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Bayesian Optimization Approach for DER Dynamic Model Calibration

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Grid Event Signature Library Project

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PNNL provided support to GESL through:

- Collecting synchrophasor measurements for various events
- Developing data readers and API
- Demonstrating the usefulness of the GESL through various use cases
  - Event detection and classification
  - Oscillation Analysis
  - Frequency Response analysis
  - Model validation

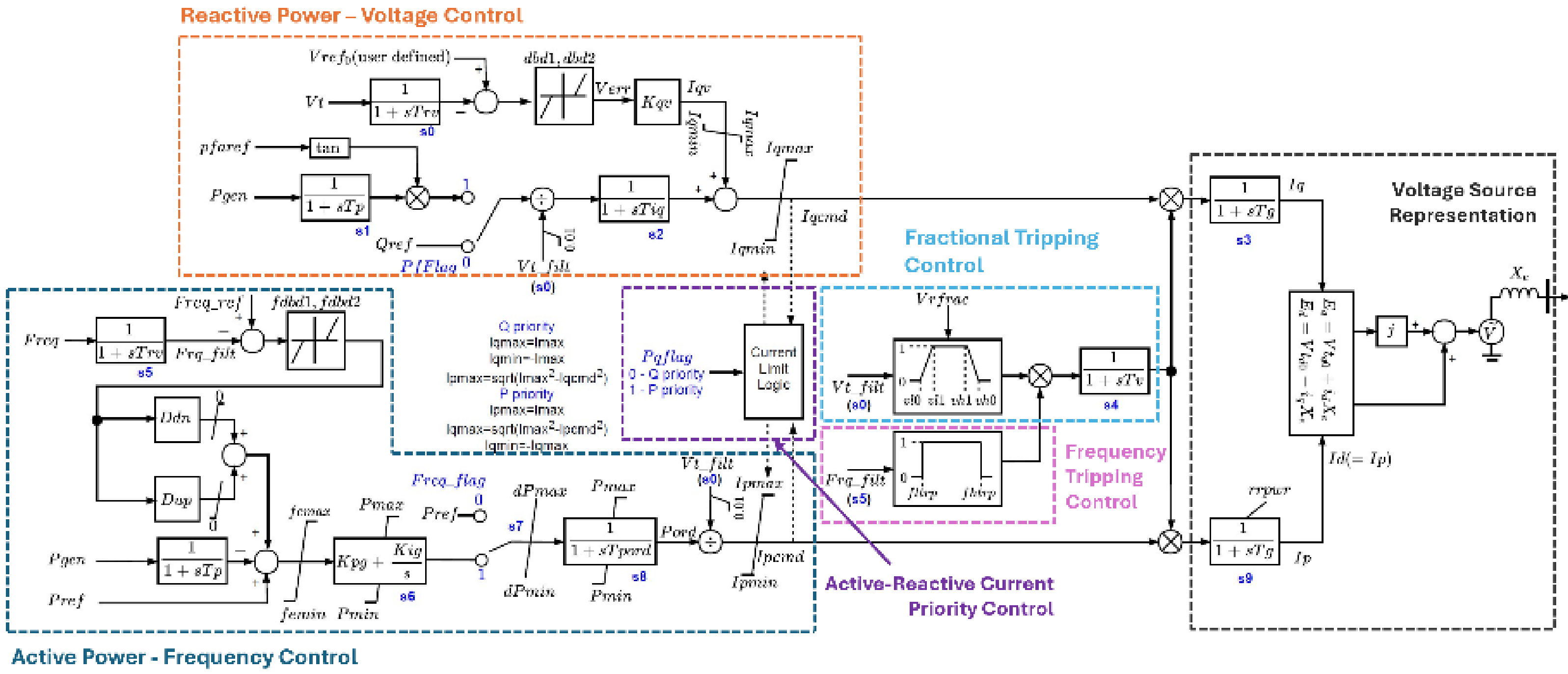
This work was funded by the DOE Office of Electricity Transmission Reliability and Renewables Integration (TRRI) Program

DER Modeling

- Increasing DER penetration requires accurate modeling in bulk power system (BPS) studies.
- The DER_A model was introduced to represent both utility-scale and distributed DERs.
- The model has 48 parameters and can function either standalone or within a composite load model.
- NERC published guideline documents providing recommended generic parameters.
- Customization of specific parameters is necessary to reflect actual DER characteristics.

- Latest GESL update includes:
  - Distribution-level PMU measurements, including those from BESS and PV, were integrated into GESL.
  - This integration enables testing of various DER modeling and calibration methods using publicly available disturbance records.

DER A model



Source: EPRI, "Model user guide for distributed energy resources: DER A model version 1.0," 2016.

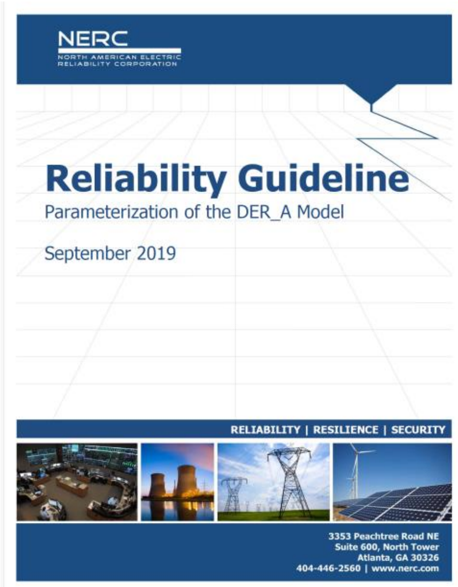


Table 2.1: Default DER_A Model Parameters					
Param[40]	IEEE Std. 1547-2003 Default	IEEE Std. 1547a-2014 Default	CA Rule 21 Default	IEEE Std. 1547-2018 Category II Default	Notes
trv	0.02	0.02	0.02	0.02	† Note 1
dbd1	-99	-99	-99	-99	† Note 1
dbd2	99	99	99	99	† Note 1
kqv	0	0	0	0	† Note 1
vref0	0	0	0	0	† Note 2
tp	0.02	0.02	0.02	0.02	†
tiq	0.02	0.02	0.02	0.02	†
ddn	0	0	20	20	Note 3
dup	0	0	20	20	Note 3
fdbd1	-99	-99	-0.0006	-0.0006	Note 3
fdbd2	99	99	0.0006	0.0006	Note 3
femax	0	0	99	99	Note 3
femin	0	0	-99	-99	Note 3
pmax	1	1	1	1	† Note 4
pmin	0	0	0	0	Note 4
dpmax	99	99	99	99	†
dpmin	-99	-99	-99	-99	†
tpord	0.02	0.02	5	5	Note 3
Imax	1.2	1.2	1.2	1.2	† Note 4
vl0	0.44	0.44	0.49	0.44	Note 5
vl1	$0.44+V_{DROP}$	$0.44+V_{DROP}$	$0.49+V_{DROP}$	$0.44+V_{DROP}$	Note 5
vh0	1.2	1.2	1.2	1.2	Note 5
vh1	$1.2-V_{DROP}$	$1.2-V_{DROP}$	$1.2-V_{DROP}$	$1.2-V_{DROP}$	Note 5
tvl0	0.16	0.16	1.5	0.16	Note 5
tvl1	0.16	0.16	1.5	0.16	Note 5
tvh0	0.16	0.16	0.16	0.16	Note 5
tvh1	0.16	0.16	0.16	0.16	Note 5

Conducted Study and Methodology

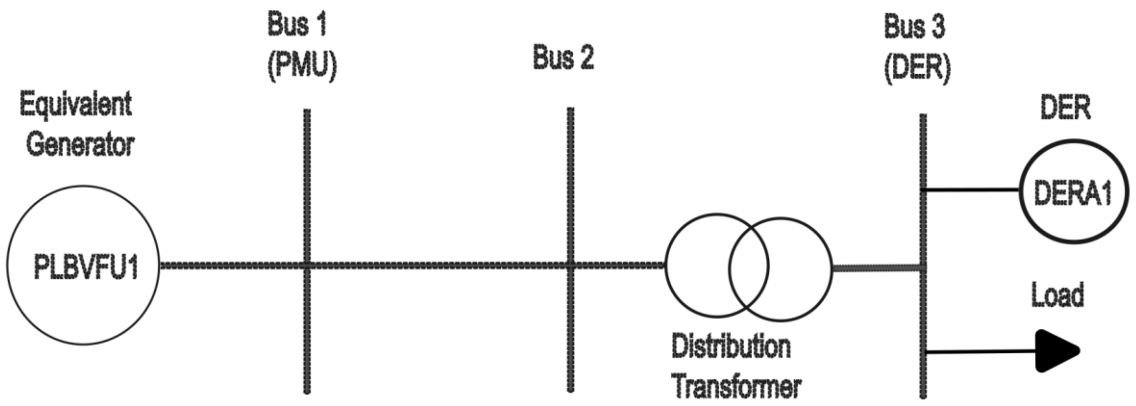
- Prior studies largely relied on simulated data, lacking real-world validation of DER model parameters.
- This work evaluates the DER_A model using publicly available PMU measurements from two electric utilities (GESL dataset).
- Measurement play-in approach was applied to validate DER_A models:
  - DER responses were simulated using IEEE 1547-2018 standard (Category II) default parameters.
  - Simulated DER active/reactive power responses were compared with actual PMU measurements.
- Parameters of DER_A were calibrated using iterative Bayesian optimization, following the methodology introduced by Biswas et al. (IEEE Access, 2024*).
- The calibrated DER_A model was verified against independent events (events not used during calibration) from the GESL dataset, demonstrating improved accuracy and robustness.

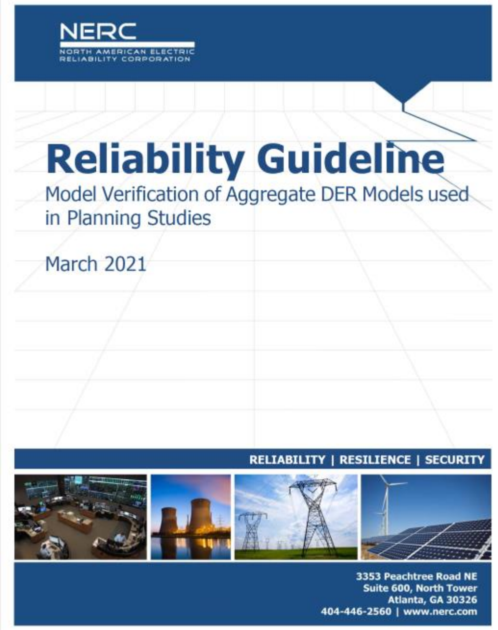
*S. Biswas, F. Tuffner, J. Follum, and T. Wall, "Inverter model validation and calibration using phasor measurement unit data," IEEE Access, vol. 12, pp. 98 990–99 001, 2024.

DER_A Play-in model validation approach

- DER aggregation represented at the point of interconnection (POI) by an equivalent voltage and frequency source.
- Actual voltage and frequency signals measured at POI are played into simulation software (PSS®E v35, using PLBVF1 model).
  - PLBVF1 model assigned to generator slack bus to play voltage/frequency from recorded PMU data (via PLB file).
  - DERA1 model assigned to distributed generation bus, initially using NERC-recommended parameters (IEEE 1547-2018, Category II).
- Connection line and distribution transformer parameters are based on NERC guidelines.
- The resulting DER active and reactive power responses are compared against recorded PMU data.

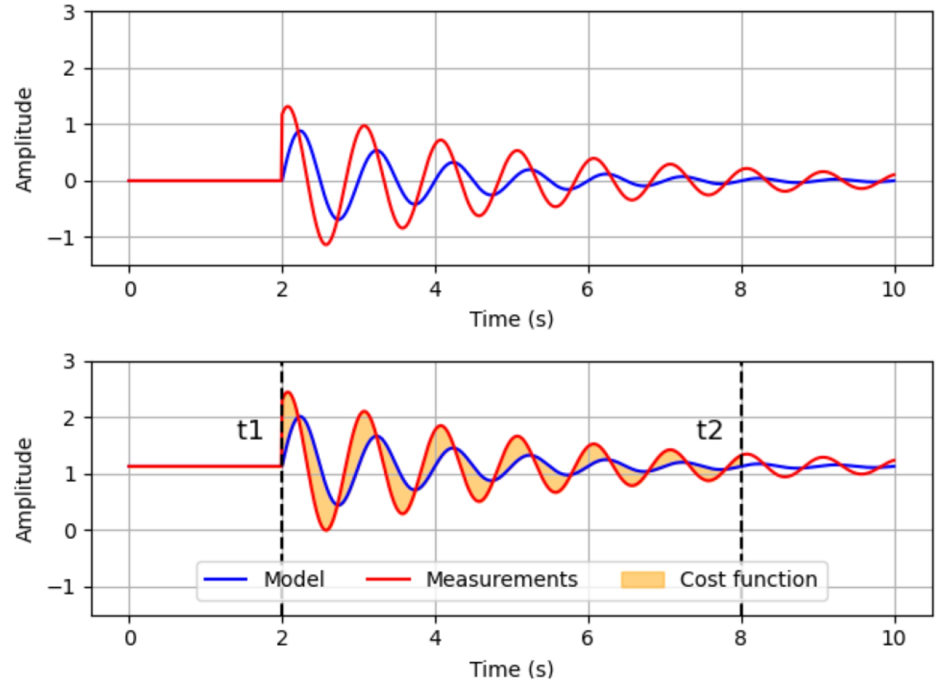
Play-in model validation





Error metric

$$err(\boldsymbol{x})_{t_1}^{t_2} = \left| \int_{t_1}^{t_2} \left[M_1(\boldsymbol{x}) - \min\left(M_1(\boldsymbol{x})_{t_1}^{t_2}, M_2(\boldsymbol{x})_{t_1}^{t_2} \right) \right] dt - \int_{t_1}^{t_2} \left[M_2(\boldsymbol{x}) - \min\left(M_1(\boldsymbol{x})_{t_1}^{t_2}, M_2(\boldsymbol{x})_{t_1}^{t_2} \right) \right] dt \right|,$$



where *err(x)* expresses the mismatch between two time series M_1 (observed response) and M_2 (model-based response) in the time range (t_1, t_2).

- This metric allows comparing signals with different temporal resolution and captures system response characteristics around a disturbance (e.g. rate of change, over/undershoot, settling values) without focusing solely on the sample-to-sample mismatch.

Calibration based on Bayesian optimization approach

- **Bayesian Optimization (BO)** is a constrained, derivative-free optimization method.
  - Ideal for cost functions that are computationally expensive or lack analytical forms.
  - Uses a **Gaussian process surrogate model** to approximate the cost function.
  - Strategically selects new evaluation points based on prior observations to efficiently find global optima.
  - Bayesian Optimization package was used: https://github.com/bayesian-optimization/BayesianOptimization
- **Parameter Grouping Strategy:**
  - Parameters divided into groups based on their influence on DER behaviors.
    - ✓ Active power-frequency response parameters.
    - ✓ Reactive power-voltage response parameters.
- **Iterative Optimization Process:**
  - Calibrate parameters in one group using Bayesian Optimization, holding other groups constant.
  - Optimized parameters from one iteration inform the next iteration.
  - Process continues iteratively until no significant improvement in cost function is achieved.
- **Benefits of this Method:**
  - Reduces the number of costly simulations.
  - Efficiently identifies optimal parameter sets.
  - Systematically captures interactions between parameter groups for improved model accuracy.

Algorithm 1 Iterative Parameter Calibration

initialize n_g: no. of parameter groups, n: iteration counter, N: max. no. of iterations, $\mathbf{x_0}$: initial parameter estimates, σ: tolerance threshold
$n \leftarrow 1$, $\mathbf{x}^* \leftarrow \mathbf{x_0}$
while $n \leq N$ **do**
    for $i = 1$ **to** n_g **step** 1 **do**
        Calibrate parameters in group i using BO keeping all other parameters fixed to obtain parameters $\mathbf{x_n}$
    end for
    Evaluate cost function $f(\mathbf{x_n})$
    if $n > 1$ **then**
        if $f(\mathbf{x_{n-1}}) - f(\mathbf{x_n}) \leq \sigma$ **then**
            break
        else $f^* \leftarrow f(\mathbf{x_n}), \mathbf{x}^* \leftarrow \mathbf{x_n}, n \leftarrow n + 1$
        end if
    end if
end while
return $\mathbf{x}^*$

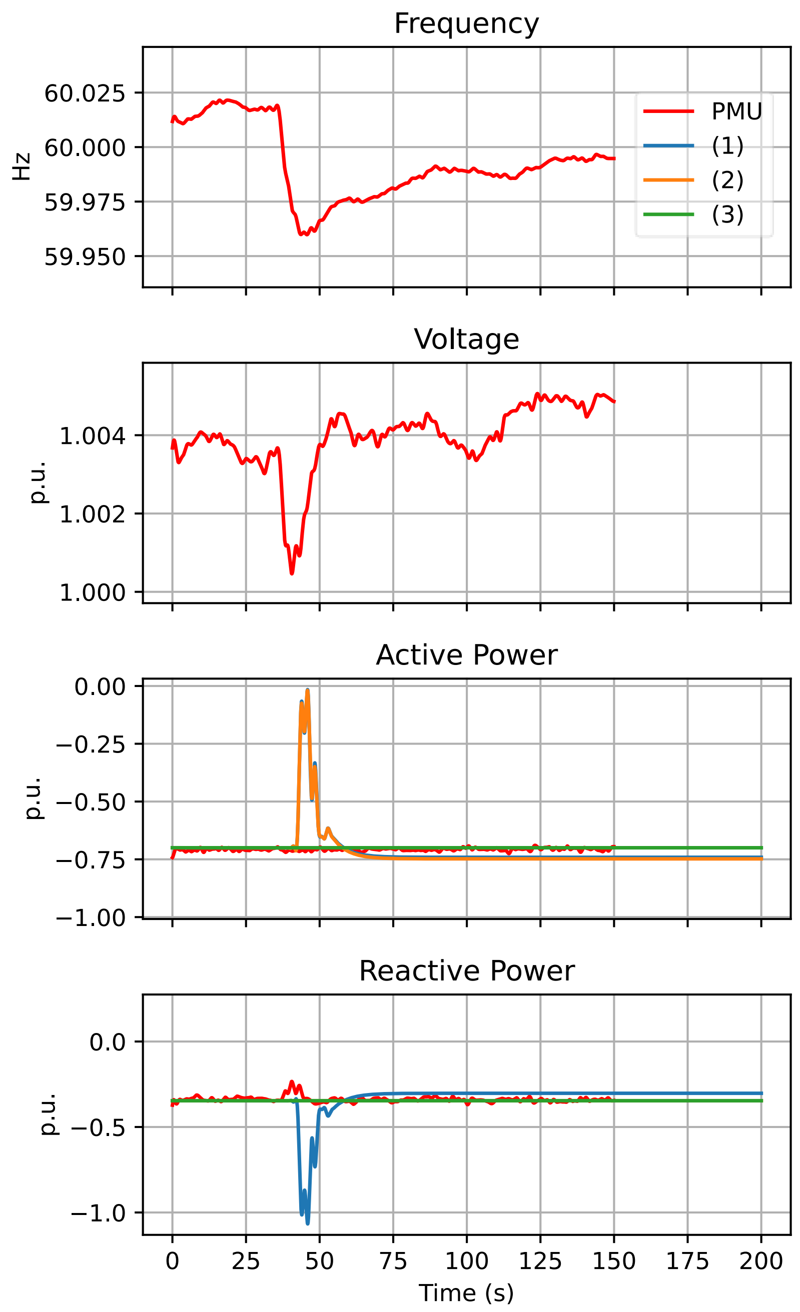
Case Study

- Analyzed data from Providers 11 and 12, including utility-scale solar PV and battery energy storage systems (BESS).
- Chose events with significant frequency deviations and minimal measurement noise.
- Extracted frequency and positive-sequence voltage measurements and saved them into PSS®E-compatible PLB files.
- Performed simulations by playing voltage and frequency measurements into the DER_A model.
- Adjusted model flags and relay settings based on engineering judgment and visual inspection.
- Optimized sensitive parameters using iterative Bayesian optimization.

DER A Model Flags

ICON	Name	Description
M	*PfFlag*	1: constant power factor, 0: constant Q control
M+1	*FreqFlag*	1: frequency control enabled, 0: disabled
M+2	*PQFlag*	1: priority for current limit, 0: Q priority
M+3	*GenFlag*	1: unit is a generator, 0: unit is a storage device
M+4	*VtripFlag*	1: enable, 0: disable
M+5	*FtripFlag*	1: enable, 0: disable

- DER_A model contains **six control flags (ICONs)** in PSS®E, which enable or disable specific control functionalities (e.g., frequency and voltage support).
- Appropriate flag values were set using engineering judgment and visual analysis of measured DER responses.
- Provider 12:
  - Observed DER had no active/reactive power response to frequency deviation.
  - Flags set: PfFlag = 0, FreqFlag = 0.
  - Multiple events confirmed BESS/PV units from Provider 12 lack frequency/voltage support functionalities.

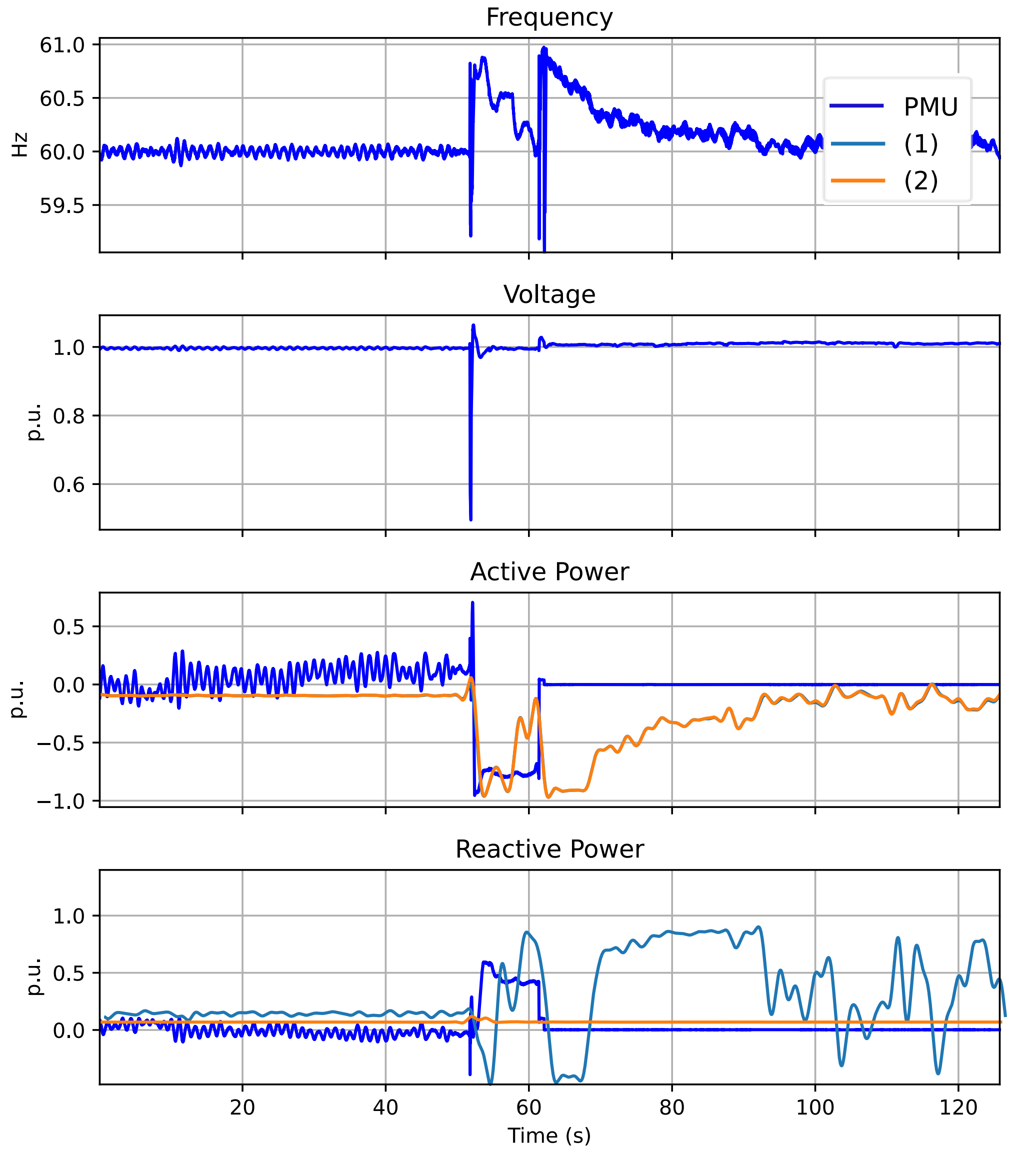


(1) Constant power factor - on, Frequency control - on;
(2) Constant reactive power - on, Frequency control - on;
(3) Constant reactive power - on, Frequency control - off.

DER A Model Flags

ICON	Name	Description
M	*PfFlag*	1: constant power factor, 0: constant Q control
M+1	*FreqFlag*	1: frequency control enabled, 0: disabled
M+2	*PQFlag*	1: priority for current limit, 0: Q priority
M+3	*GenFlag*	1: unit is a generator, 0: unit is a storage device
M+4	*VtripFlag*	1: enable, 0: disable
M+5	*FtripFlag*	1: enable, 0: disable

- Provider 11 (Signature ID 6012):
  - BESS actively provided frequency support and reactive power control.
  - Flags set: FreqFlag = 1, PfFlag = 1, PQFlag = 0, GenFlag = 0 (since it's a BESS).
  - Observed frequency-triggered tripping confirmed setting FtripFlag = 1.
  - Default frequency trip parameter (fhtrp = 61.2 Hz) from IEEE Std.1547-2018 was too high.
  - Adjusted frequency protection thresholds to IEEE Std.1547-2003 values (fhtrp = 60.5 Hz, fltrp = 59.3 Hz) to accurately simulate measured device response.

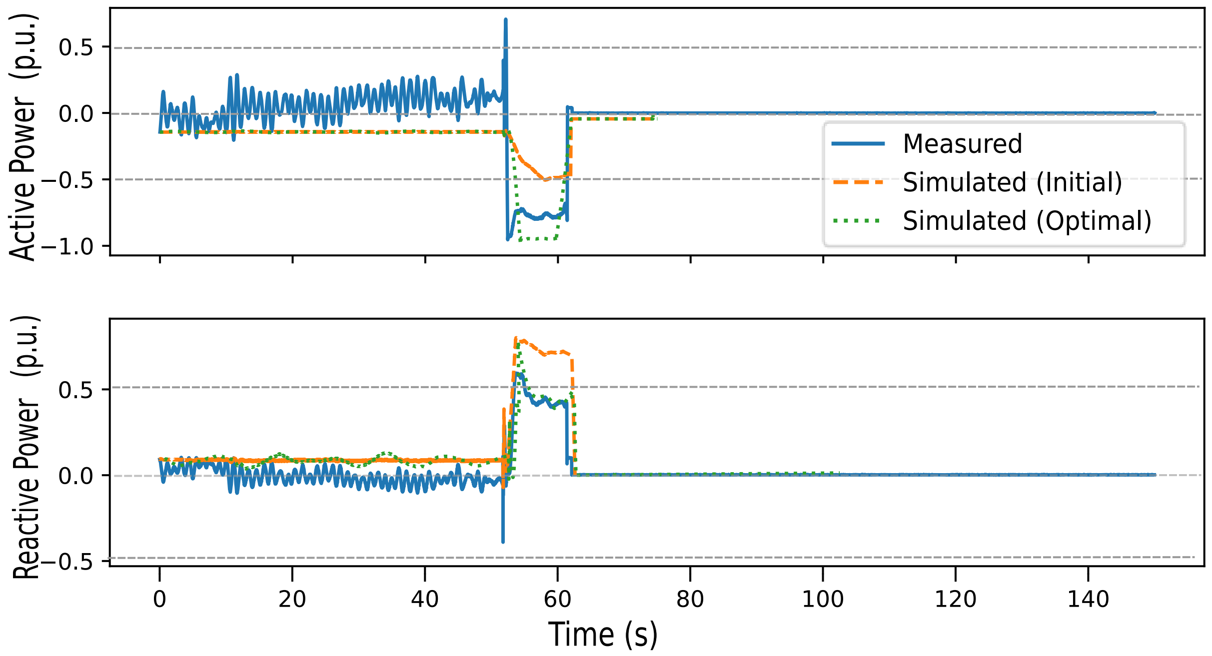


(1) Constant power factor - on, Frequency control - on;
(2) Constant reactive power - on, Frequency control - on;

Calibration Results

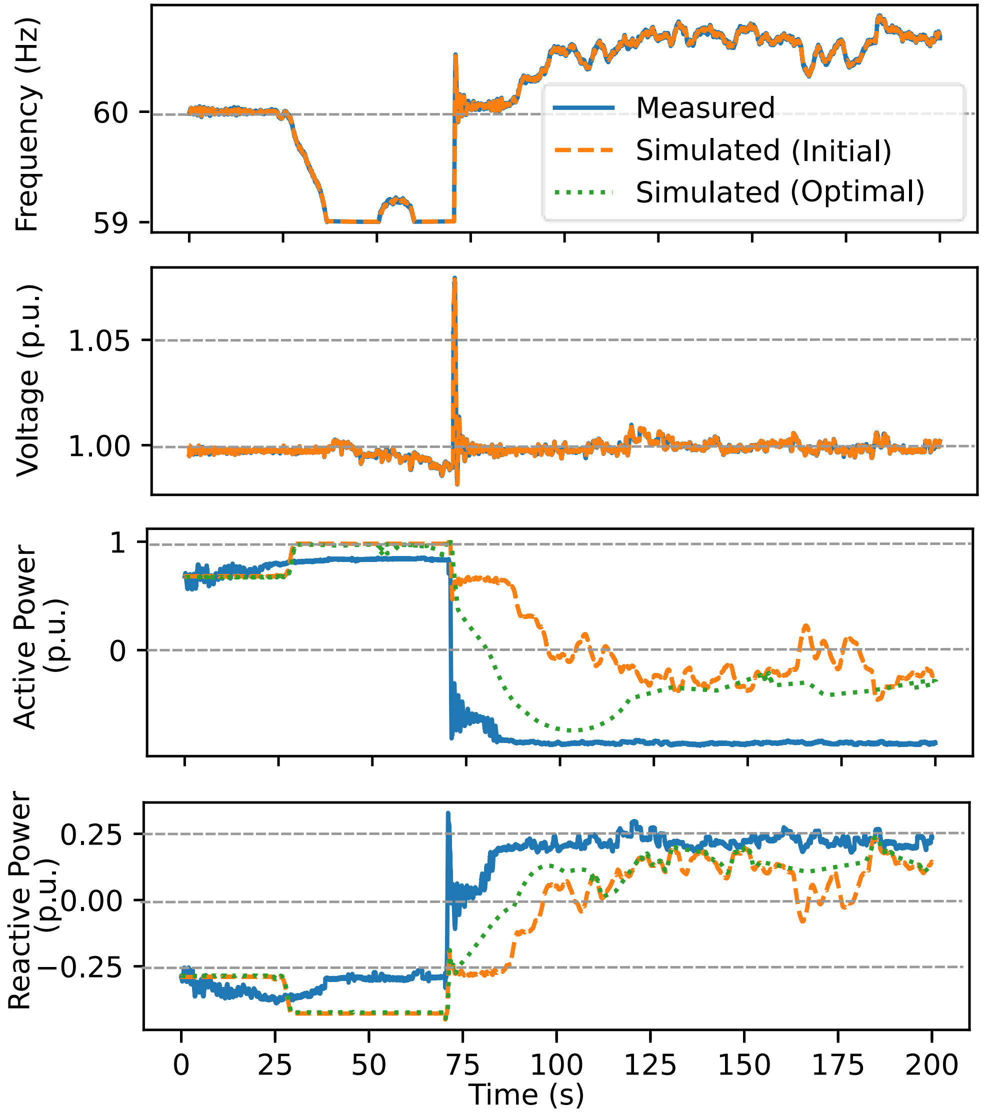
- DER_A model comprises **48 parameters**, making sensitivity analysis crucial for efficient calibration.
- Leveraged prior studies and engineering judgment to select the **most influential parameters** for calibration (listed in Table II).
- Parameters were grouped based on the aspects they impact:
  - **Active power-frequency response**
  - **Reactive power-voltage behavior**
- **Calibration Process:**
  - Used **three disturbance events** from the GESL dataset (Signature IDs: 6011, 6012, 6030).
  - Employed **iterative Bayesian optimization** to minimize total mismatch between simulated and measured responses.
  - Calibration completed in approximately **15 minutes** (Intel Core i7, 32 GB RAM).
- **Results:**
  - Calibrated parameters improved the match between DER model responses and actual field measurements.
  - Adjusted **frequency protection thresholds** ensured accurate tripping behavior aligned with observed data (trip at ~61s).

CON	Name	Description	Initial	Final
Group 1: Enabling Frequency Control				
J+1	Trf	Freq. measurement time const.	0.02 s	0.01 s
J+6	Tp	Power measurement time const.	0.02 s	0.01 s
J+19	Kpg	PI controller proportional gain	0.1p.u.	0.2 p.u.
J+20	Kig	PI controller integral gain	10 p.u.	8.5 p.u.
Group 2: Enabling Voltage Control				
J	Trv	Voltage measurement time const.	0.02 s	0.02 s
J+4	Kqv	Proportional voltage control gain	0 p.u.	0.9 p.u.
J+7	Tiq	Q-control time constant	0.02 s	0.025 s



Calibration results verification

- Independently verify calibrated DER_A parameters using a previously unused event (GESL Signature ID: 6064).
- Calibrated model outperformed the default parameter set.



Conclusion

- Developed a model validation testbed using the measurement play-in approach in PSS®E.
- Evaluated the performance of the generic DER_A model using real-world PMU measurements.
- Demonstrated that commonly used NERC-recommended default parameters may not accurately capture actual DER behavior across diverse scenarios.
- Highlighted the importance of measurement-based verification and calibration for aggregated DER models in reliability studies.
- Future work:
  - Collect and analyze measurements from DER-rich feeders across various operating conditions.
  - Further assess the adequacy and general applicability of DER_A models.