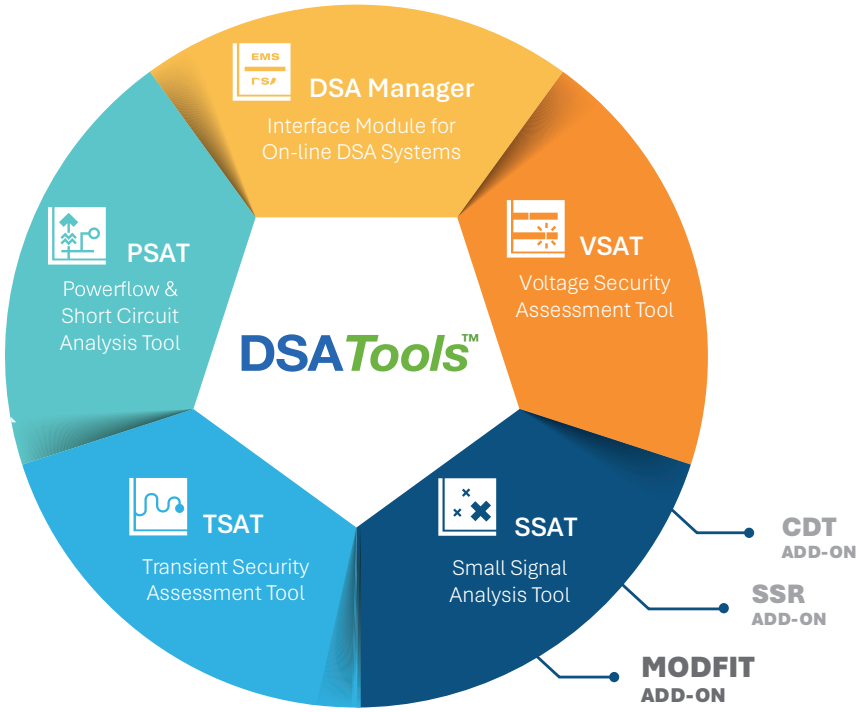
MODFIT: USE BLACK-BOX EMT MODELS IN SMALL-SIGNAL STABILITY ANALYSIS TOOLS FOR OSCILLATORY STUDIES

A DSATools™ Add-On from Powertech Labs Inc.

Study oscillations and control interactions between inverter-based resources using models fitted to their Black-Box EMT counterparts

Powertech | August 2026 | Public/External Distribution



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ABSTRACT

As renewable generation, battery energy storage systems, and inverter-based resources (IBRs) continue to reshape power systems worldwide, utilities and system operators face a growing challenge: how do we identify stability risks quickly without compromising the level of detail in the underlying system dynamics?

ModFit helps bridge that gap. As a DSATools™ add-on developed by Powertech Labs, ModFit enables utilities, planners, consultants, and developers to leverage existing black-box PSCAD™ models for rapid small-signal stability assessments. This allows organizations to evaluate significantly more operating conditions and contingencies without requiring access to proprietary detailed device and controller information.

By automatically scanning EMT models, creating reusable fitted representations, and integrating them directly into the Small Signal Analysis Tool (SSAT), ModFit combines the fidelity of electromagnetic transient (EMT) studies with the speed and efficiency of modal analysis.

SSAT performs small-signal stability analysis by combining power-flow solutions with dynamic models to create a linearized state-space representation of the bulk power system. Engineers use this representation to identify oscillatory modes, evaluate damping, determine modal participation, and assess risks such as inter-area oscillations, local oscillations, and sub-synchronous control or torsional interactions. Traditionally, these studies rely on generic dynamic models or user-defined models developed specifically for SSAT. ModFit extends this capability by enabling fitted models derived from detailed EMT or black-box PSCAD™ plant representations to be used directly within SSAT studies, providing a more

This white paper explores the challenges associated with evaluating IBR stability, outlines the ModFit workflow, and demonstrates how the technology supports faster contingency screening, weak-grid assessments, transfer studies, and long-term system planning. Most importantly, it highlights a practical advantage: once fitted models have been created, stability screening studies that would traditionally require hours (or days) of EMT simulation can be completed in minutes. This allows engineers to reserve computationally intensive EMT studies for the relatively small number of contingencies that are flagged as higher risk through SSAT analysis.

KEY TAKEAWAYS

- Stability studies that traditionally require hours of EMT simulation can be completed in seconds using ModFit and SSAT.
- ModFit works directly with black-box PSCAD™ models without requiring access to proprietary inverter controls
- Utilities can evaluate significantly more contingencies, dispatch scenarios, and transfer conditions with the same study resources.
- Analysis with ModFit and SSAT provides deeper insight into stability risk, oscillation frequency, and damping than SCR-based screening methods.
- Fitted models can be reused across multiple studies, creating a scalable framework for planning and operational analysis.
- The methodology has been validated against full EMT simulations using benchmark test systems and realistic weak-grid applications.confidence in results.

AUDIENCE

Electric Utilities & System Operators
Organizations responsible for planning, operating, and maintaining reliable power systems that must evaluate stability risks associated with growing inverter penetration.

Independent System Operators (ISOs) & Transmission Operators
Stakeholders evaluating network security, transfer capability, weak-grid performance, and contingency resilience.

Consultants & Engineering Firms
Teams performing stability studies, interconnection assessments, and renewable integration planning.

Equipment Manufacturers & Project Developers
Organizations seeking efficient ways to evaluate inverter performance under a wide range of operating conditions while preserving proprietary model information.

Typical Deliverables

- Stability screening reports
- Contingency analysis results
- Weak-grid assessments
- Modal analysis reports
- Oscillation identification and damping analysis
- Planning study recommendations

WHY STABILITY ASSESSMENT IS BECOMING MORE CHALLENGING

The rapid growth of inverter-based resources is fundamentally changing power system behaviour. Solar generation, battery energy storage systems, wind generation, and other inverter-connected technologies introduce dynamic interactions that are different from those in systems dominated by synchronous generation.

As system strength decreases and inverter penetration increases, utilities must evaluate a growing number of operating scenarios to identify potential risks. These risks can include sub-synchronous oscillations, control interactions between resources, weak-grid instabilities, and other dynamic phenomena that may not be detected using conventional screening methods.

At the same time, many inverter models are supplied as encrypted or black-box PSCAD™ models, limiting the ability to adapt them for large-scale planning studies or integrate them into faster analysis workflows.

COMMON CHALLENGES IN IBR STABILITY ASSESSMENT

- EMT simulations can require hours to evaluate a single contingency.
- Large-scale N-1 contingency studies may require hundreds of simulations.
- Screening methods such as SCR and weighted SCR cannot fully capture inverter interactions.
- Black-box OEM models often cannot be adapted to conventional modal analysis approaches.
- Grid-forming and grid-following resources may respond differently under weak-grid conditions.
- Stability studies require solutions that scale across many operating points, transfer levels, and dispatch conditions.

ModFit provides a practical bridge between detailed EMT simulation and fast small-signal stability analysis. By automatically scanning black-box PSCAD™ models and creating reusable fitted models, ModFit enables organizations to perform comprehensive stability screening without requiring access to proprietary inverter controls.

The workflow has two stages. The offline stage is performed once per plant:

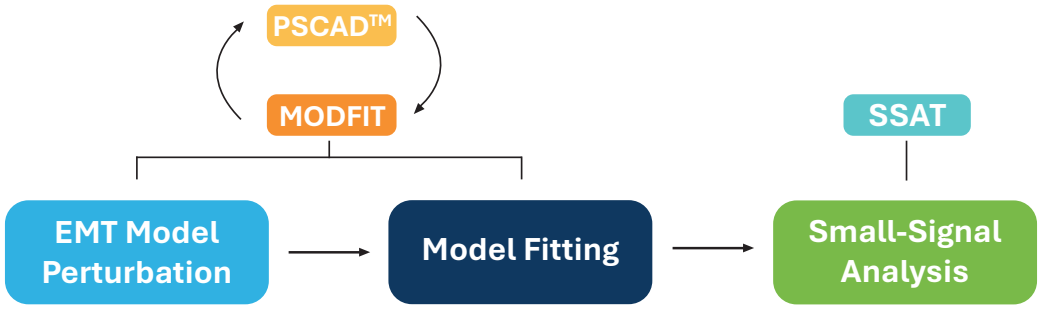
1. Scan the black-box model in PSCAD™. ModFit connects a purpose-built scan module to the model at its point of interconnection (POI) and applies small voltage perturbations to measure the plant's dynamic response.
2. Fit a small-signal model to the scan results, capturing the plant's stability characteristics across a range of operating conditions.

The online stage is fast and repeatable:

3. Assess small-signal stability in SSAT for present conditions, contingencies, and transfers, using the fitted models within the full SSAT modal-analysis toolkit.

Because the fitted models are reusable and can be interpolated across operating points, the computationally expensive scanning step is performed only once per plant. All subsequent stability screening across dispatch levels, contingencies, and network configurations reuses the same fitted models.

THE MODFIT SOLUTION



ModFit addresses this challenge by automating the extraction of small-signal frequency-response behavour from detailed EMT plant models and converting that behaviour into fitted state-space representations that can be used in SSAT. This workflow allows users to retain the value of vendor-supplied black-box models while avoiding the need to run full-system EMT simultations for every contingency, dispatch point, or transfer condition.

THE TECHNICAL APPROACH

ModFit is delivered as three integrated components that span the workflow from EMT model to SSAT result. First a PSCAD™ simulation is performed where the plant model is perturbed and its response recorded. Second, the ModFit model-fitting application converts those responses into a reusable fitted model. Third, the MATREAD interface brings the model into SSAT so it can be used in system-level stability studies.

SIMULATION OF PERTURBATIONS IN THE EMT DOMAIN

Each IBR plant EMT model is simulated independently, connected to an ideal voltage source at the POI. The model includes the entire plant, comprising the multiple inverters, collector system, substation equipment, and power plant controller, so that all dynamics relevant to the aggregated plant response are captured.

After a sufficient start-up time for the plant to reach steady state, small sinusoidal voltage disturbances are superimposed on the voltage source in the synchronous dq frame. Disturbances are applied to the d- and q-axis voltage at a discrete set of frequencies over the range of interest, and the resulting d- and q-axis currents are recorded. These results provide a comprehensive view of the small-signal characteristics of the device, including the coupling between the d- and q-axis quantities. This process is fully automated by ModFit, which repeats these perturbation tests across a user-specified range of active power and reactive power (or POI voltage) operating points.

MODEL FITTING

A fitted model is a compact mathematical representation that reproduces the small-signal response of the plant over the scanned operating range. This is what allows SSAT to study the plant's dynamic behaviour quickly while the original black-box model remains protected.

The magnitude and phase of the d- and q-axis current responses are used to compute the dynamic dq-frame admittance matrix of the device at each scan frequency f:

$$\boldsymbol{Y}(s) = \begin{bmatrix} Y_{dd}(s) & Y_{dq}(s) \\ Y_{qd}(s) & Y_{qq}(s) \end{bmatrix}, s = j2\pi f$$

To find a linear system that represents the observed small-signal behaviour of the device, the vector fitting algorithm is applied to the admittance matrices computed over the scan frequencies. The algorithm identifies a multi-input, multi-output transfer function that approximates the amittance matrices as a sum of pole-residue terms plus a constant term:

$$\boldsymbol{Y}(s) \approx \sum_{n=1}^{N} \frac{\boldsymbol{R}_n}{s - p_n} + \boldsymbol{D}$$

where the poles pn and residues **R**n capture the dynamic response of the device and the state-independent (proportional) response is captured in ***D***. The number of poles N is adjusted iteratively to determine the model order required to represent the dynamic response.

To interface the small-signal device model with a system level dynamic model, the transfer function is converted to a state-space representation with device matrices ***A, B, C***, and ***D*** such that

$$\dot{x} = \boldsymbol{A}x + \boldsymbol{B}v, \quad i = \boldsymbol{C}x + \boldsymbol{D}v$$

where $\boldsymbol{v} = [v_d, v_q]^T$ and $\boldsymbol{i} = [i_d, i_q]^T$ are the ***dq*** frame voltages and currents of the device. The state variables in x arise from the identified poles and do not correspond to physical controller states within the device; they are latent variables used to reproduce the dynamic behaviour. Nonetheless, the appearance of a device's states in the mode shape or participation factor of a given mode identifies the involvement of that device in that mode, which provides valuable diagnostic information.

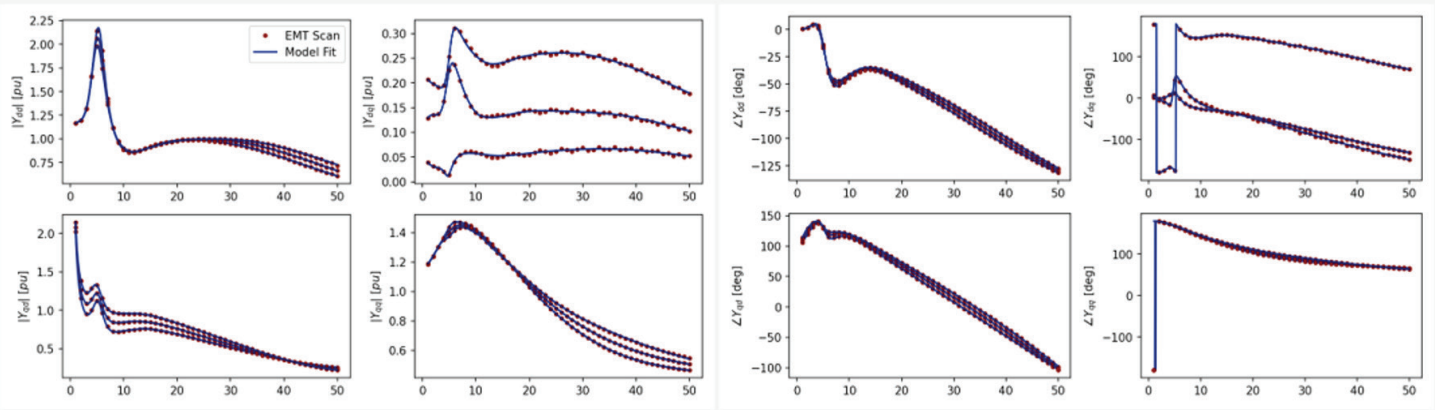


Figure 1: Admittance scan curves and fitted models obtained from ModFit

REUSABLE MODELS ACROSS OPERATING CONDITIONS

Rather than creating models that are only valid at a single operating point, ModFit scans the plant across a two-dimensional range of operating points defined by active power set-point and either POI voltage (for plants with Q/V droop control) or reactive power output (for plants with fixed-voltage control). The fitted models are then interpolated so that a single fitted model represents the plant across its full scanned P/Q/V range. Additional scan points can be placed around known discontinuities, for example where a plant reaches its reactive-power limit, to preserve accuracy.

SMALL-SIGNAL ANALYSIS IN SSAT

To assess system-level stability, the fitted device matrices are interfaced with SSAT through the MATREAD user-defined model (UDM). MATREAD reads the matrices produced by ModFit, maps each fitted plant model to a generator in the SSAT power-flow case and interpolates the fitted model to the steady-state operating point obtained from the power-flow solution.

With SSR mode enabled, SSAT includes dynamic models of the passive network (transmission lines, transformers, shunt and series capacitors, and generator stator windings), which is essential for accurate assessment at sub-synchronous frequencies. The passive network data and conventional generator modelling are obtained from standard powerflow and dynamic data, while fitted models are only required for plants and equipment to be captured from detailed EMT models. Eigenvalue analysis is then used to identify any unstable or poorly damped modes and to compute participation factors, revealing both whether the system is stable and which resources are involved in any mode of concern.

VALIDATION AGAINST EMT SIMULATION

The accuracy of the method has been established through a staged program of benchmarking against full-system EMT simulation, progressing from simple test systems to a realistic system case. The frequency and damping of the modes identified by SSAT are verified against Prony analysis of the EMT simulation results.

IEEE 14-BUS TEST SYSTEM

To demonstrate the ability of models fitted from EMT scans using ModFit to accurately predict the dominant oscillatory behaviour of the system, the IEEE 14-bus test system was modified to represent weak system conditions with high IBR penetration, with IBRs connected at buses 10, 13, and 14. Publicly available EMT models were used for the IBRs, including a solar plant model at bus 10 that supports both grid-following (GFL) and grid-forming (GFM) control. Instability is triggered by removing a synchronous condenser at bus 6 to further reduce system strength.

Each IBR EMT model was scanned individually in its own single-machine infinite-bus case with ModFit and fitted to a state-space small-signal model. The fitted models were then combined with the power-flow and dynamic data for the 14-bus system in SSAT, where the MATREAD user-defined model maps each fitted model to its IBR generator and standard models are used to specify synchronous machine dynamics. Eigenvalue analysis was run with SSR mode enabled to represent the network dynamics at sub-synchronous frequencies, and the resulting modes were compared against Prony analysis of the EMT simulation.

With all IBRs in GFL control mode, EMT simulation exhibits a growing voltage oscillation that develops into a limit cycle after the synchronous condenser is removed. SSAT correctly identifies this instability, reporting a mode near 4.1 Hz with negative damping.

When the IBR at bus 10 is switched to GFM control, the system remains stable after the same disturbance, and SSAT again predicts the correct outcome by reporting positive damping for the corresponding oscillatory mode. This demonstrates a capability that heuristic methods cannot provide: distinguishing the stabilizing effect of grid-forming control in a mixed-IBR system.

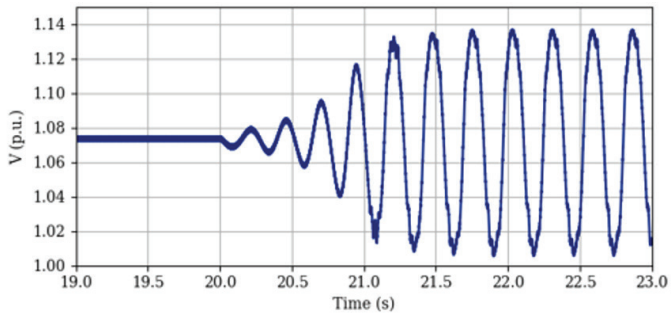


Figure 2: EMT results of IEEE 14 Bus system with all IBRs GFL

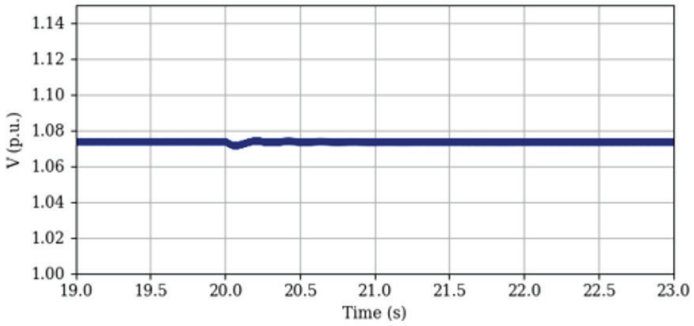


Figure 3: EMT results of IEEE 14 bus system with bus 10 IBR

REAL-WORLD APPLICATION: WEAK SYSTEM ASSESSMENT

Utilities increasingly need to evaluate how large numbers of inverter-based resources behave under changing system conditions. To demonstrate ModFit's ability to support practical planning studies, the methodology was applied to a realistic weak-system pocket containing multiple black-box inverter models operating across a range of dispatch conditions and contingencies.

- Five IBR plants (denoted IBR A through IBR E) represented by black-box PSCAD™ models, interconnected through a weak 69 kV network.
- Study area size: approximately 240 buses in the PSCAD™ case (using E-Tran+ parallelization) and 713 buses in the SSAT case, with SSR mode enabled to represent network dynamics.
- 9 single- and double-circuit contingencies under study. The base dispatch was found to be severely unstable across many contingencies. To identify conditions under which the pocket could operate securely, a total of eight dispatch scenarios were evaluated in SSAT:
  - the base dispatch;
  - curtailment of the IBR plants at two levels;
  - one IBR plant out of service, at base and curtailed dispatch levels; and
  - two IBR plants out of service (two combinations).

Only the scenarios with two IBR plants out of service showed potential for secure operation. The remaining scenarios exhibited unstable modes or power-flow non-convergence in one or more contingencies. Because each SSAT run completes in seconds, this entire exploration was carried out in less time than it would take to run a single EMT contingency.

Table 1. Dominant mode of the IEEE 14-bus system after loss of the synchronous condenser (small-signal versus EMT).

Case	SSAT frequency (Hz)	SSAT damping (%)	EMT (Prony) frequency (Hz)	EMT (Prony) damping (%)
IBR at bus 10 in GFL mode	4.086	−10.22 (unstable)	4.091	−11.00
IBR at bus 10 in GFM mode	4.537	14.49 (stable)	4.606	14.46

Key results. The value of rapid screening is illustrated by contrasting two of the two-plant-out scenarios. Removing IBR A and IBR B leaves the pocket insecure, with unstable modes identified by SSAT and confirmed by EMT simulation. When IBR B and IBR C are removed instead, no unstable modes are identified by SSAT and EMT simulation indicates secure operation. Analyzing many such combinations in SSAT pinpoints which specific plant outages are required to secure the pocket, which would be impractical to determine with EMT simulation alone.

THE SPEED ADVANTAGE

For this case, Table 2 compares computation time between the small-signal method and full-system EMT simulation across eight dispatch scenarios and nine contingencies.

Table 2. Computation time comparison for the weak system pocket case.

Task	System-level EMT (PSCAD™)	SSAT
Per-contingency analysis	3 h 38 min	1.6 seconds*
Full set (8 dispatch scenarios x 9 contingencies)	261 h 36 min	115 seconds*

* Before the SSAT analysis, the five IBR plant models are scanned across their range of operating points, a one-time cost of approximately 59 h 28 min. This cost is not included in the full-set time above because the resulting fitted small-signal models are reused across all scenarios and contingencies in this study, and can be applied to additional studies (further dispatch conditions, contingencies, and transfers) without re-scanning.

As shown in **Table 3**, contingencies which require hours of simulation time in system-level EMT simulation can be assessed in seconds with IBR models fitted from black-box EMT models using ModFit. Because fitted models can be reused, the benefit compounds as teams explore more dispatch conditions, contingencies, and transfers. The scanning effort is front-loaded; the follow-on screening becomes fast enough to support a much wider planning study by **allowing processing of each contingency in seconds rather than hours.**

APPLICATIONS

The model-fitting solution provided by ModFit supports a wide range of studies, including:

- **Weak-grid and low-SCR stability assessment in IBR-rich networks**
- **Assessment of system stability with a mixture of grid-following and grid-forming IBR plants**
- **Small-signal stability risk from large inverter-based loads (IBLs)**
- **Interaction of IBRs and IBLs with network resonant modes in series-compensated networks**
- **Transfer analysis and N-1 contingency analysis for sub-synchronous instability risk**
- **Planning studies in systems with high IBR penetration**
- **On-line, real-time stability assessment using vendor black-box plant models**

PLANNING A STABILITY STUDY?

Evaluating weak-grid conditions, renewable integration, or large-scale contingency scenarios?

Powertech's software and power systems specialists can help you assess stability risks, validate inverter models, and develop scalable study workflows using ModFit and the DSATools™ suite. **Contact our team to discuss your upcoming project and determine whether ModFit is the right solution for your application.**

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