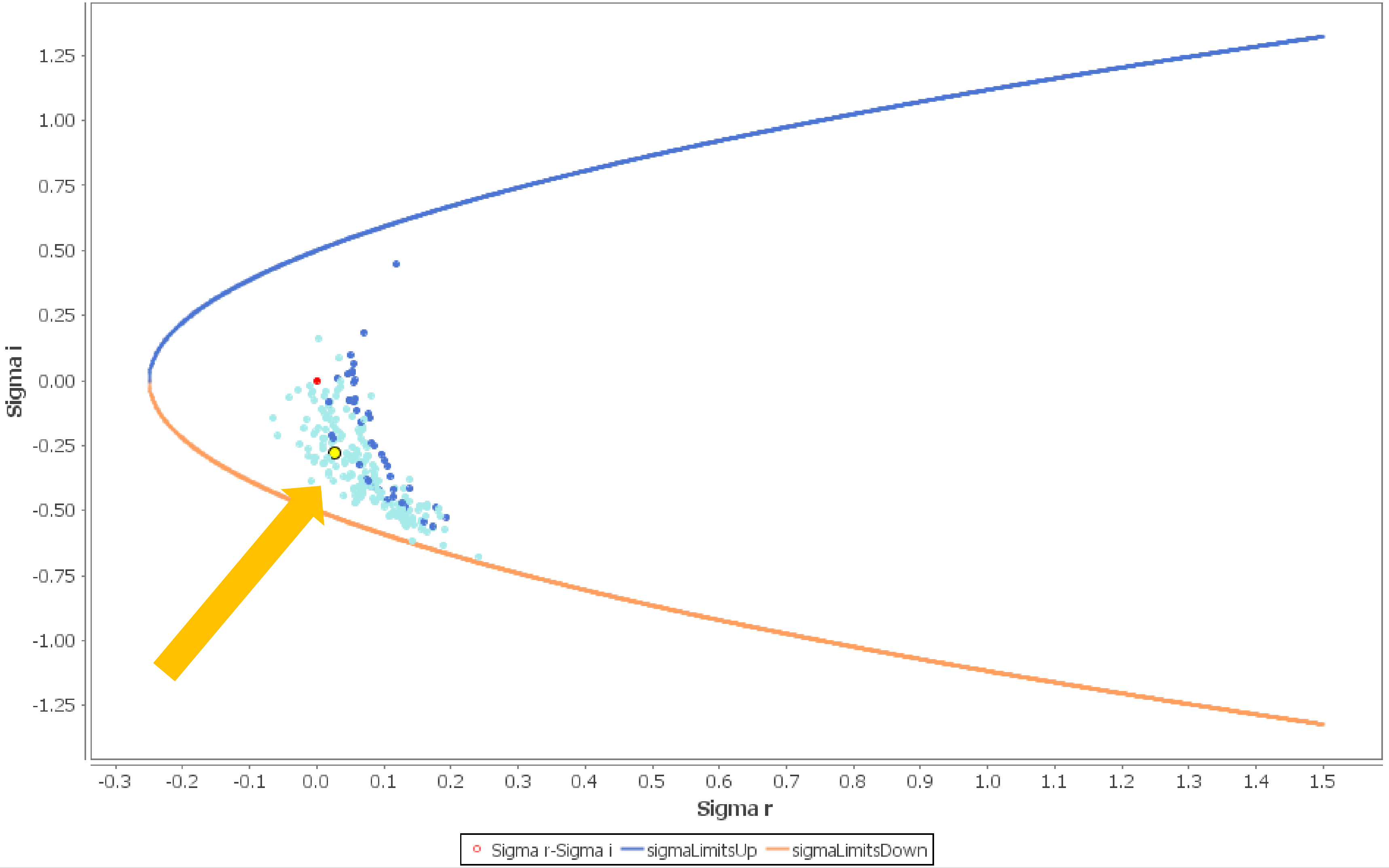
Last viable point at 517MW

The Sigma Plot – Case 2 – IEEE300



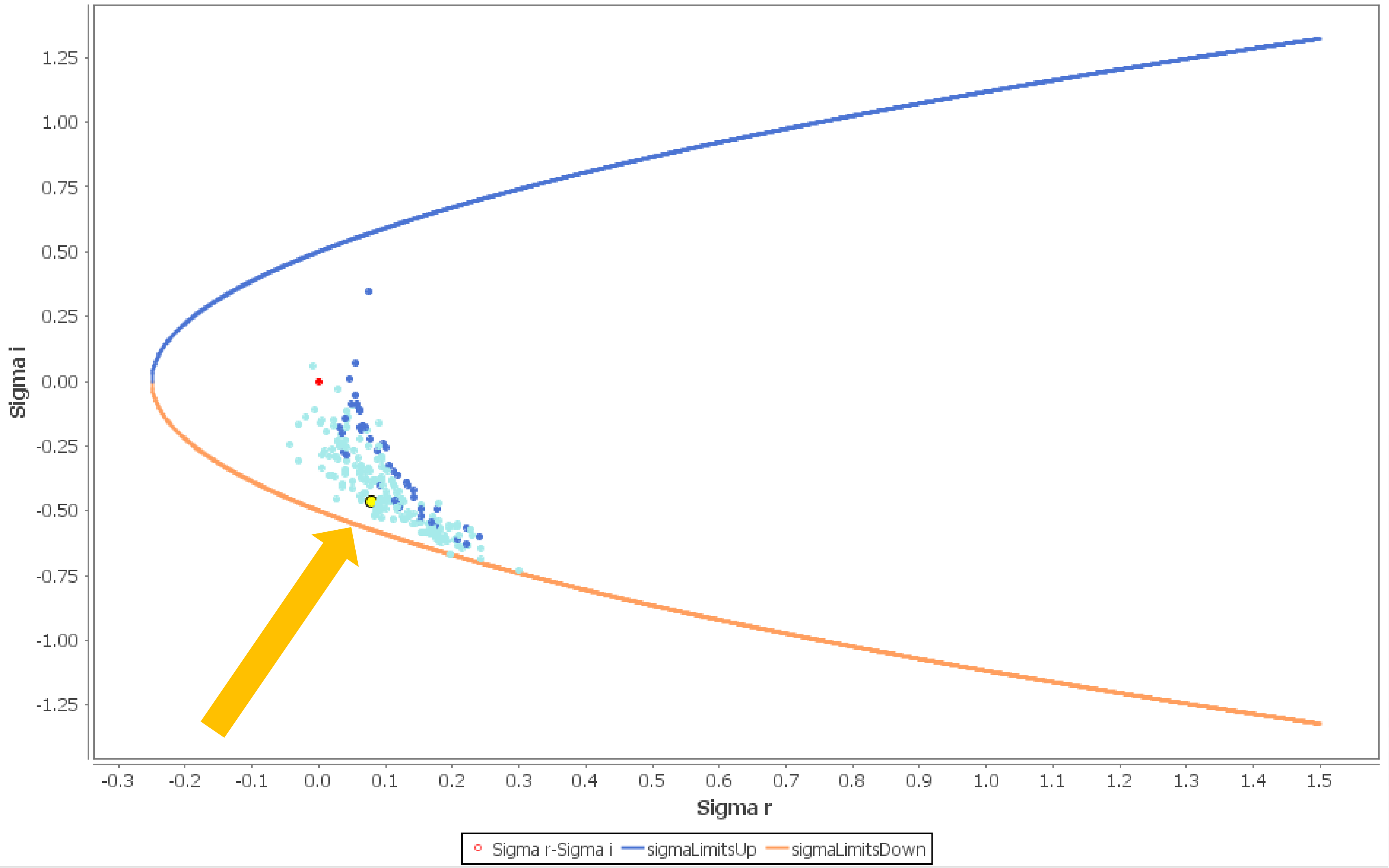
Bus 25 – Load = 100MW

The Sigma Plot – Case 2 – IEEE300



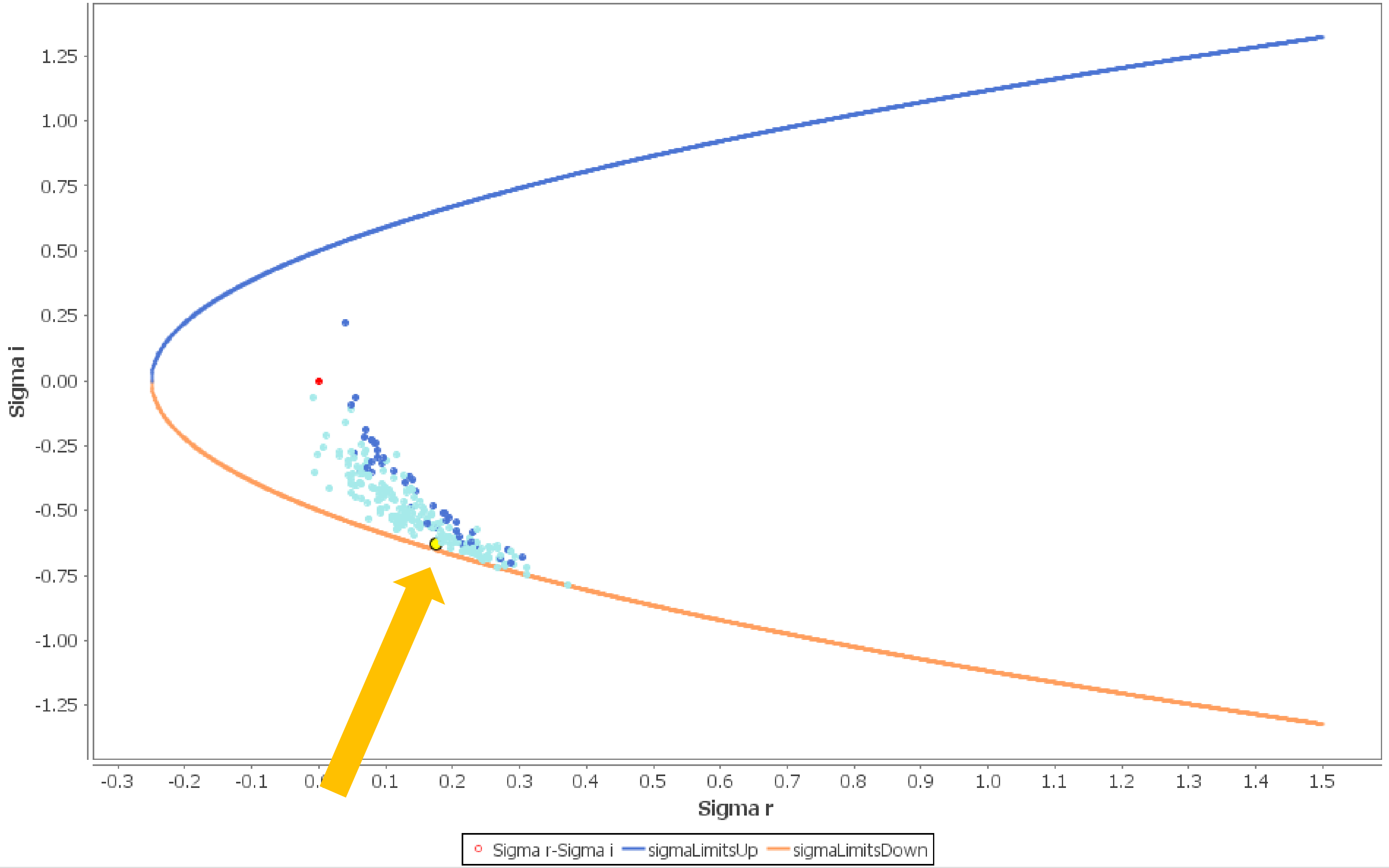
Bus 25 – Load = 200MW

The Sigma Plot – Case 2 – IEEE300



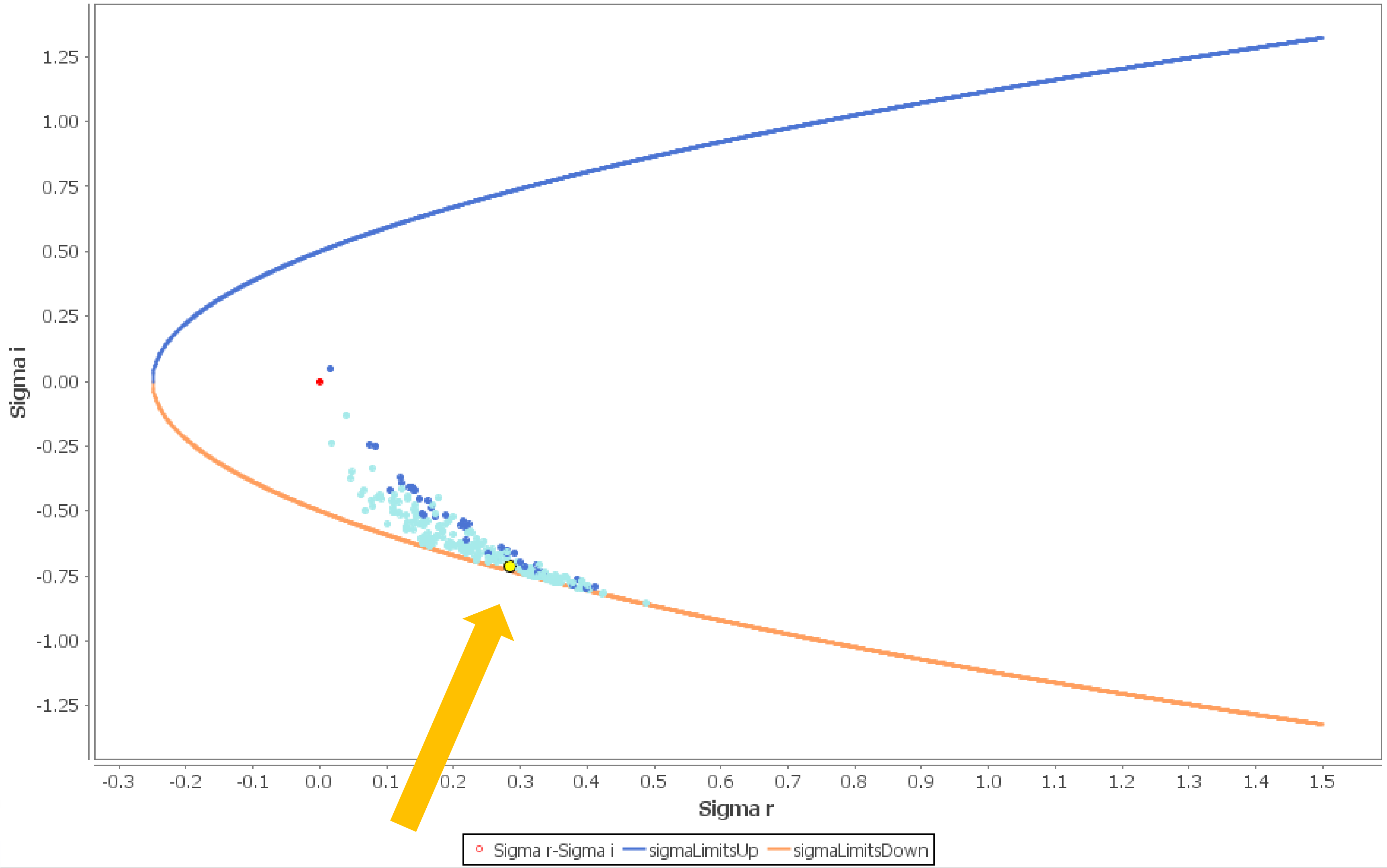
Bus 25 – Load = 300MW

The Sigma Plot – Case 2 – IEEE300



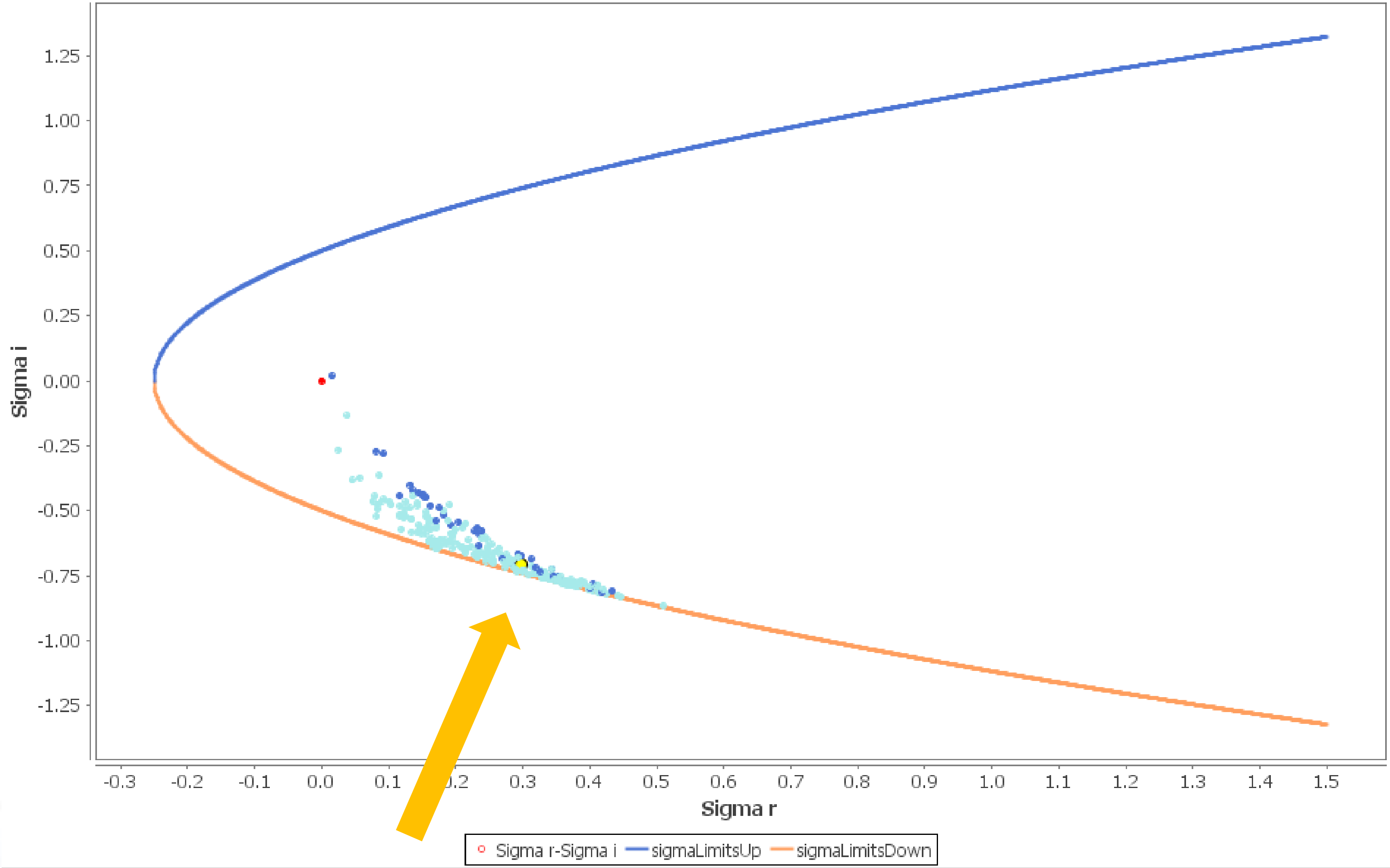
Bus 25 – Load = 400MW

The Sigma Plot – Case 2 – IEEE300



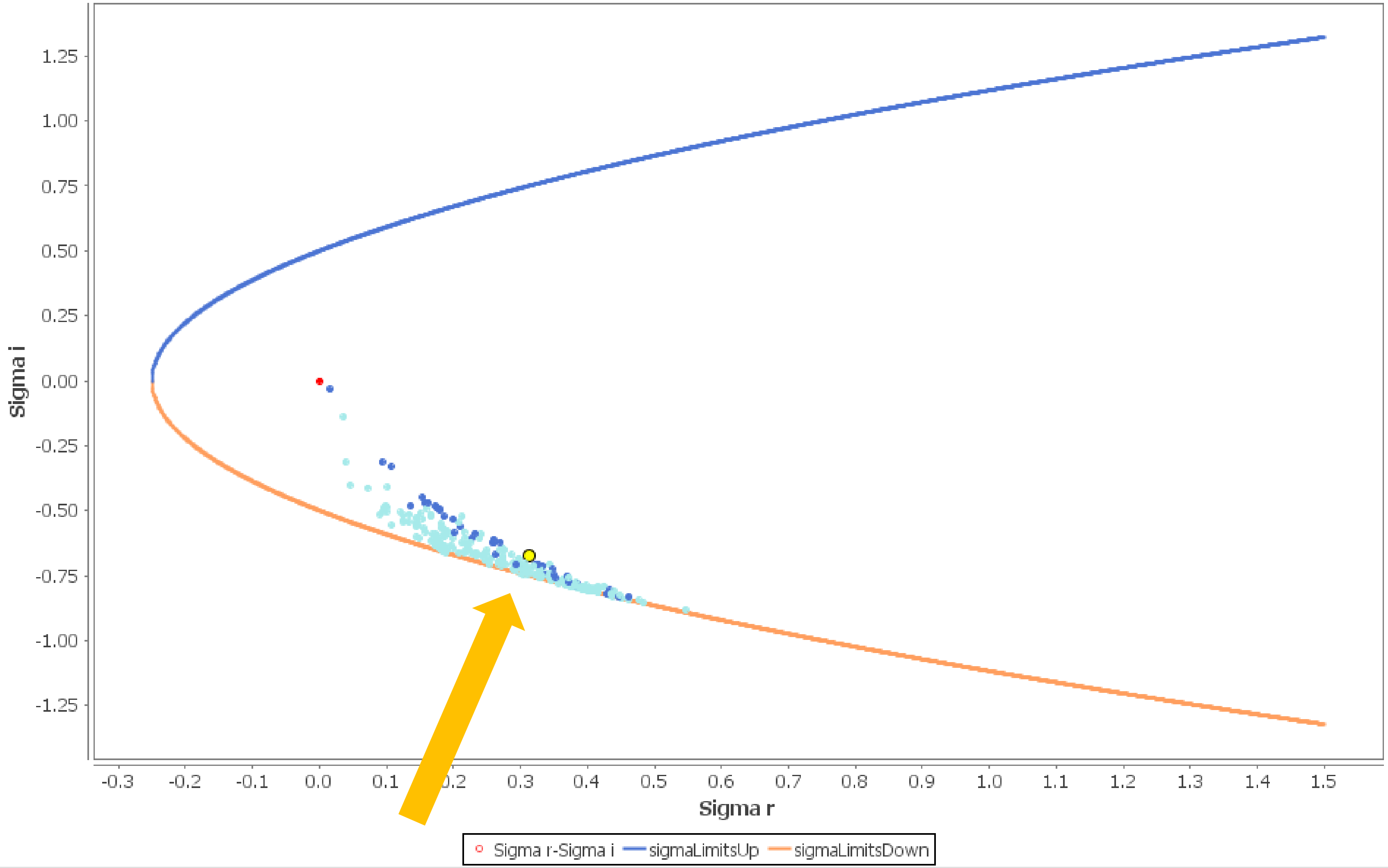
Bus 25 – Load = 500MW

The Sigma Plot – Case 2 – IEEE300



Bus 25 – Load = 510MW

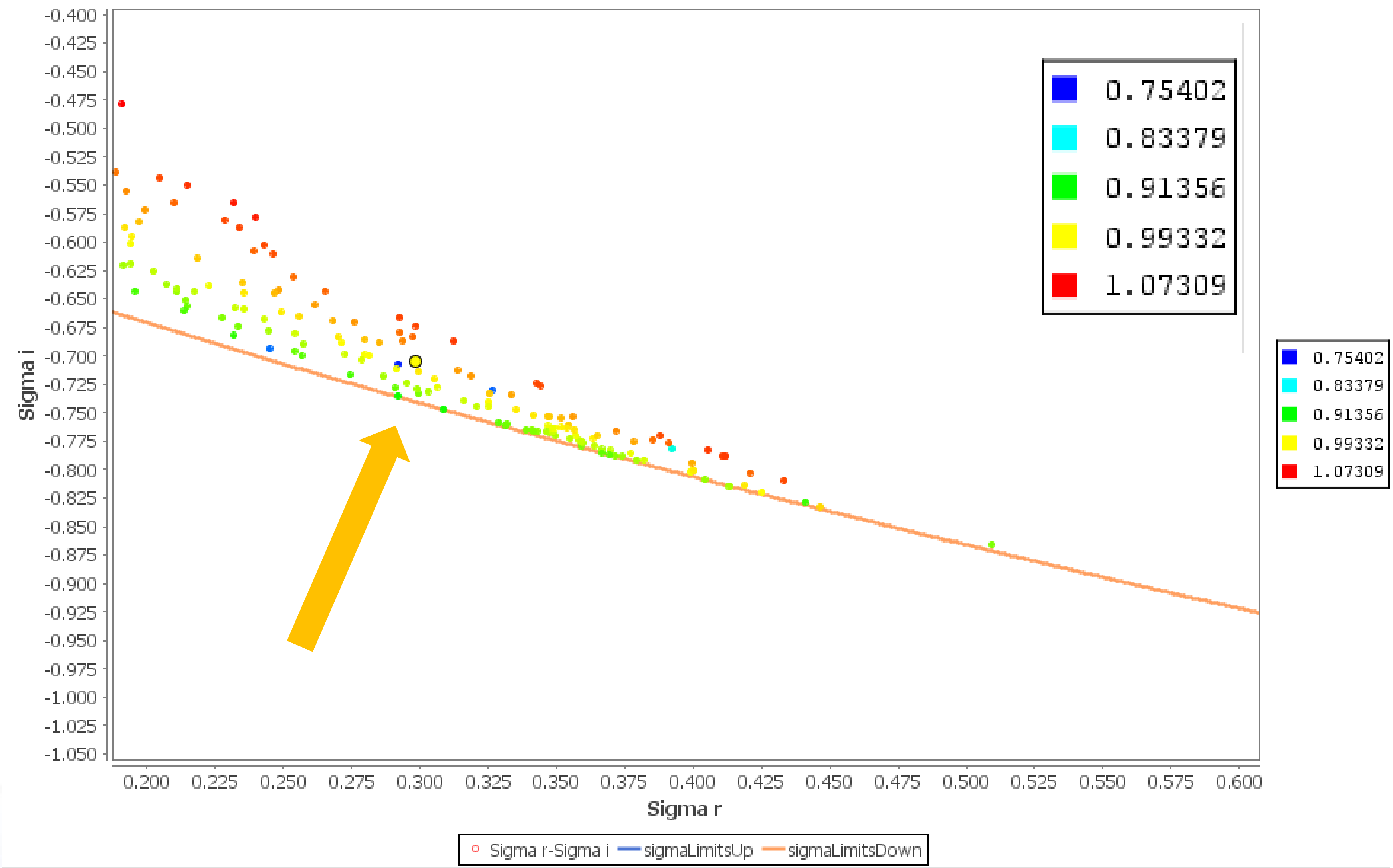
The Sigma Plot – Case 2 – IEEE300



Bus 25 – Load = 520MW

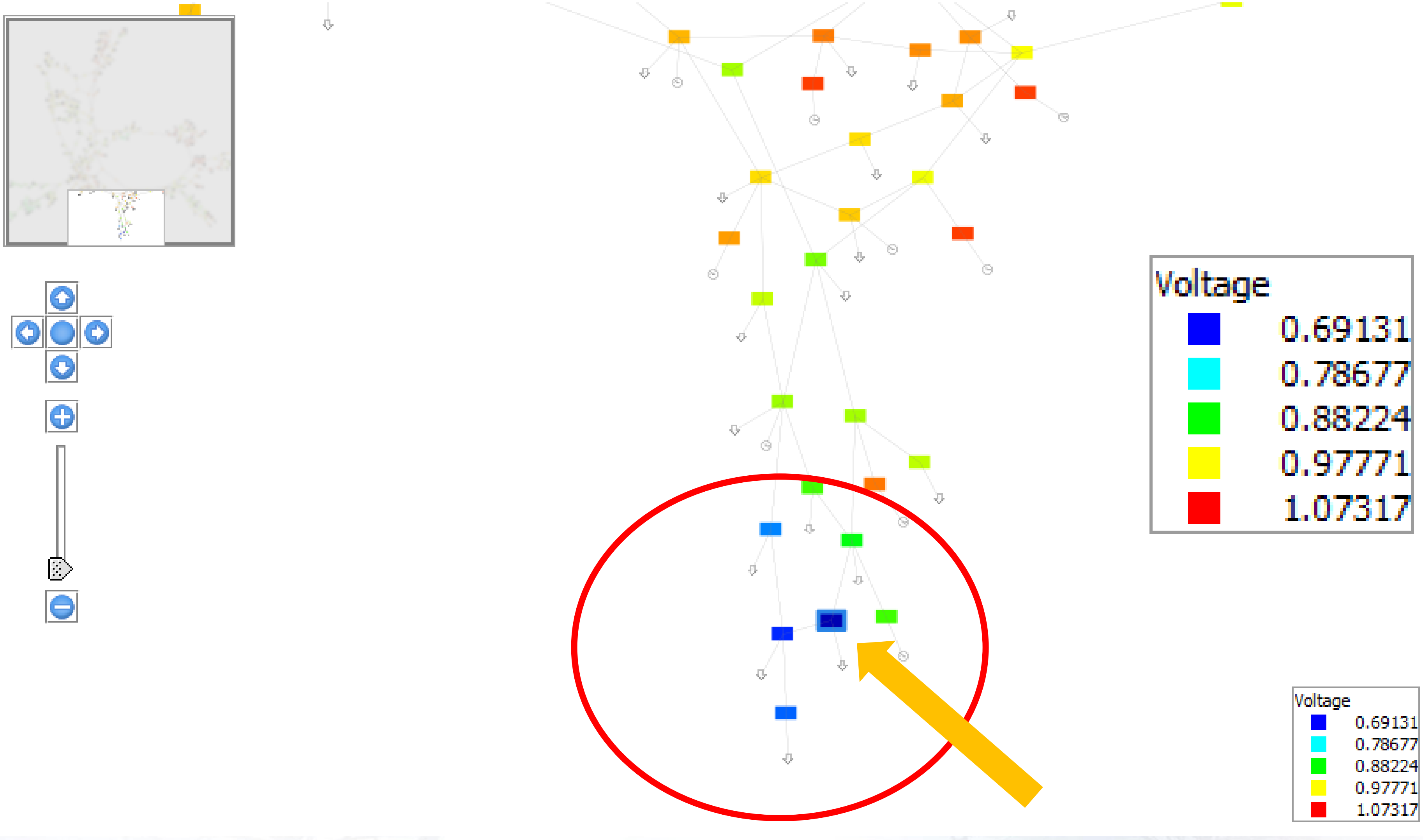
System Collapse

The Sigma Plot – Case 2 – IEEE300



Bus 25 – Load = 520MW – zoom and color coded for unit voltage (Collapse)

The Sigma Plot – Case 2 – IEEE300



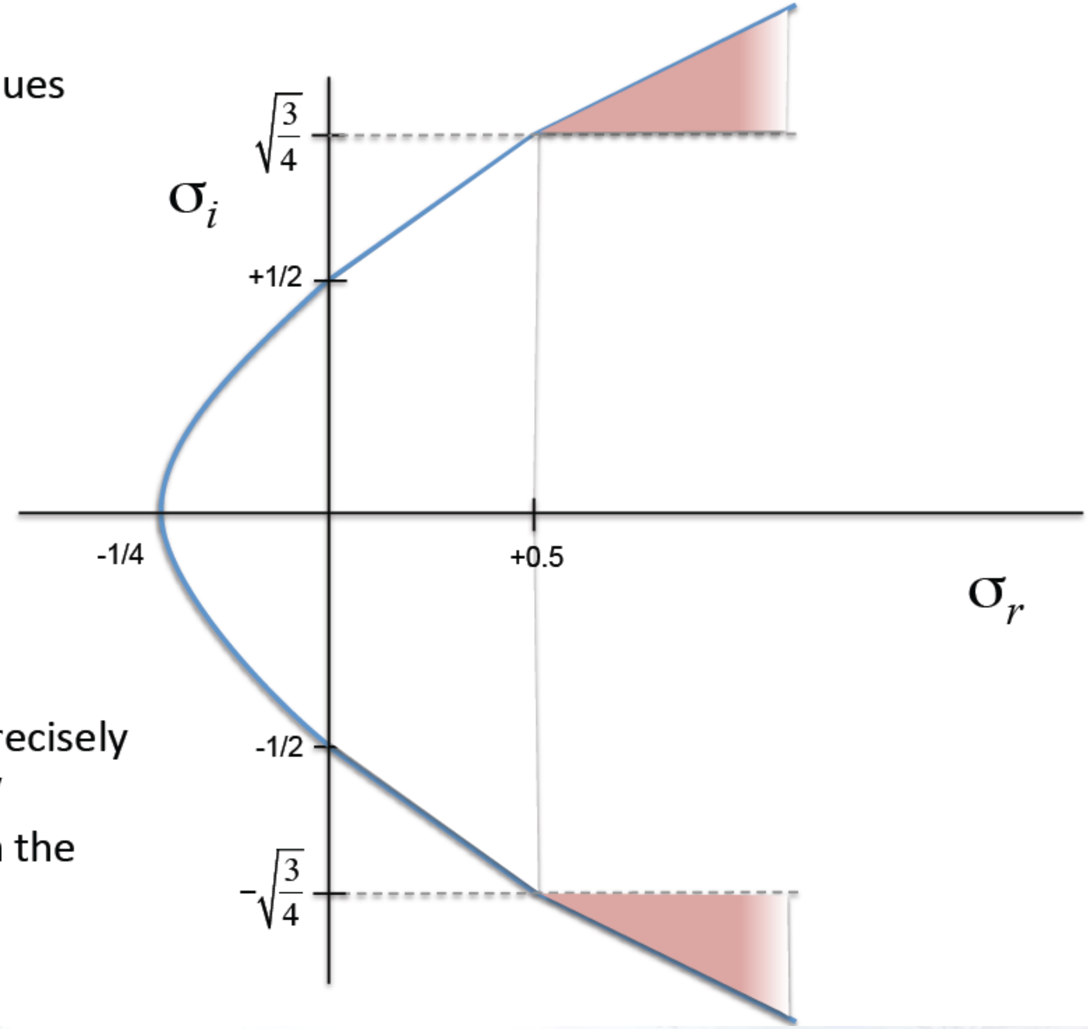
Bus 25 – Neighboring nodes also in an under-voltage state

Teaser – Solution Instability (PV/QV)

PV nodes with sigma values approximately:

$$|\sigma_i| > \sqrt{\frac{3}{4}}$$

are “unstable”



But this is seen more precisely in the Sigma Plot for PV nodes, as it depends on the value of $|V|$.

If a PV node is turned into PQ, the original operational solution will often be non-operational

HELM™ Offers a Useful Visualization of Voltage Stability

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- HELM-Flow™ commercial release in July – contact Battelle
- Put sigma visualization to work
- Steve Krak – krak@battelle.org

Trias, Toni. "The Holomorphic Embedding Load Flow Method." IEEE PES General Meeting, July 2012.

US Patent No. 7,519,506 B2. "System and Method for Monitoring and Managing Electrical Power Transmission and Distribution Networks."

US Paten No. 7,979,239 B2. "System and Method for Monitoring and Managing Electrical Power Transmission and Distribution Networks."

Thank You!
Battelle Grid Services Team
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