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POWER SYSTEMS · AI · RESEARCH

Technical Note 001: Grid Forming Inverter Fault Contribution in IEC 60909 / ENA G74

N-001

This is preliminary research and has not been validated or peer-reviewed. It could therefore be totally wrong.

Key Concepts

- GFM is still an emerging technology – there are very few established standards. The UNIFI / WECC – REGFM_B1 is a well-established model.

- Despite its advances, the key constraint of a GFM is its current limitation logic and control system. Different approaches are used, but most used a combination of physical current limit and voltage limit.

- GFM technology has two distinct modes of operation.
  - Current Limiting (CL)
  - Voltage Source (VS)

- How best to represent a GFM in formal fault studies like IEC 60909 and ENA G74 is unclear:
  - Full Size Converter (FSC)
  - Equivalent Synchronous Machine (ESM)
  - Voltage Source behind a Thevenin Impedance (VSC)
  - Hybrid Model

- Static simplified fault studies are very different to RMS / EMT analysis.

Ideas Explored

- IEC 60909 method is simple and static. ENA G74 (Complete Method), uses a pre-fault load flow and a super-position principle – potentially giving more accurate results.
- We need a way or representing a GFM for static fault current analysis. Which is the most appropriate model?
- The behaviour of a GFM is determined by several parameters, which are most important?
- Is the fault contribution of the GFM is set by the retained voltage during a fault or a voltage phasor shift?
- Does a GFM perform differently for heavy faults (large voltage phasor shift) and light disturbances (low voltage phasor shifts)?
- When and how does is it driven into Current Limiting mode?
- How would it behave in a low strength system?

Parametric Sweep

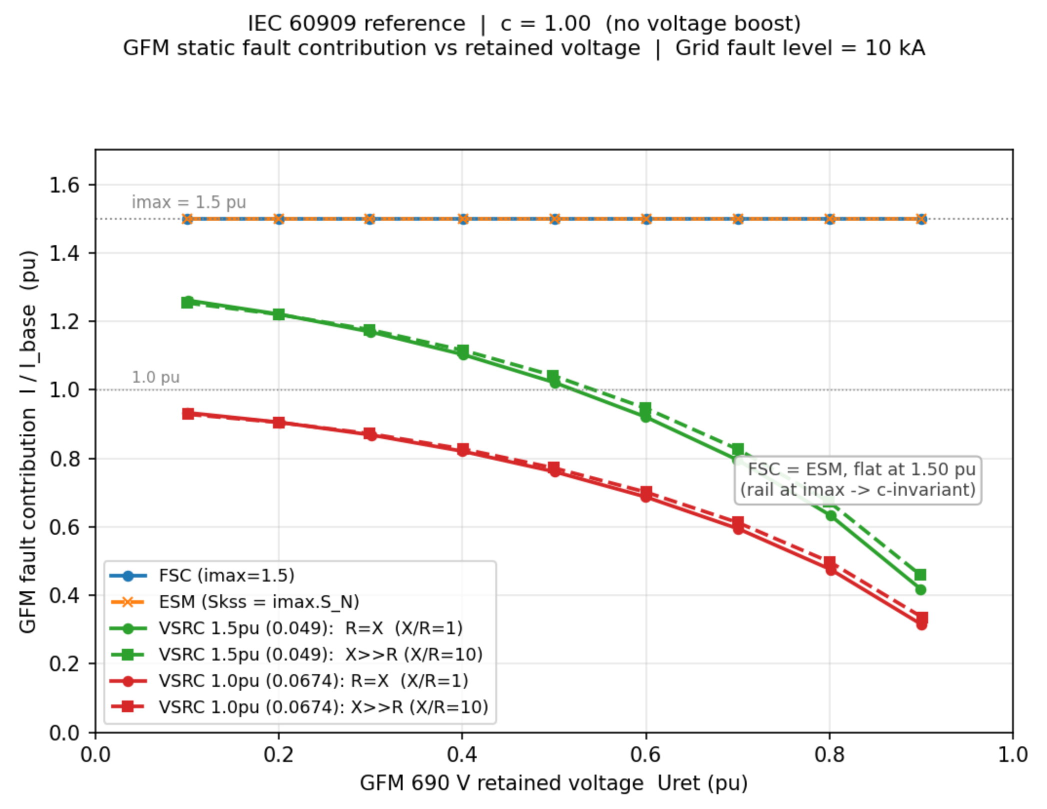
- GFM standards have differing levels of documentation and accuracy. Transfer functions may not tell the whole story.

- DIgSILENT have produced their own VSM model, it is similar the REGFM_B1, but contains virtual impedance and some additional control loops.

- Whilst most parameters are clear, their operation is not always as expected. Checking the VSM models manually is a slow and tedious process.

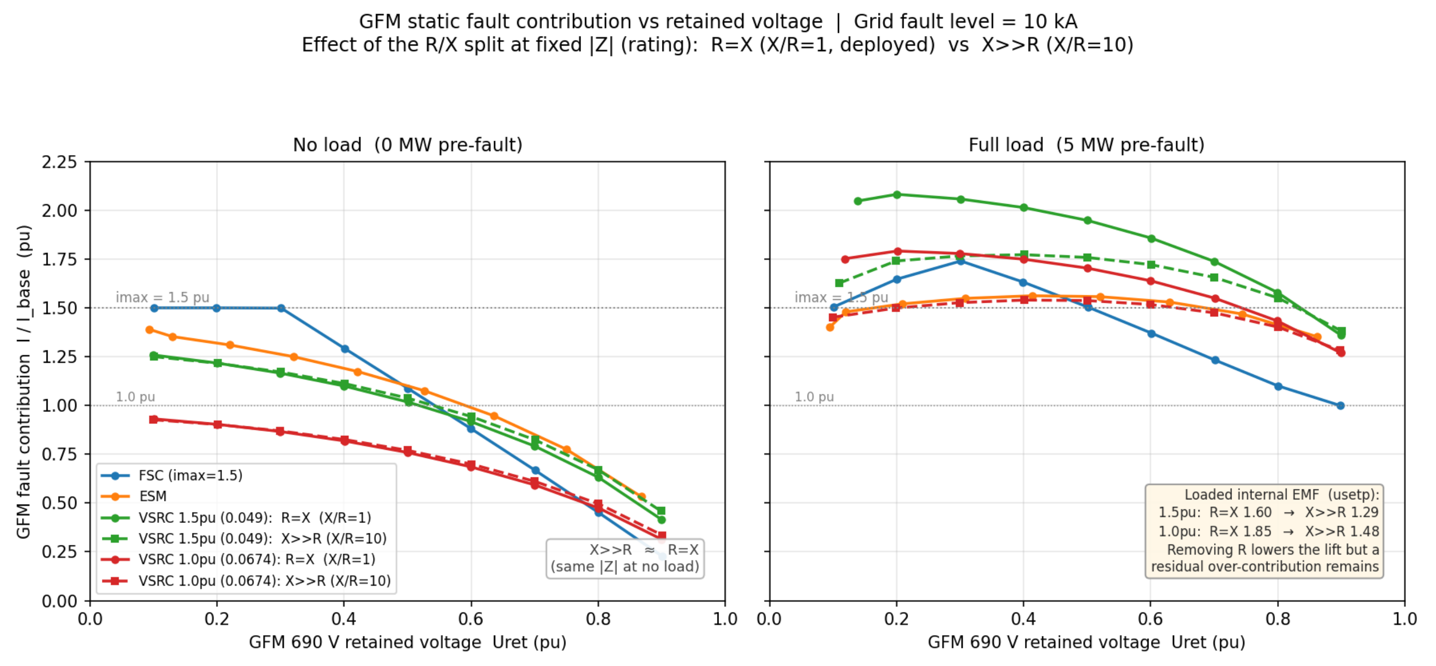
- The project used an AI to automate parametric sweeps of the VSM parameters, and help with the data analysis:
  - Fault impedance for 0.1 to 0.9
  - i_max (current limit) 1.25, 1.5, 2.0
  - Virtual impedance (r=x) 0.05, 0.10, 0.15pu
  - X_series 0.05, 0.10, 0.15 pu
  - Pre-fault loading: 0, 50, 100 %
  - Upstream Fault level: 5, 20 kA

IEC 60909 Results – FSC, ESM and VSC



Engineering takeaway: FSC has fixed constant current output regardless of retained voltage, but ESM and VSC drop off.

ENA G74 (Complete Method) Results – FSC, ESM and VSC



Engineering takeaway 1: In the ENA G74 (Complete Method) approach the FSC drops off with retained voltage, based on a voltage-dependent current relationship.

Engineering takeaway 2: Prefault loading introduces errors that that exceeds the nominal rating limit.

Proposed Model

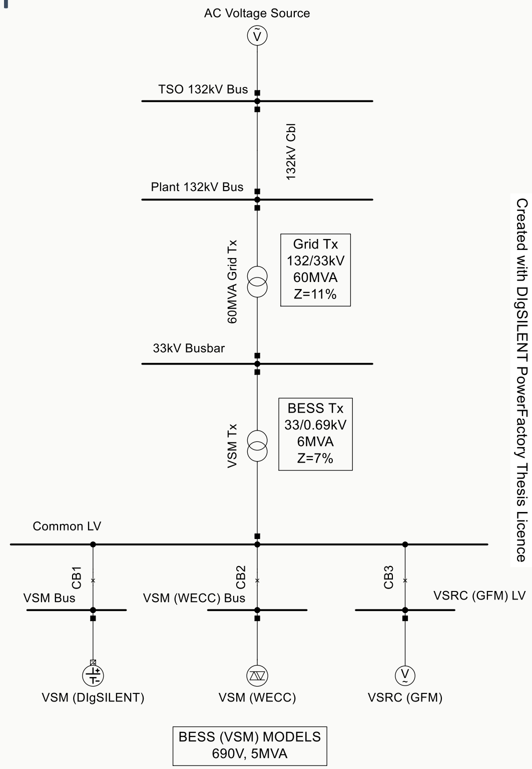
- Model of a VSM can be based on identifying the critical voltage where it changes from VS to CL regime.

- Fault output can then be defined on the VSM parameters and magnitude of the voltage change

$\Delta u = \frac{\lvert\overline{U_{ldf}} - \overline{U_{ret}}\rvert}{U_N}$	1
$\Delta I_q = \sqrt{\left(i_{max}^2 - i_{d,pre}^2\right)} - I_{q,pre}$	2
$\Delta u_{crit} = \lvert r_t + jx_t\rvert \cdot \Delta I_q$	3
$\begin{cases} \Delta u \geq \Delta u_{crit} = \text{ CL} \\ \Delta u < \Delta u_{crit} = \text{ VS} \end{cases}$	4
$V_{crit} = \sqrt{\left(\lvert\overline{U_{ldf}}\rvert - x \cdot \Delta I_q\right)^2 + \left(r \cdot \Delta I_q\right)^2}$	5
$\Delta I = \begin{cases} I_{max} \cdot I_n \text{ ifCL} \\ I_{max} \cdot I_n \cdot \left(\frac{\Delta u}{\Delta u_{crit}}\right)^n \text{ if VS} \end{cases}$	6

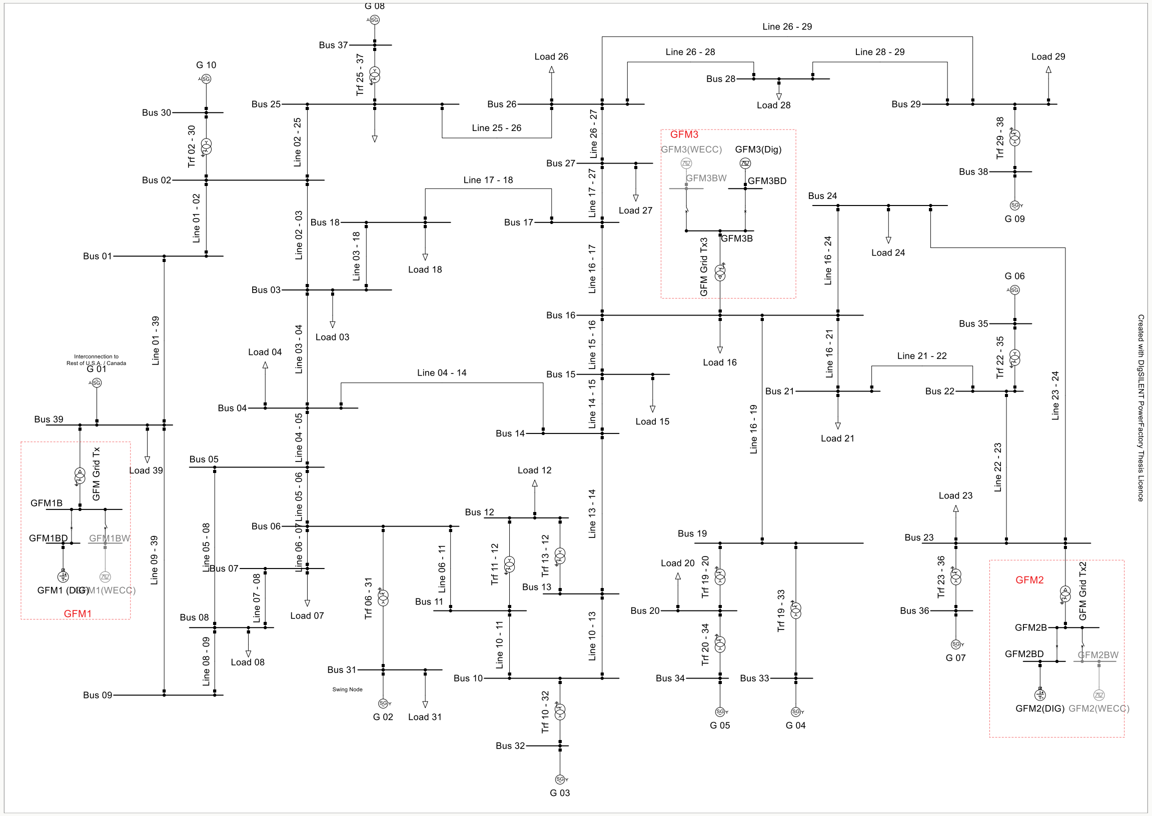
Test Network 1: Simple Radial

- Simple Radial network allows easy testing of behaviour in IEC 60909, ENA G74 (Complete Method) and RMS simulations.
- Static fault calculations in radial networks are simplified.
- Parametric sweep is easy and allows testing variables sequentially to build up a clear picture.
- Faults applied at 132kV with a resistive component to cause a voltage phasor shift at GFM terminals.
- Voltage dips applied at 132kV to show a simple magnitude change at GFM terminals.



Test Network 2: IEEE 39-Bus

- More realistic network than a radial network. GFMs added at 3 locations, to allow a full picture. Both REGFM B1 and DigSILENT models checked.
- Faults applied at all the 345 kV busses sequentially to give a blend of voltage dips and phase angle changes.



Parametric Sweep Results

- The parametric sweep results generated an interesting set of results – most were expected, but some were not.
  - The *i_max* current limit value was the single most important parameter. The higher the value – the larger voltage phasor change needed before CL is hit.
  - *Xseries* was a first order effect, lowering the value means that the CL regime is more quickly, and modest faults can cause the GFM to limit.
  - Virtual impedance was a second order effect, that was only applicable to the DIgSILENT model and altered the response of the GFM in the VS regime.
  - GFM pre-fault loading was only a minor factor and reduced some of the available headroom.

- The DIgSILENT VSM model, also measured the voltage vector change rather than just the simple voltage magnitude.

- Grid Stiffness had no noticeable effect, the GFM response was governed by the voltage vector change. However, grid strength impacts the given voltage vector change in response to a fault.

RMS Approach Results

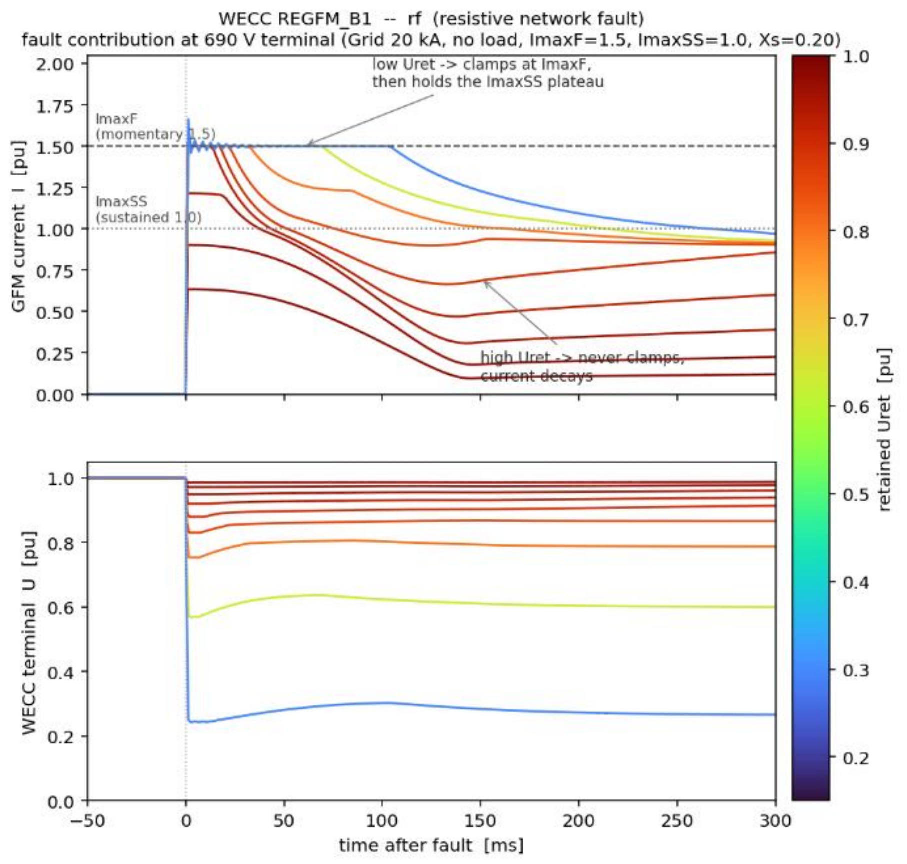
- Two types of fault applied – resistive faults causing a large phase angle jump and simple voltage dips with zero phase jump.

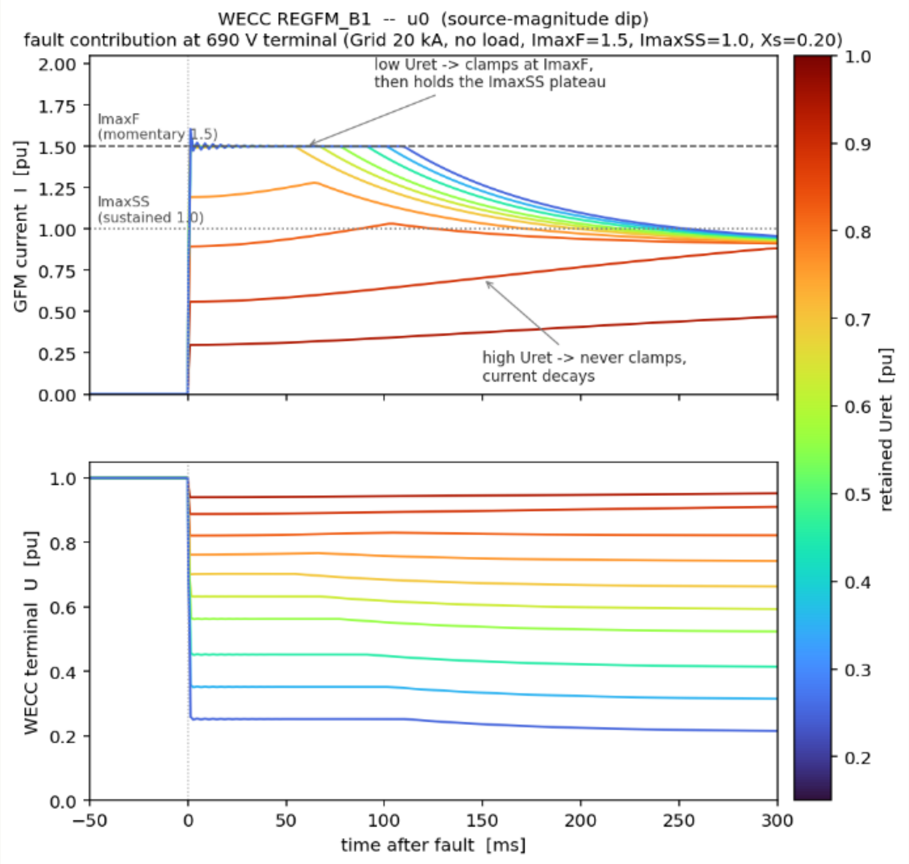
- RMS studies are time based, choosing when, how and where to measure the fault current is not always obvious.

- The two fault types and two VSM models gave very different results
    - Resistive faults cause bigger phase angle jumps (generally) and drive into CL mode
    - Simple voltage dips cause the VSM stay outside of CL mode.
    - The REGFM_B1 tend to be more linear and drop off with time.
    - The DIgSILENT model fault output rises slightly with time.

- Fault current measured at a fixed moment t=20ms and a window average of 10-30ms.

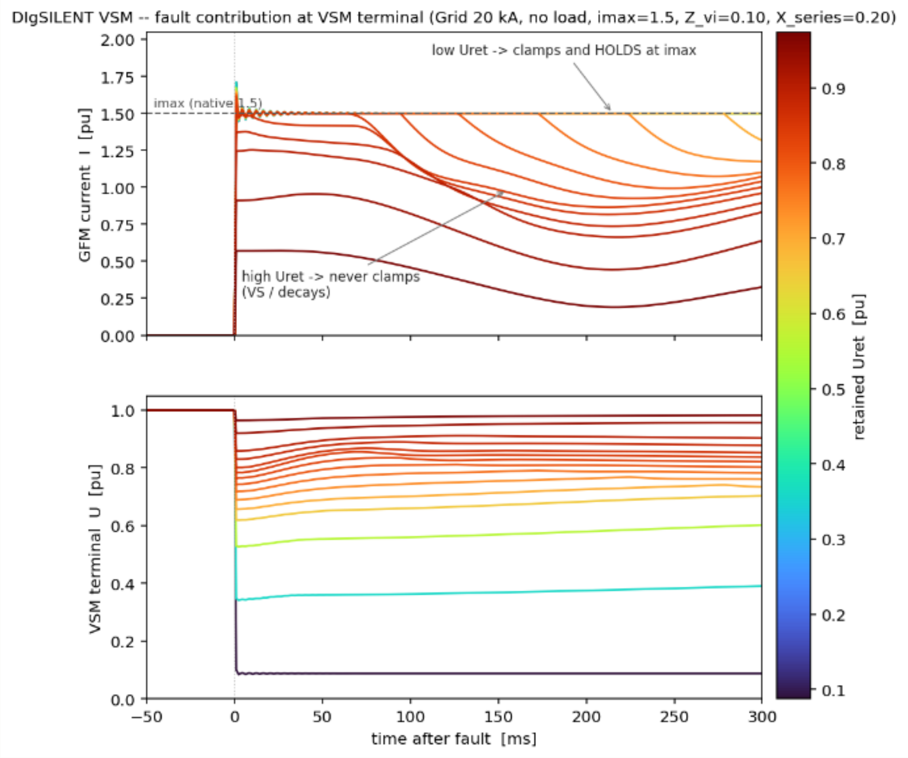
WECC REGFM – Resistive Faults vs Voltage Dips

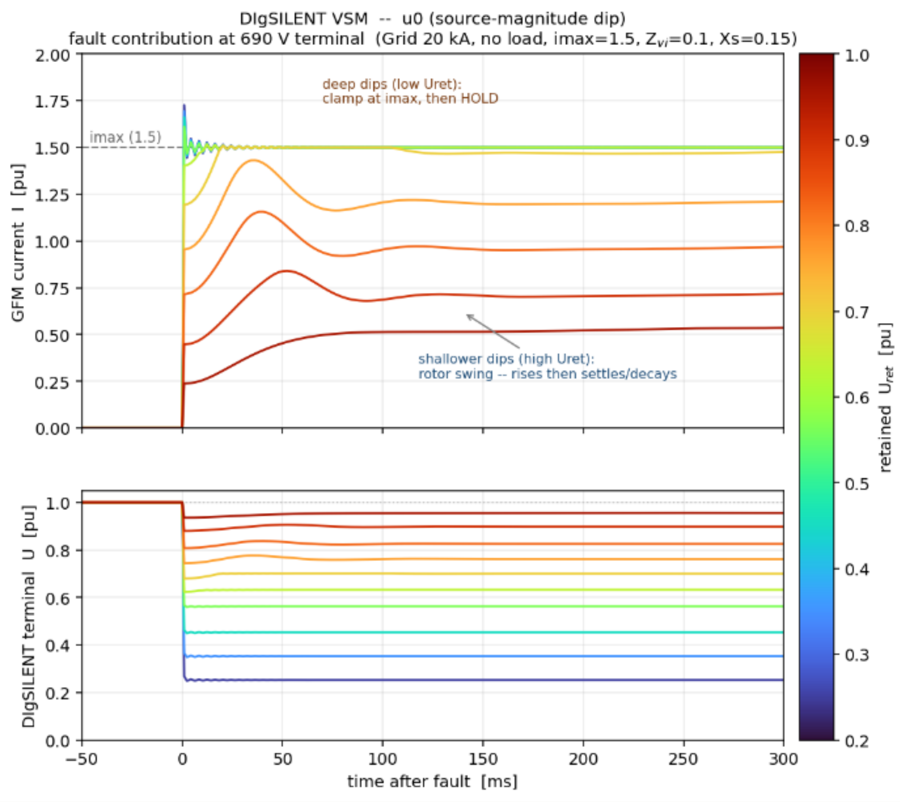




Engineering takeaway: Resistive faults cause bigger phase angle jumps (generally) and drive into CL mode. The output is fairly linear and drops with time.

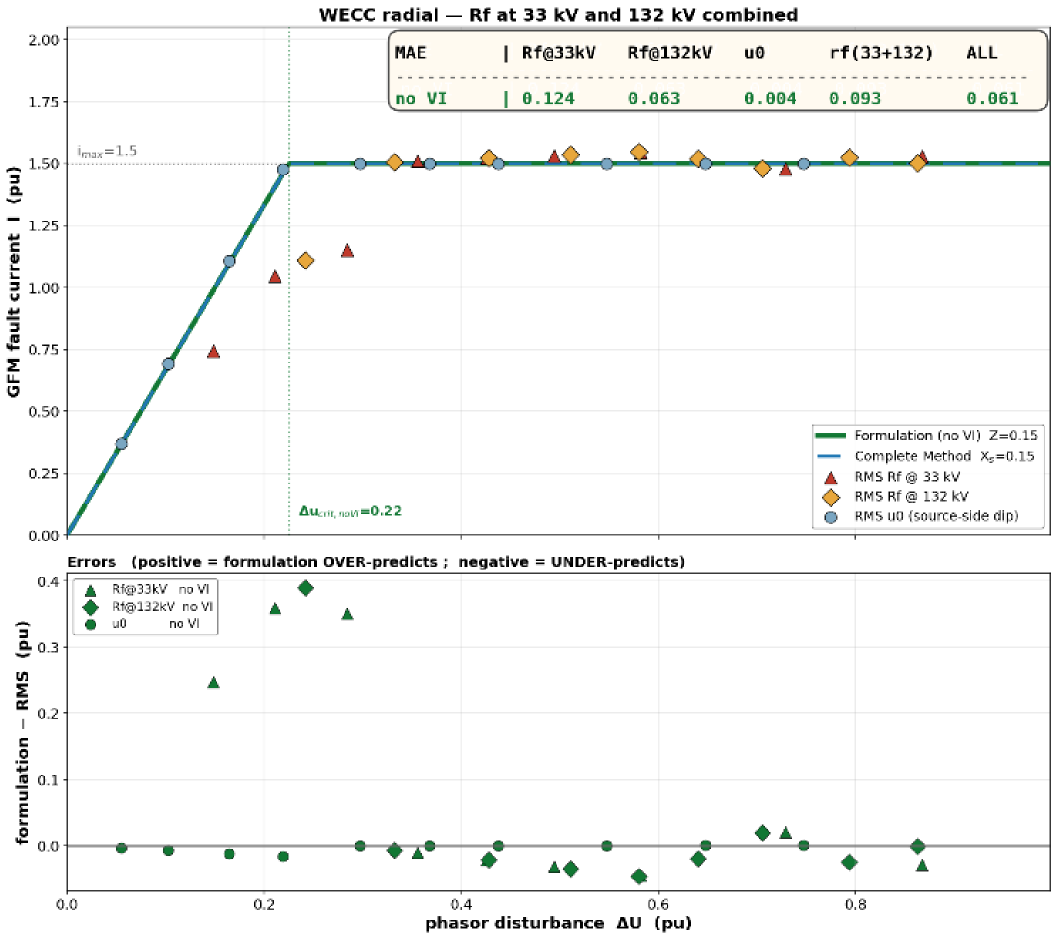
DIgSILENT– Resistive Faults vs Voltage Dips





Engineering takeaway: Resistive faults cause bigger phase angle jumps (generally) and drive into CL mode. The output rises with time in simple voltage drops.

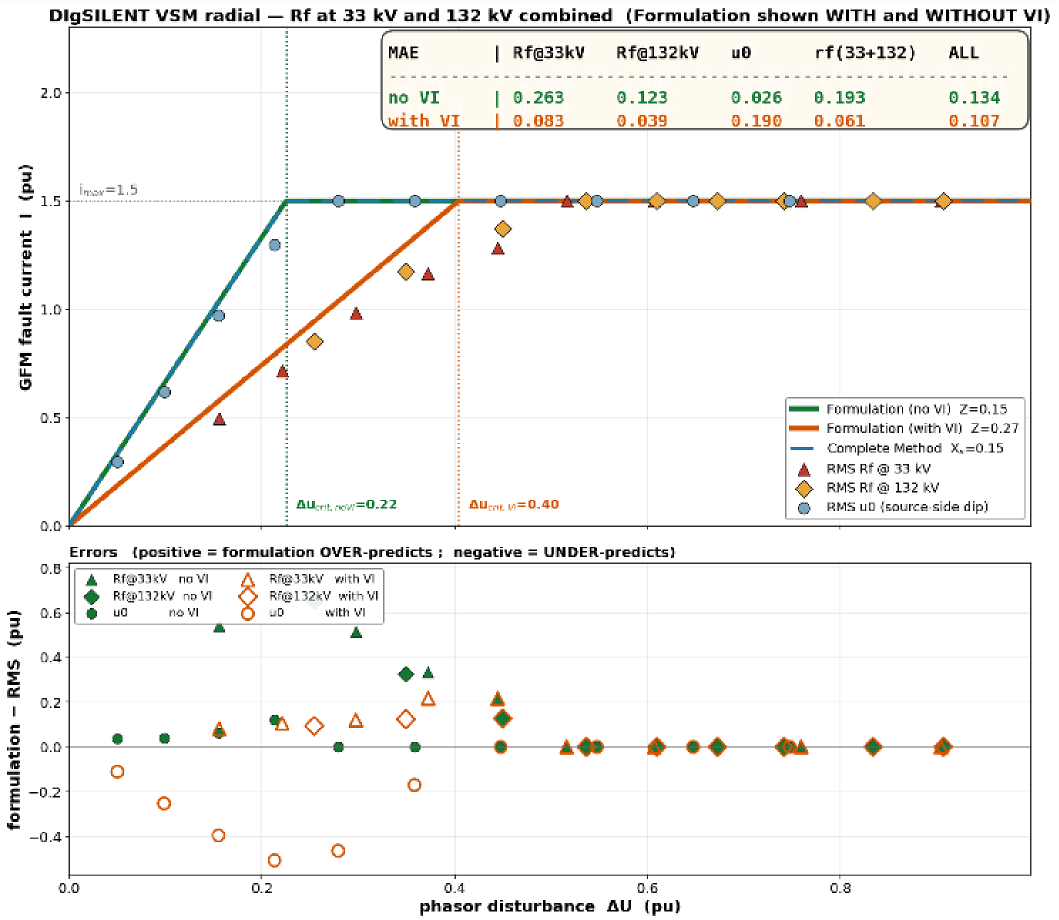
WECC – RMS Results vs Static Model



MAE	Rf@33kV	Rf@132kV	u0	rf(33+132)	ALL
no VI	0.124	0.063	0.004	0.093	0.061

Engineering takeaway: RMS and Static model matched well, but with a drop off in accuracy around the transition from CL to VS regime

DIgSILENT– RMS Results vs Static Model



MAE	Rf@33kV	Rf@132kV	u0	rf(33+132)	ALL
no VI	0.263	0.123	0.026	0.193	0.134
with VI	0.083	0.039	0.190	0.061	0.107

Engineering takeaway: RMS and Static model matched well, but the virtual impedance significantly complicated matters in the VS regime causing a different linear response

Summary

- The use of AI helped massively in this type of analysis. Rapid creation and customisation of scripts and analysis of large data sets, allowed parametric sweeps to test the VSM. Turned a long tedious process into something quick and efficient.

- The AI was accurate, but I still implemented Check and Hold flags for human checking.

- The model behaved as predicted, *Vcrit* is a definable and testable value and the knee point between CL and VS regimes is definable.

- A modified version of the FSC can be used until a detailed model is available. The voltage-dependent current relationship can be tuned by adjusting the k factor to se the CL / VS boundary.

- Output of a GFM can be predicted well for fault studies, but the error increases in the shallow regime.