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PNNL-35082

# Introduction to ALERT: A User-Interface Tool for Resilient Optimization

Technical Report

October 12, 2023


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U.S. DEPARTMENT OF ENERGY

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# 1.0 Introduction

Current resilience practices in cyber-physical systems (such as electrical power grid) either involve long-term, and expensive, investment decisions; or are reactive in nature, relying on predominantly ad-hoc (simulations-based) strategies that fail to provide resilience guarantees and/or requiring intervention of human operators who are prone to mistakes and introduces response delays. Moreover, it is often cost-prohibitive to redesign existing baseline controls for resilient performance. As the cyber-physical systems grow in complexity, there is a need for proactive resilience strategies such as the ones proposed here, that involve online, adaptive control actions to best prepare for any impending adversarial events. It is desirable that such a resilient control design would render an add-on layer such as the one proposed for a more preferable, easily implementable, and reconfigurable solution. Finally, system theoretical guarantees of (quantitative) resilience performance measures would not only help develop trust in the automated control algorithms and accelerate real-world deployment, such guarantees would also provide quantitative specifications of sensor/control performance for resilient co-design efforts. In this effort, the objective was to design online strategies for adaptive tuning of existing optimal control solutions in response to cyber-physical adversarial events; and assure (quantifiably) sufficient margins of resilience. The developed solution acts as a resilient add-on layer and replaces the need for cost-prohibitive redesign of existing baseline controls for assured resilience. One key outcome of this effort is a design of Adaptive Learning-Enabled Resilient Tuning (ALERT) controls for cyber-physical systems, with quantitative assurance of resilience to adversarial events, validated on (single and networked) microgrid use-cases.

## 1.1 Overview

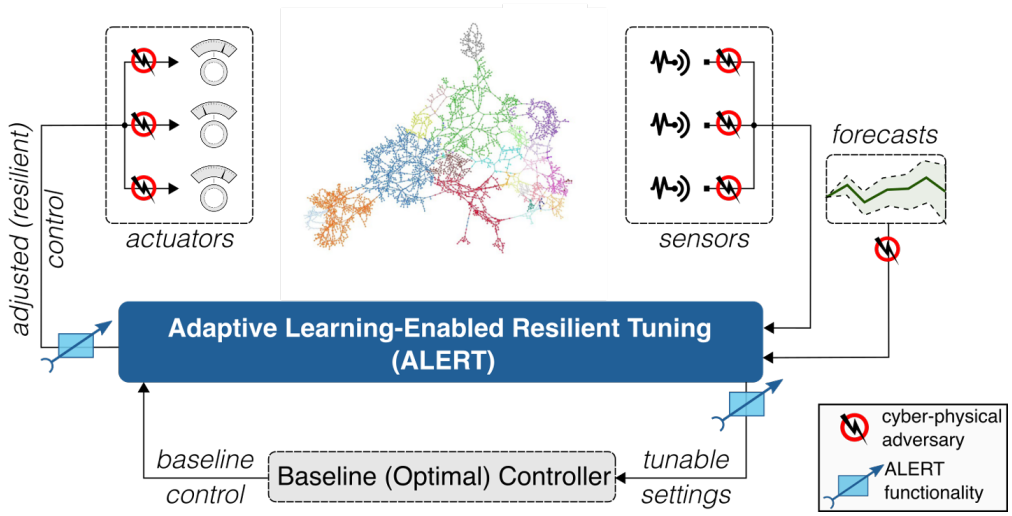



Figure 1: Basic idea of the ALERT controls.

In this technical effort, the project team designed and demonstrated online strategies – henceforth referred to as ALERT controls – for proactive and adaptive tuning of existing optimal controls in a microgrid, with quantifiably assured margins of resilience to various cyber-physical adversarial events. The overall idea of the ALERT controls is summarized in Fig. 1. ALERT controls sits on top of the existing (i.e., baseline) system-level optimal controllers, and only minimally

adapts (i.e., tunes) the baseline controllers' settings and its output to ascertain the satisfaction of resilience constraints. Real-time sensor updates, and time-series forecasts are fed as input to the ALERT algorithm which then adjusts the controller settings and actuator set-points to ensure that the system maintains resilience under cyber-physical adversarial events. A brief outline of the ALERT algorithms is presented in Section 2.0, with more details found in [1].

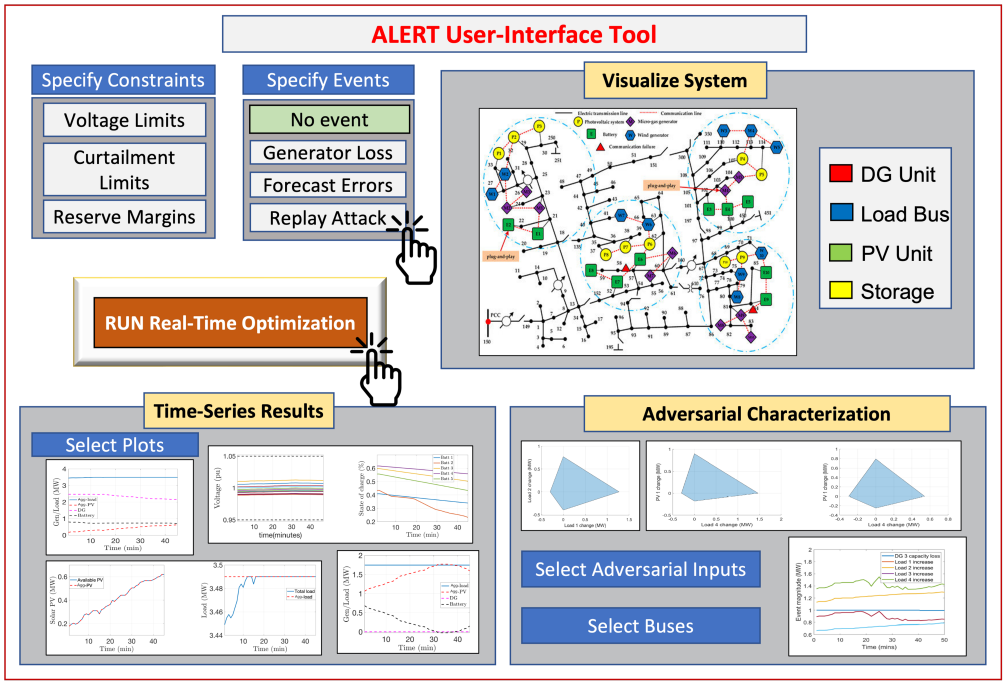



Figure 2: Schematic outline of the ALERT user-interface.

This ALERT functionality is made available to the end-users, e.g., the system operators, via an interactive user-interface, a schematic outline of which is shown in Fig. 2. On this user-interface, the end-users will have the options of entering their system details (e.g., microgrid network models, information on the dispatchable resources), resilience specifications (e.g., load curtailment limits, reserve margins, voltage limits), and specify cyber-physical events of interest (e.g., physical disruptions, cyber attacks, forecast errors). The user-interface will process the visualize the entered information, along with displaying the ALERT control outcomes via time-series results, as well as novel time-varying adversarial set plots (see [1] for details). The end-users will not only be able to use the interface to visualize the system's operation under various cyber-physical adversarial scenarios, but also evaluate the amount of tolerance the system has against selected adversarial perturbations of interest (e.g., malfunctioning sensors, suspected attacked measurements) via the adversarial plots. Details of the prototype user-interface and some illustrative results are discussed in Section 3.0. A current implementation of the user-interface is available at: `https://devops.pnnl.gov/alrt-client`.

## 1.2 Report Structure

In this technical report, we briefly outline the algorithmic modules of the developed ALERT control technology (in Section 2.0), and introduce the user-interface tool that allows end-users (e.g., microgrid operators) to enter their system description, specify various operational and resilience requirements, and evaluate the impact of the control decisions via illustrative plots (in Section 3.0).

# 2.0 ALERT Algorithmic Components

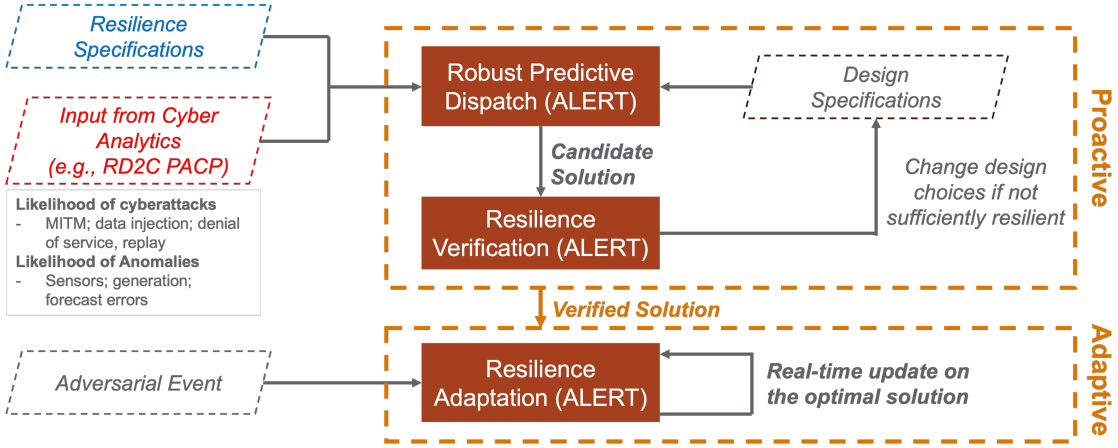



Figure 3: Essential building blocks of the ALERT technology.

A brief outline of basic work-flow of the ALERT technology is shown in Fig. 3. The core ALERT technology can be broken down into a proactive and an adaptive module. The proactive module processes as inputs user-defined resilience specifications (e.g., reserve margins, curtailment limits, voltage limits) and associated cyber analytics (e.g., likelihood of cyberattacks, likelihood of other anomalies) to output resilience-verified optimal control set-points (e.g. dispatching DERs) that are guaranteed to ensure system's resilience under the predicted (i.e., likely) adversarial scenarios. The adaptive module takes as input real-time updates (via sensor measurements) of the system's conditions under unforeseen adversarial events, and performs online adjustment of the control set-points to track the resilience specifications under evolving adversarial conditions. It has three sub-modules that implement proactive and adaptive responses:

- **(Proactive) Robust Predictive Dispatch** to optimally allocate set-points and reserves to distributed energy resources (DERs).
- **(Proactive) Resilience Verification** via bi-level optimization to quantify the tolerable adversarial set.
- **(Adaptive) Resilient Online Adaption** of set-points via sensitivity-based feedback control to safeguard against adversarial events.

Next we briefly describe the three sub-modules which are presented in details in [1, 2].

## 2.1 Robust Predictive Dispatch

In this sub-module, a multi-periodic, robust, predictive optimization is solved to optimally allocate set-points and reserves to meet resilience specifications under uncertainties. In the most general form, the robust optimization problem for a system can be expressed in the following form:

$$\min_{u} \max_{w} f(u, w) \tag{1a}$$

$$s.t.\ g(u, w) \leq 0 \qquad \forall w \in \Omega_W \tag{1b}$$

where $g(u, w)$ are the different system-level operational, and resilience constraints (see [1] for example). The above optimization problem (1) can be converted to a robust formulation using the *explicit maximization method* (see [3]) in the following form:

$$\min_{u} \widehat{f}(u)\,, \quad \text{s.t. } \widehat{g}(u) \leq 0 \tag{2}$$

where $\widehat{f}(u) = \max_w f(u, w)$ and $\widehat{g}(u) = \max_w g(u, w)$. The new model does not contain any disturbance terms and if the functions $\widehat{f}(u)$ and $\widehat{g}(u)$ are convex, then the optimization problem is convex, which can be solved efficiently [1]. Resilience is enforced in a robust sense via inclusion of penalties on resilience violations and/or hard constraints of resilience performance. These robust dispatch problems can also accommodate risk-based and probabilistic constraints – often reflected in estimated likelihood of cyberattacks – as shown in [2]. An outcome of the robust predictive dispatch problem is a set of set-points and reserve margins.

## 2.2 Resilience Verification

In this sub-module, candidate solutions from the robust predictive dispatch – in the form of optimal set-points and reserves – are used to quantify the largest set of $w$ (i.e., adversarial disruption-s/perturbations) that the system can tolerate without violating critical resilience specifications. This is achieved by solving the following problem:

$$\max_{w} \quad |w - w^*| \tag{3a}$$

$$\text{subject to:} \quad g(u^*, w) \leq 0 \tag{3b}$$

$$w \in \Omega_W \tag{3c}$$

where $u^*$ are the candidate solutions (optimal set-points) from the robust predictive dispatch, $w^*$ are the best-known estimates of the adversarial input, and $w - w^*$ are the adversarial perturbations. A polytopic inner approximation of the largest tolerable adversarial set $\Omega_W$ can be constructed via tractable optimization formulations as described in details in [1]. The calculated adversarial sets are used to inform design decisions around sizing of the dispatchable resources and/or quality of the sensors which can in turn be used to update the predictive dispatch solutions.

## 2.3 Resilient Online Adaptation

In this sub-module, online adaptive control laws are designed, which allow tapping into the available reserves to maintain resilience under adversarial events, by tuning the optimal set-points from the proactive module under unforeseen cyber-physical events. Sensitivity-based feedback control policy such as the following is used for real-time adaptation of optimal control set-points to safeguard against evolving (and largely unforeseen) adversarial events:

$$u = u^* + K\, y(u, w) \tag{4}$$

where $u^*$ are the dispatched set-points from the proactive module, $K$ is a feedback control gain, $w$ are the actual adversarial perturbations (which are unknown), $y$ are the sensors updates (capturing the system states under adversarial perturbations), and $u$ are the real-time adjusted set-points. An example of the online adaptive implementation is provided in [1].

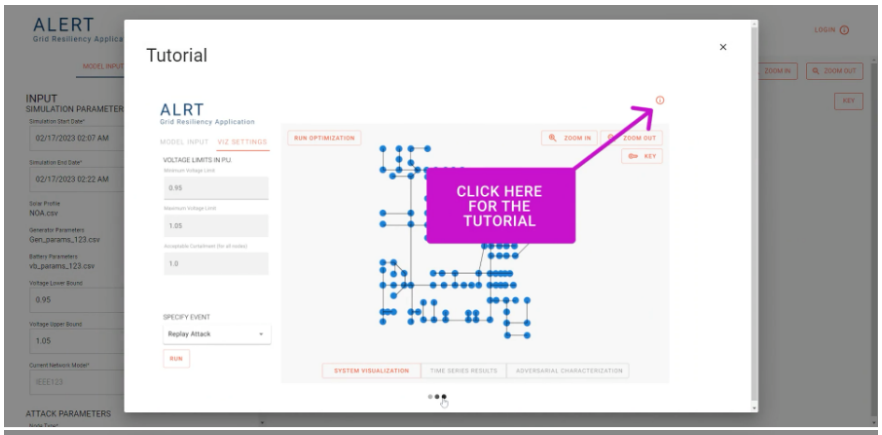
# 3.0 ALERT User-Interface Tool

In this section, we introduce the interactive user-interface tool for the ALERT controls. A current implementation of the user-interface is available at the PNNL GitLab page: `https://devops.pnnl.gov/alrt-client`. It has a set of simple instructions to install and run the user-interface:

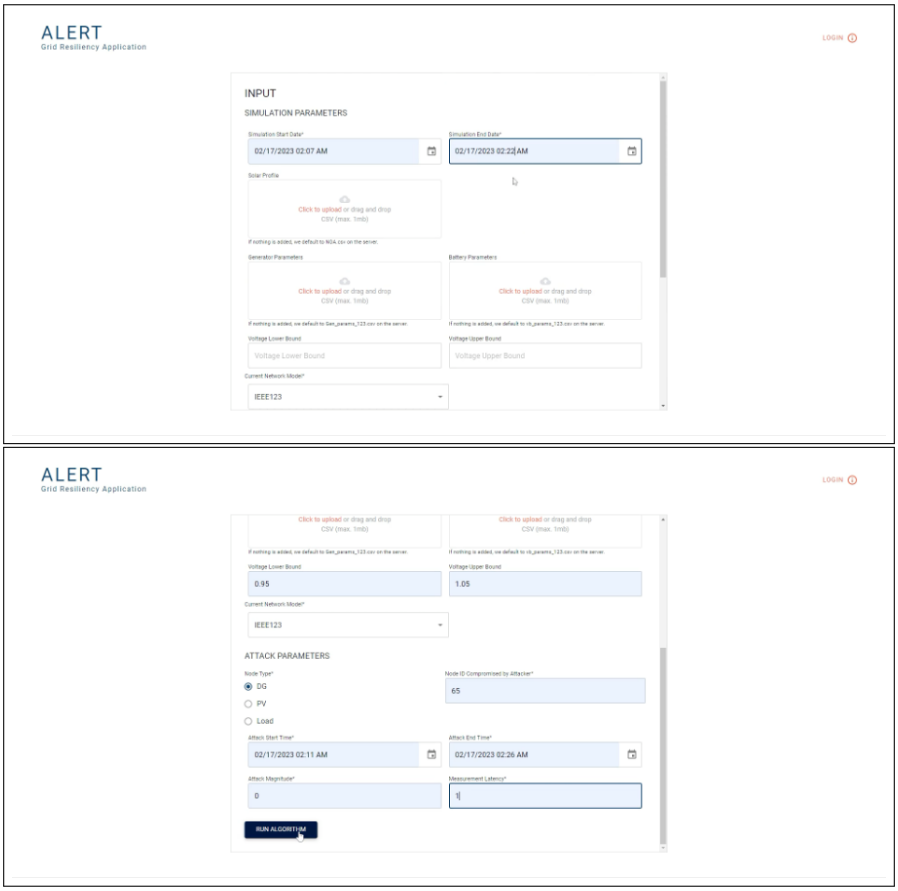
### How to Install and Run

- [ ] Clone Repo
- [ ] Run `npm install`
- [ ] Add SERVER_USERNAME and SERVER_PASSWORD to the .env file. This should be your local credentials to connect to the constance server
- [ ] Once everything is installed, run "npm run dev:backend". This will start up your node middleware to communicate with the server
- [ ] Run `npm start` to start the front end. This will start running the appication

**Brief Tutorial.** To help end-users quickly go over the available functionalities that the user-interface offers, there is a short tutorial (a collection of slides) made available on the interface. Illustrative screenshots from the tutorial are shown below.

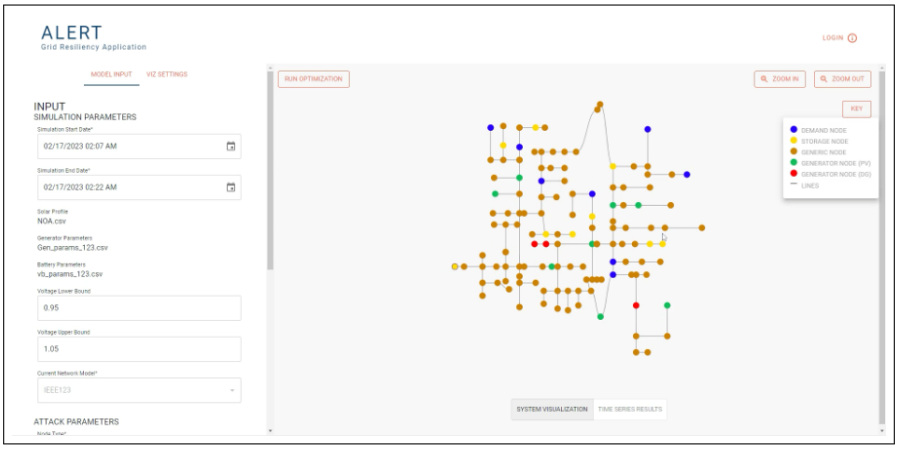



**Enter and Visualize System Information.** At the welcome page (or, home screen) of the user-interface ALERT tool, the end-user has access to the all the input settings for the system model, including the start and the end time of the simulations, the system information (e.g., the size and locations of the dispatchable resources), the operational limits and/or resilience specifications, as well as different cyber-physical adversarial scenarios of interest. Default input files containing IEEE 123-node microgrid network – e.g., default solar profiles, diesel generator parameters, and dispatchable load parameters – are also made available for an easy and quick set-up of the simulations.

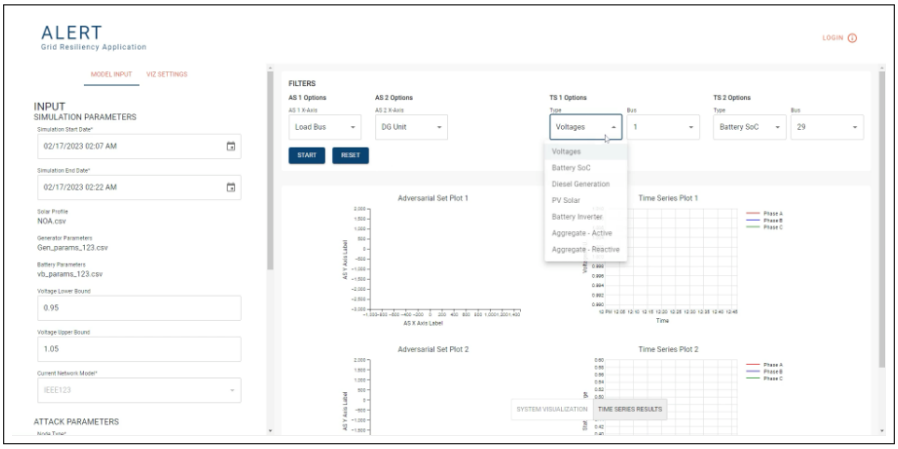


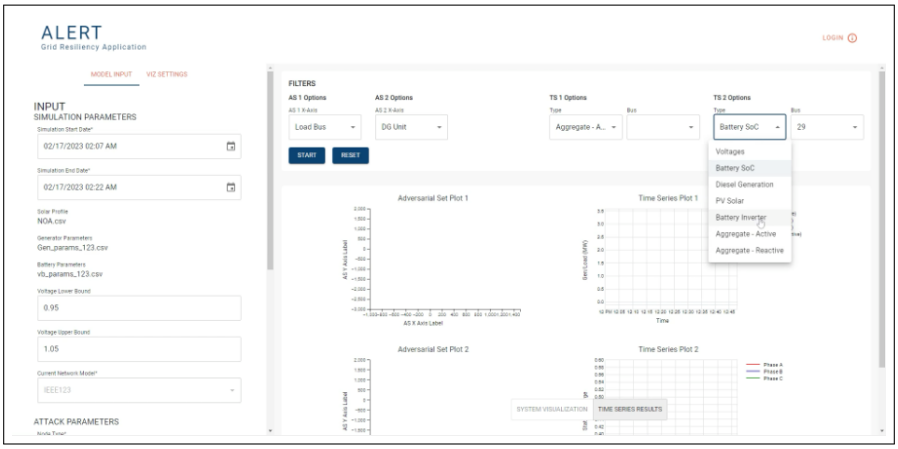

After entering all the simulation parameters, system information, and scenarios, the user hits 'RUN ALGORITHM' and lands on the system visualization page. At this page, the entered system

is visualized along with all its controllable resources for the users to verify the accuracy of the entered information. Different types of resources are associated with different keys to clearly mark those out on the network. Zoom-in and zoom-out options are available, along with options to click on the resources (represented as nodes/circles) to see additional information about those resources. The input settings and parameters are also made accessible on the left panel, which can be modified to re-run the ALERT optimization on the selected scenario.

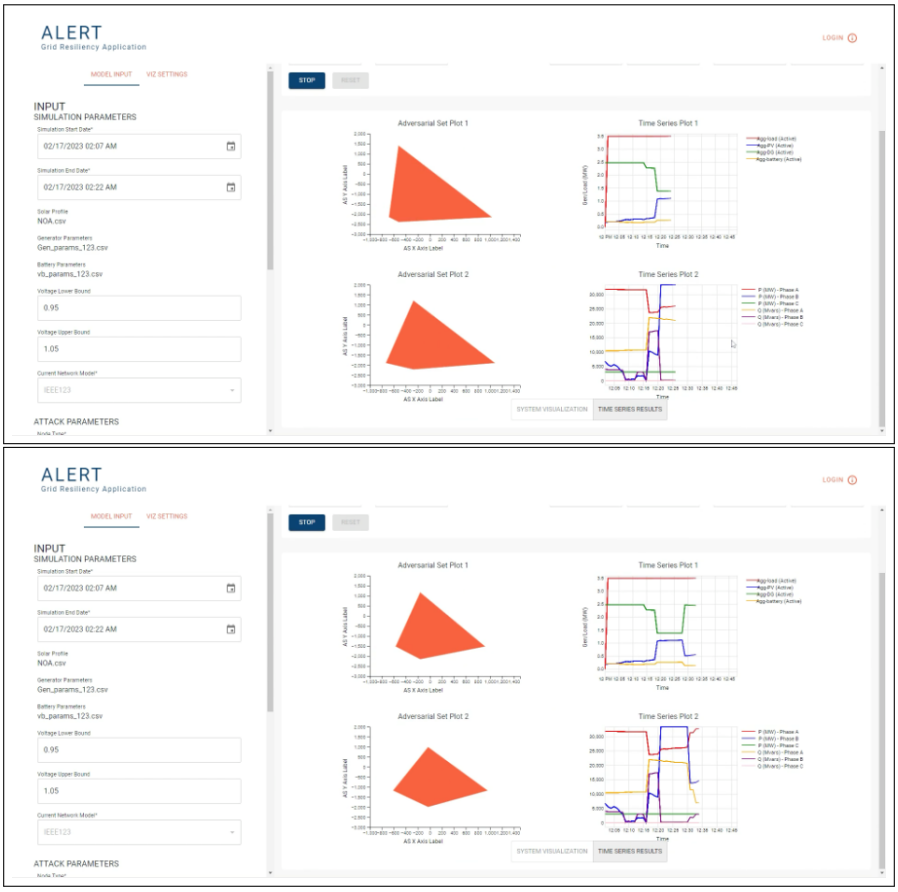



**Visualize Simulation Outcomes.** Once the back-end completes the simulation of the ALERT controls with the entered settings and parameters, the end-user is able to visualize the outcomes via two different sets of plots: *adversarial set (AS) plots* and *time-series (TS) plots*. The user may choose which AS and TS variables (up to two each at a time) are of interest for the plotting purpose, by selecting the appropriate variables from the drop-down lists, as illustrated below.






Once the AS and TS options are selected, the user clicks on 'START' to view the results in a streaming fashion in the form of both AS and TS plots. As time progresses, the AS plots show the updated adversarial sets of the selected AS variables, informing the user of the time-varying tolerance of the system to adversarial perturbations in the selected variables – with larger sets demonstrating greater tolerance (and less sensitivity) to adversarial perturbations. Similarly, the TS plots show the resulting time-varying values of the selected TS variables as a result of the ALERT controls. The 'RESET' option allows the user to view the results again by selecting different sets of AS and TS variables.



# 4.0 Conclusions

In this report, we provide a brief introduction to the user-interface tool demonstrating the performance of the ALERT controls to ensure resilience of a microgrid under various cyber-physical adversarial scenarios. While the current implementation demonstrates some key functionalities of the user-interface, future developmental efforts will focus on generalizing the interface to other cyber-physical system applications, along with a deployment of the application to the cloud for wider access to users who would like to test the ALERT functionalities.

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