



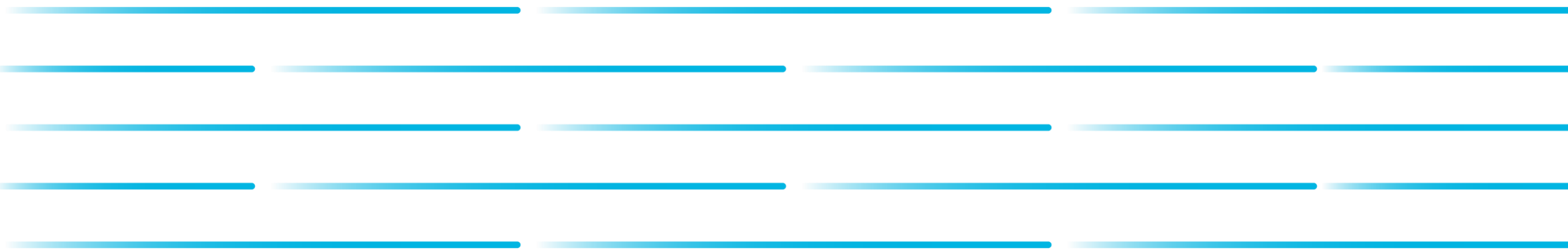
Enhanced protection modelling approach for power system transient stability studies using individual phase and sequence voltages

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In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered "non-GAAP financial measures" under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE's cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity

Introduction

Existing state-of-the-art protection models for transient stability studies

- For typical dynamics studies, the network is assumed to be balanced.
- Hence these studies typically involve the representation of positive-sequence networks and models only.
- Unbalanced faults are represented by an effective fault impedance in the positive sequence network.
- Existing protection models used in transient stability studies (generator protection, load shedding, etc.) use only positive sequence quantities such as voltages, currents etc. to trigger any actions.
- Given that majority of the faults seen in the system are unbalanced faults, this could be inadequate with the increasing penetration of inverter-based resources.



Limitations of the existing models

- The voltages of the un-faulted phases in the vicinity of an unbalanced fault may reach very high levels, likewise the faulted phase voltages may reach very low levels causing high phase currents.
- These severe conditions may persist for a duration sufficiently long to trigger tripping actions by the protection elements or protective functions in IBR controllers.
- Likewise, there may be some protection elements utilizing the negative sequence voltages/currents.
- If standard positive sequence protection models are used for dynamic simulations, one could fail to predict the loss of some units.



Proposed modifications

- Use of protection models using sequence/individual phase quantities.
- No additional data necessarily required than that used for standard transient stability simulations.
- Minimal additional computations needed over existing computations involved in transient stability simulations.
- Could have a significant impact on studies involving delayed clearing of faults.
- Not practical to model entire interconnection-wide base cases in a detailed three-phase domain for all transient stability studies, proposed approach is aimed at trying to achieve a middle ground, such that more information about the system behaviour is obtained and protection systems are more realistically represented in RMS studies.

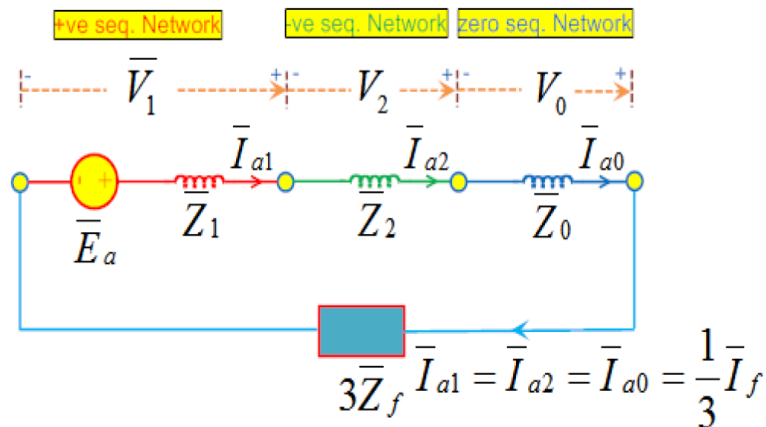


Data assumptions

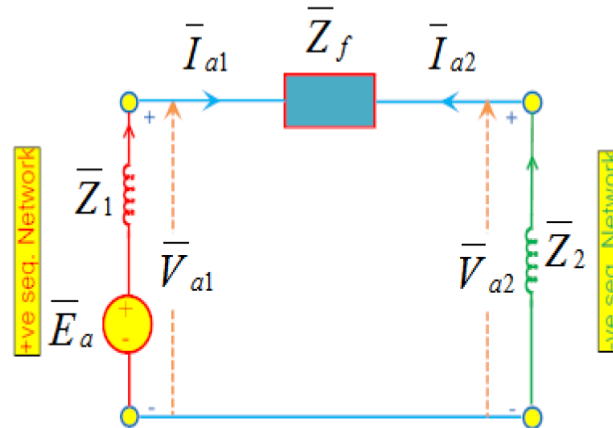
- If zero, negative sequence data is available, it is used for the calculations
- In the absence of negative sequence and zero sequence network data, set up default data using the positive sequence data (e.g. For transmission lines, $Z_2 = Z_1, Z_0 = 3 \cdot Z_1$)

Sequence Network for Unbalanced Faults

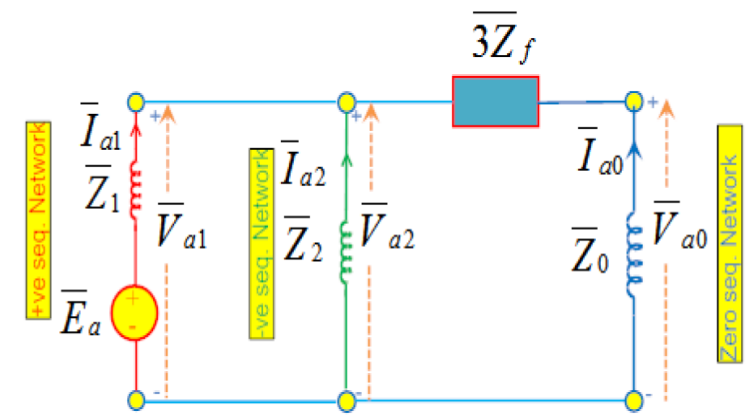
SLG fault:



LL fault:



LLG fault:

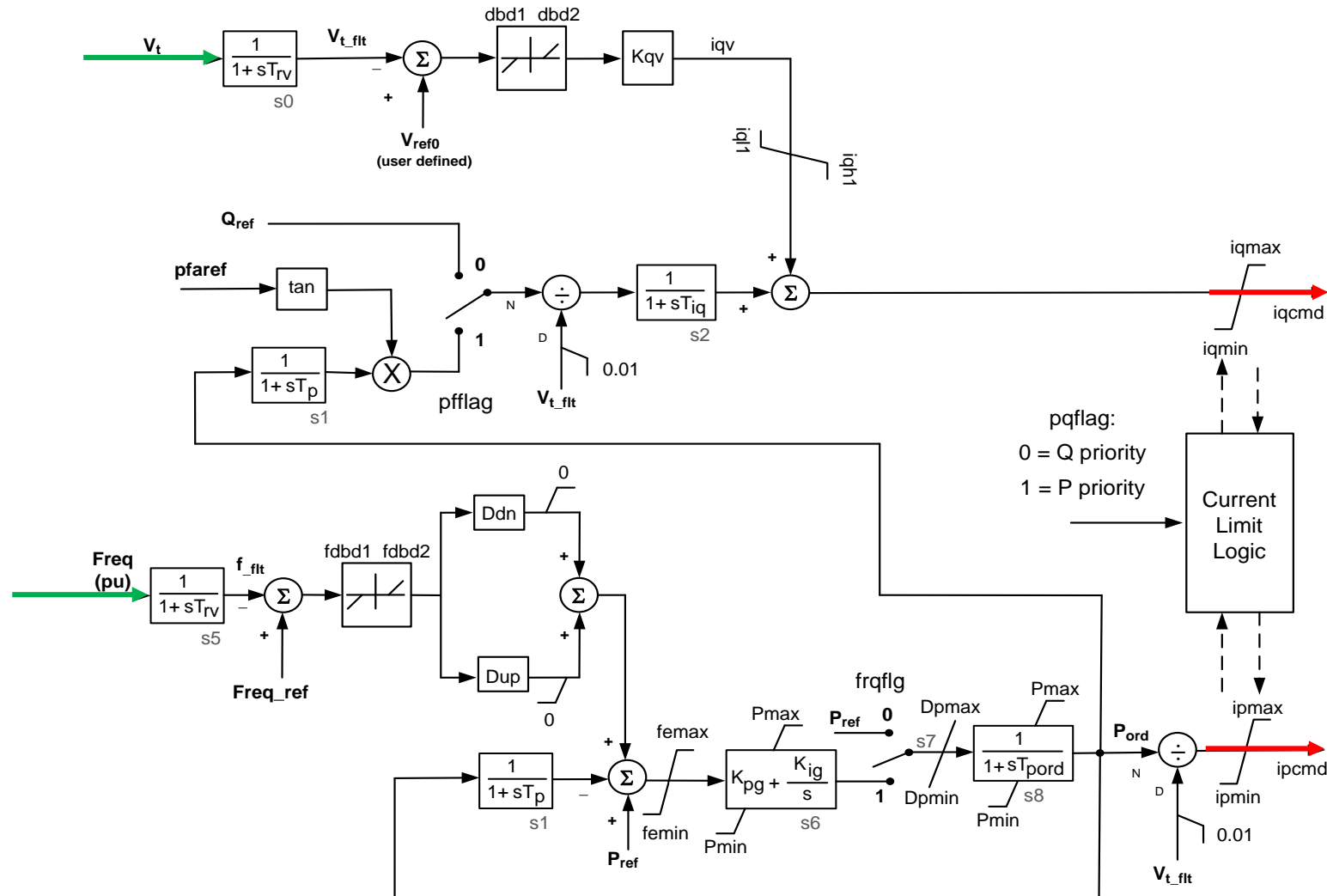


Applications

Experimental modified version of distributed energy resources model (*der_a*) accounting for individual phase voltages in voltage cut-out block

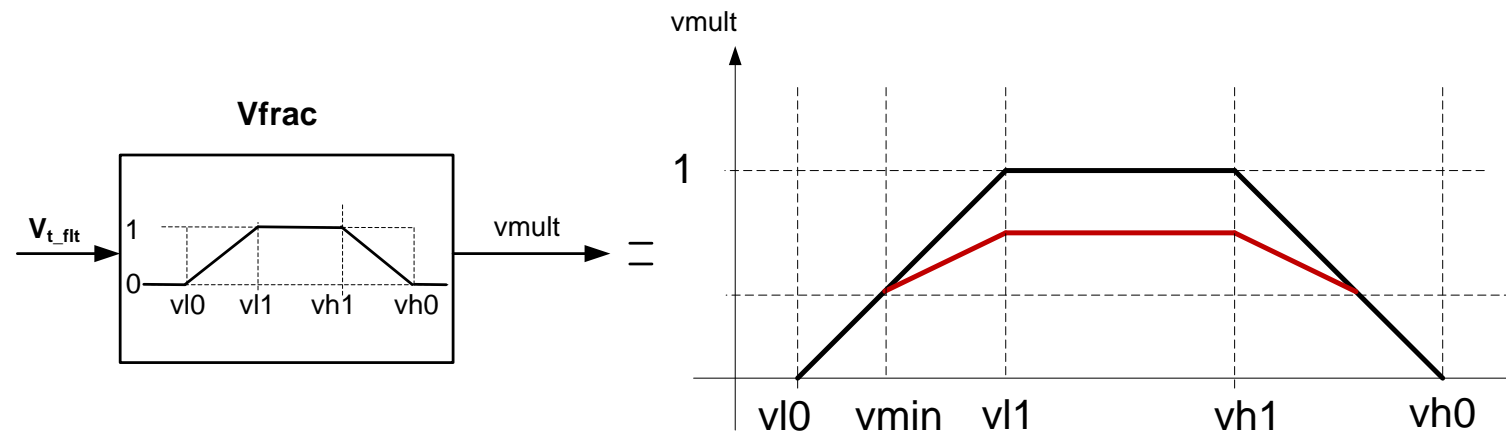


der_a model



Experimental *der_a_ph* model: Use of individual phase voltage for the voltage cut-out block in *der_a*

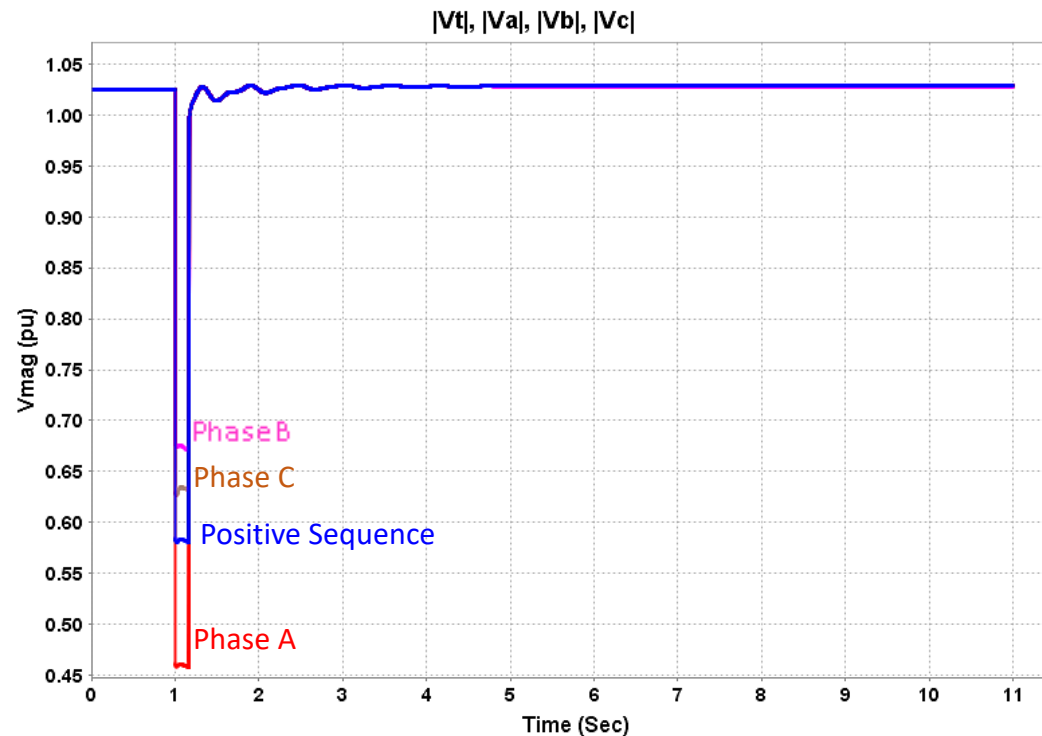
- Modified the voltage cut-out block logic in *der_a* to trip based on the lowest/highest phase voltage magnitudes instead of the positive sequence voltage magnitude
- ***NOTE: Experimental model for demonstration ONLY



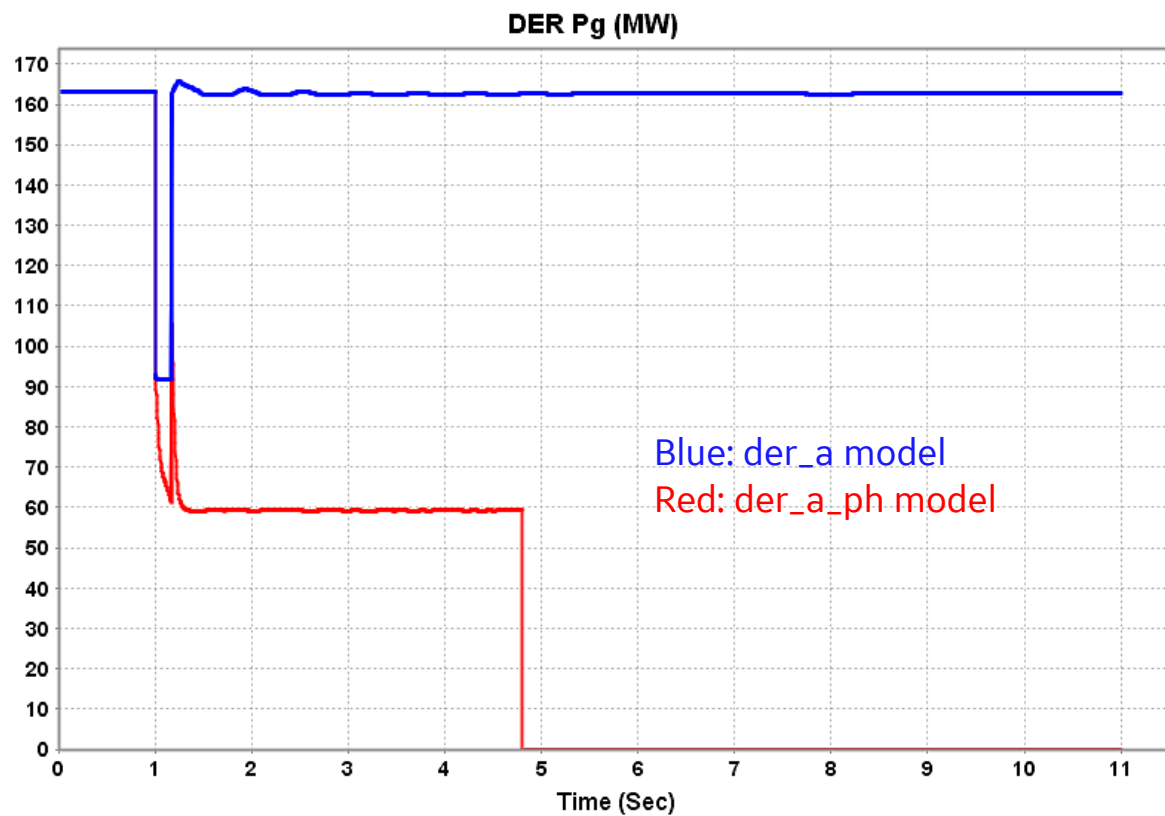
Experimental *der_a_ph* model: Use of individual phase voltage for the voltage cut-out block in *der_a*

- Test: 9-bus simplified WECC system
 - 10-cycle SLG bus fault at high-side of GSU xfmr
- Default parameters used from NERC guideline ^[1]

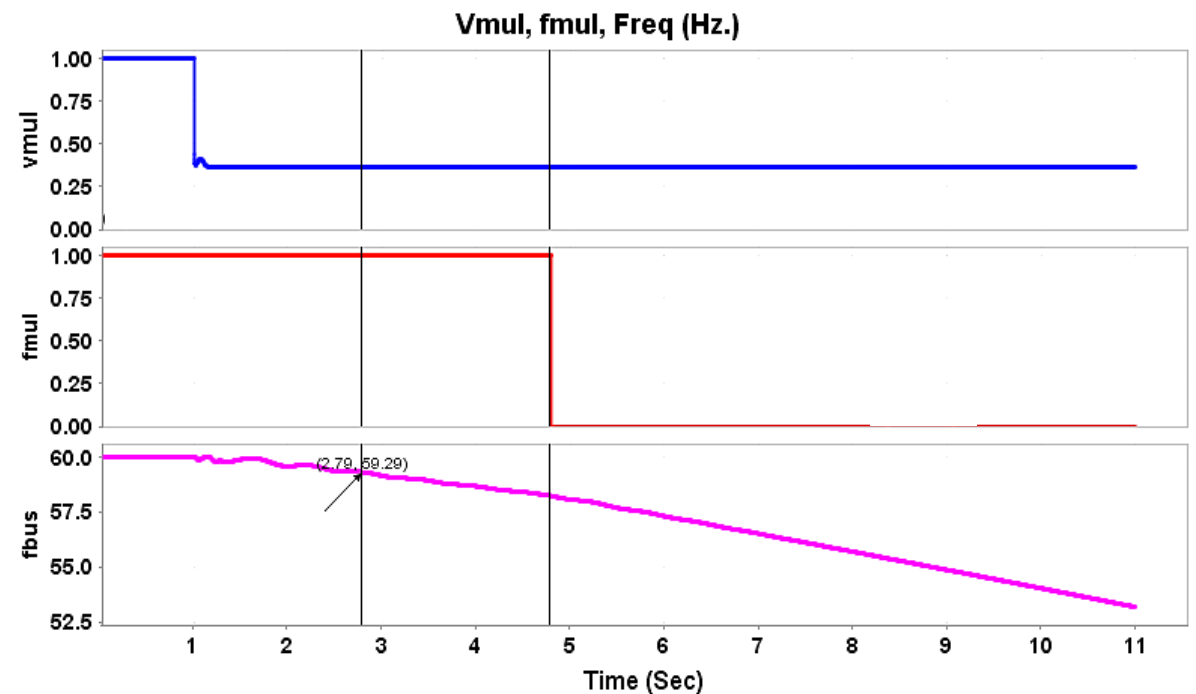
Param	Value
<i>v</i> /0	0.44 pu
<i>v</i> /1	0.49 pu
<i>vh</i> 0	1.2 pu
<i>vh</i> 1	1.15 pu
Timers	0.16 s



Experimental *der_a_ph* model: Use of individual phase voltage for the voltage cut-out block in *der_a*



Voltage cut-out block output with *der_a_ph* model



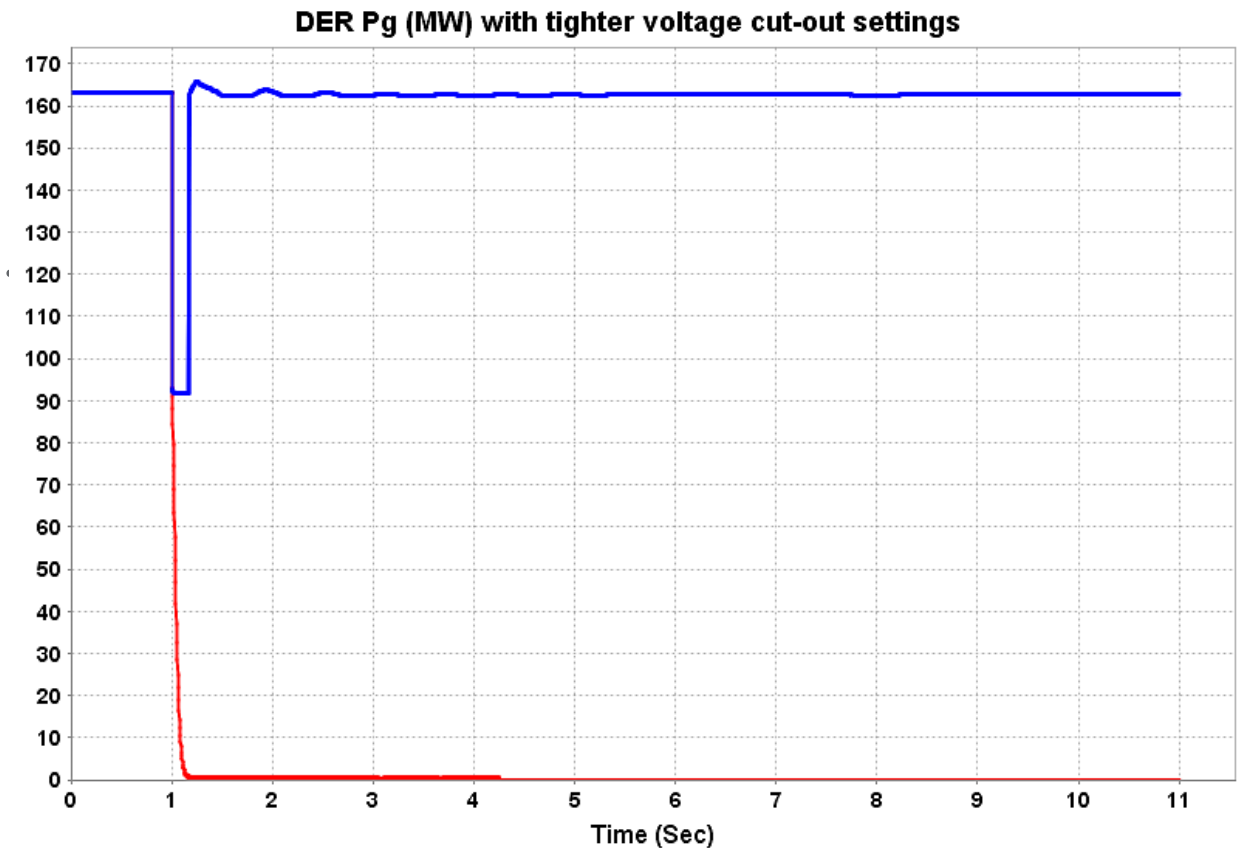
Experimental *der_a_ph* model: Use of individual phase voltage for the voltage cut-out block in *der_a*

- Slightly tighter voltage trip thresholds
- Modified parameters: $v/0=0.47$, $v/1=0.52$

9-bus system, 10-cycle SLG bus fault at high-side of GSU xfmr:

Blue: *der_a* model

Red: *der_a_ph* model



Experimental modified version of generator low/high voltage protection model (*lhvrt*) accounting for individual phase voltages



Allow Per-phase Voltage/sequence Voltage-based Protection Modeling (user-defined models)

If lhvrt trips based on lowest/highest phase voltage:

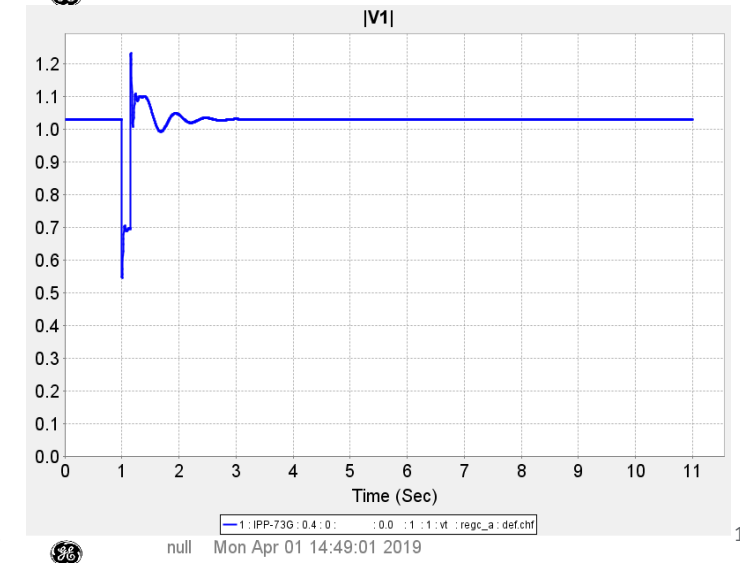
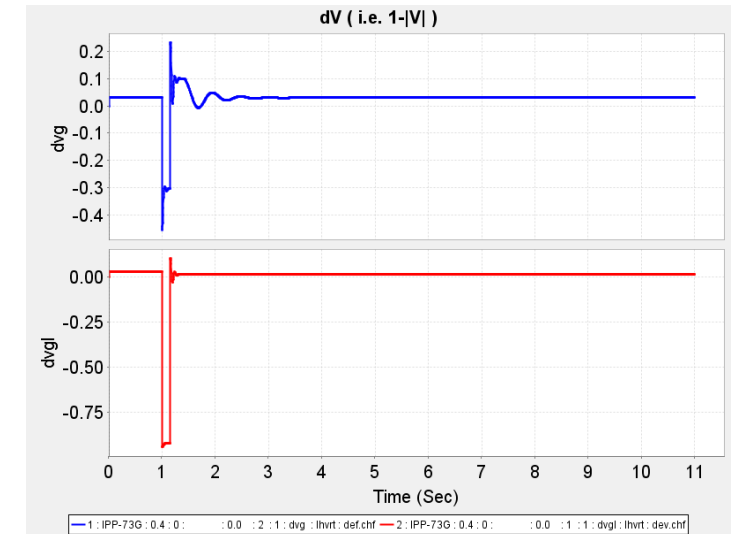
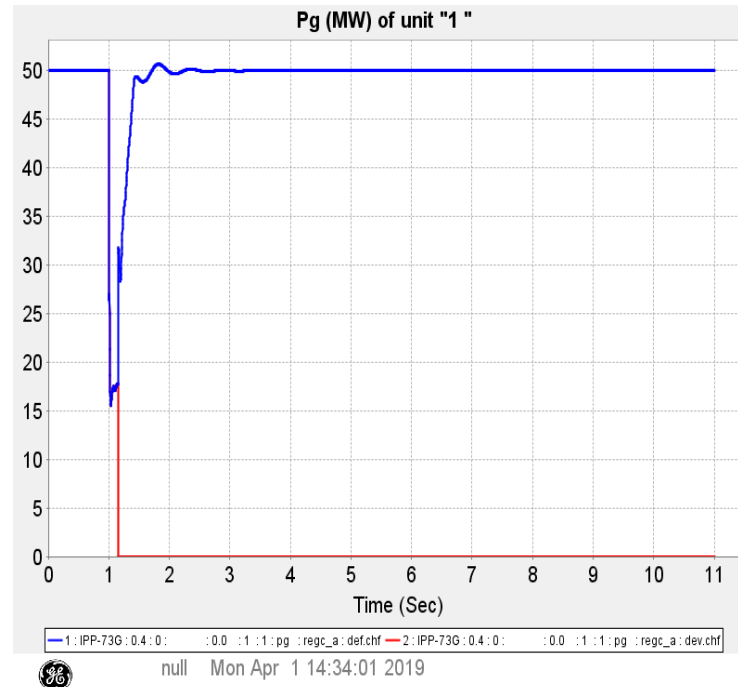
9-cycle single-line-ground fault applied at the high-side bus of step-up transformer for two PV plants :

Blue: Official lhvrt model

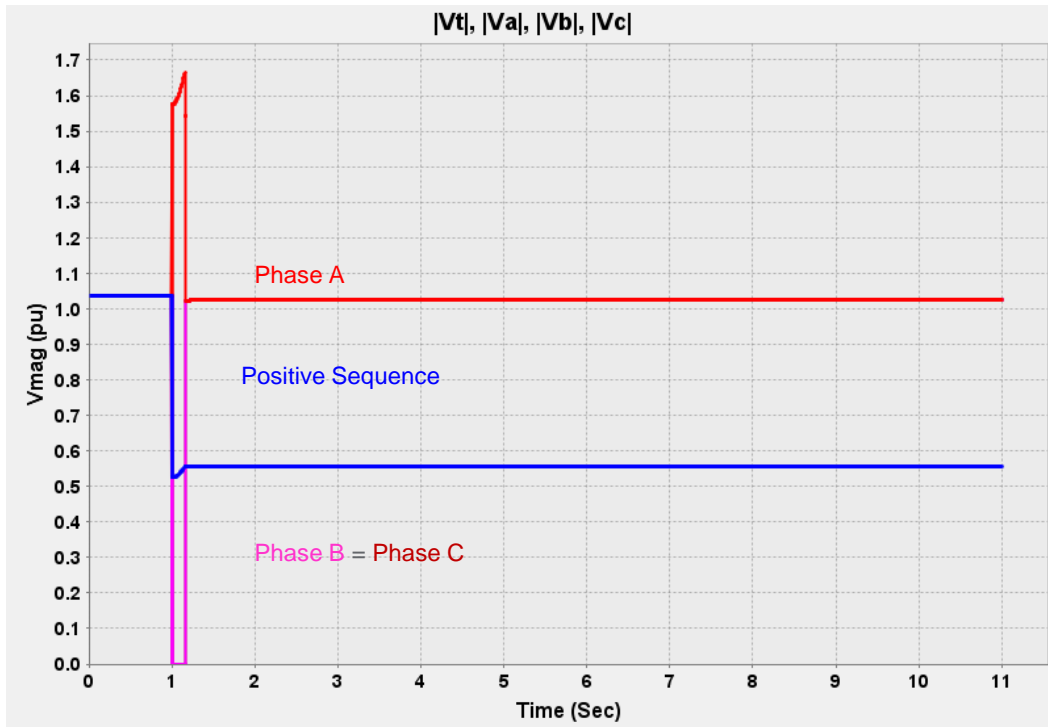
Red: Experimental lhvrt model

Two units tripped ~70 MW

***NOTE: Experimental model for demonstration ONLY



Modified *lhvrt* model

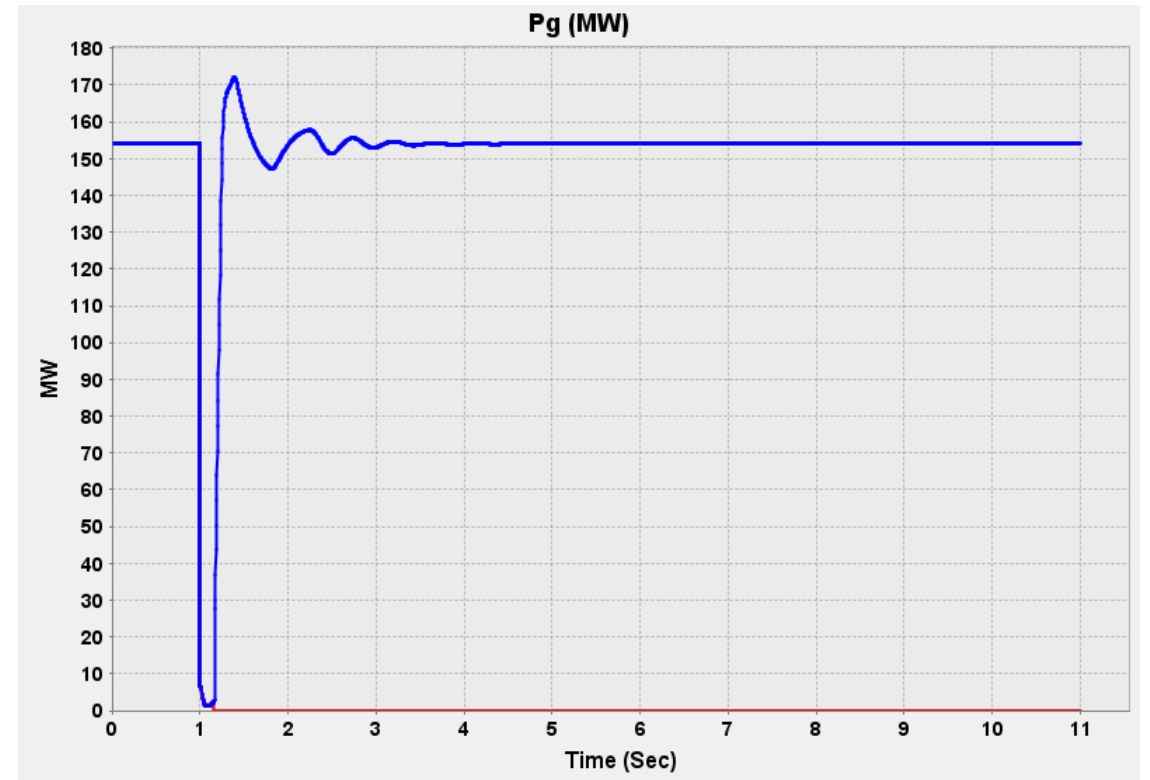


Phase A, B, C and positive sequence voltages at the PV terminal for LLG fault

WECC case 10-cycle solid LLG fault is applied at the terminals of a PV plant generating 155MW:

Blue: *der_a* model

Red: *der_a_ph* model



Output of the PV unit for LLG fault: Blue : Original *lhvrt* model, Red : Modified *lhvrt* model using phase voltages.



Other uses

- Could help parameterization of the der_a model unbalanced faults appropriately, since individual phase voltages can be monitored.
- Negative sequence current relay operation in conventional generators could be estimated during prolonged unbalanced conditions, such as a single line reclosing.
- The signals could also be used to capture motor contactor opening/closing actions more accurately.



Other uses

- Monitoring
- As more and more loads in the grid become drive-connected, one could also possibly take advantage the sequence/phase quantities to capture the behaviour such variable frequency drives more accurately in their models.
- Having access to these quantities could be useful in more accurate modelling of inverter-based resources such as the ability to model converter controls' protective functions, controls that actively suppress the negative sequence current produced by the inverter, and other such controls that use or control the negative sequence or zero sequence current injections.



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