# Research Performance Progress Report (RPPR-1)

| | | |
|---|---|---|
| a. **Federal Agency** | Department of Energy | |
| b. **Award Number** | DE-EE0036461 | |
| c. **Project Title** | Enabling Extended-Term Simulation of Power Systems with High PV Penetration | |
| d. **Principal Investigator** | David Schoenwald<br>Principal Member Technical Staff<br>daschoe@sandia.gov<br>(505) 284-6285 | |
| e. **Business Contact** | Sharon Salazar-Gomez<br>Project Controller<br>ssalaz@sandia.gov<br>(505) 284-8560 | |
| f. **Submission Date** | February 4, 2022 | |
| g. **DUNS Number** | 007113228 | |
| h. **Recipient Organization** | Sandia National Laboratories | |
| i. **Project Period** | **Start**: 04/01/2020 | **End**: 11/30/2021 |
| j. **Reporting Period** | **Start**: 04/01/2020 | **End**: 11/30/2021 |
| k. **Report Term or Frequency** | Final | |
| l. **Submitting Official Signature** | | |

## Major Goals & Objectives:

The goal of this project is to advance the understanding of the grid impact of high penetration of photovoltaic (PV) generation by developing novel numerical methods to solve the differential algebraic equations (DAEs) that define power systems. This will overcome the limitations of current software packages – namely that they only consider fast dynamics over brief time periods. The work presented in this final project report covers results over the entire period of the project. This includes results on model development, code development for the PST repository, datasets in the PST repository, algorithm development and results from variable time-step simulations, development and results from multirate simulations, and sensitivity analysis of key parameter in variable time-step methods. In addition, this report discusses project outreach activities to stakeholders, and a summary of project products. Also covered in this final report is the writing of two conference papers (one of which has already been accepted) and a journal paper. In addition, the updating of two inverter models (both grid forming and grid following) to be compatible with the latest version of PST software is discussed.





Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

## Background:

With the rapid proliferation of inverter-based PV generation on the grid along with other inverter-based resources (IBRs), e.g., wind farms and energy storage, the dynamic behavior of the grid is becoming increasingly dependent on fast-acting power electronics and intermittent highly variable renewable energy generation. Therefore, the dynamics of IBRs and PV variability need to be captured in models and simulations used by transmission planners in their studies of grid behavior. Among the ways in which Inverter-Based Resources (IBRs) differ from traditional synchronous generation:

1. Grid interconnection is realized via electronic converters.
2. Injected power from IBRs is often highly variable and intermittent.

1. ➔ Problem of simulating the interface of a fast dynamic component (electronic converter) with a slower system (power grid).

2. ➔ Need to run simulations spanning longer time frames than those associated with typical transient stability simulations.

Combined, 1. and 2. ➔ Simultaneous simulation of fast and slow dynamics.

Numerical integration algorithms currently deployed in power system dynamic simulation tools were not designed to study these vastly different dynamic phenomena in a single simulation scenario. Table 1 presents the current state-of-the-art in simulation tools available for studying grid dynamic behavior over a wide range of timescales.

Table 1. Current practice in simulation of power system dynamics.

| **Dynamics** | **Timescale** | **Simulation Toolsets** | **Examples** |
|---|---|---|---|
| Electromagnetic Transients (EMTP) | $10^{-6}$ – $10^{-2}$ seconds | Three phase simulation, e.g., EMTP, Spice | • Faults<br>• Voltage spikes<br>• Harmonics |
| Transient Stability | $10^{-2}$ – 100 seconds | Positive sequence simulation, e.g., PSLF, PSSE, PowerWorld | • Inertia dynamics<br>• Generator controls<br>• Induction motor stalls |
| Extended Term Dynamics | 100 seconds – hours | Capability gap – analysis of a set of power flow cases is used | • Automatic Generation Control<br>• FIDVR<br>• Frequency response |
| Steady State | hours – years | Positive seq. power flow – nonlinear eqns | • Equipment overloading<br>• Reactive resource mgmt<br>• System losses/econ |

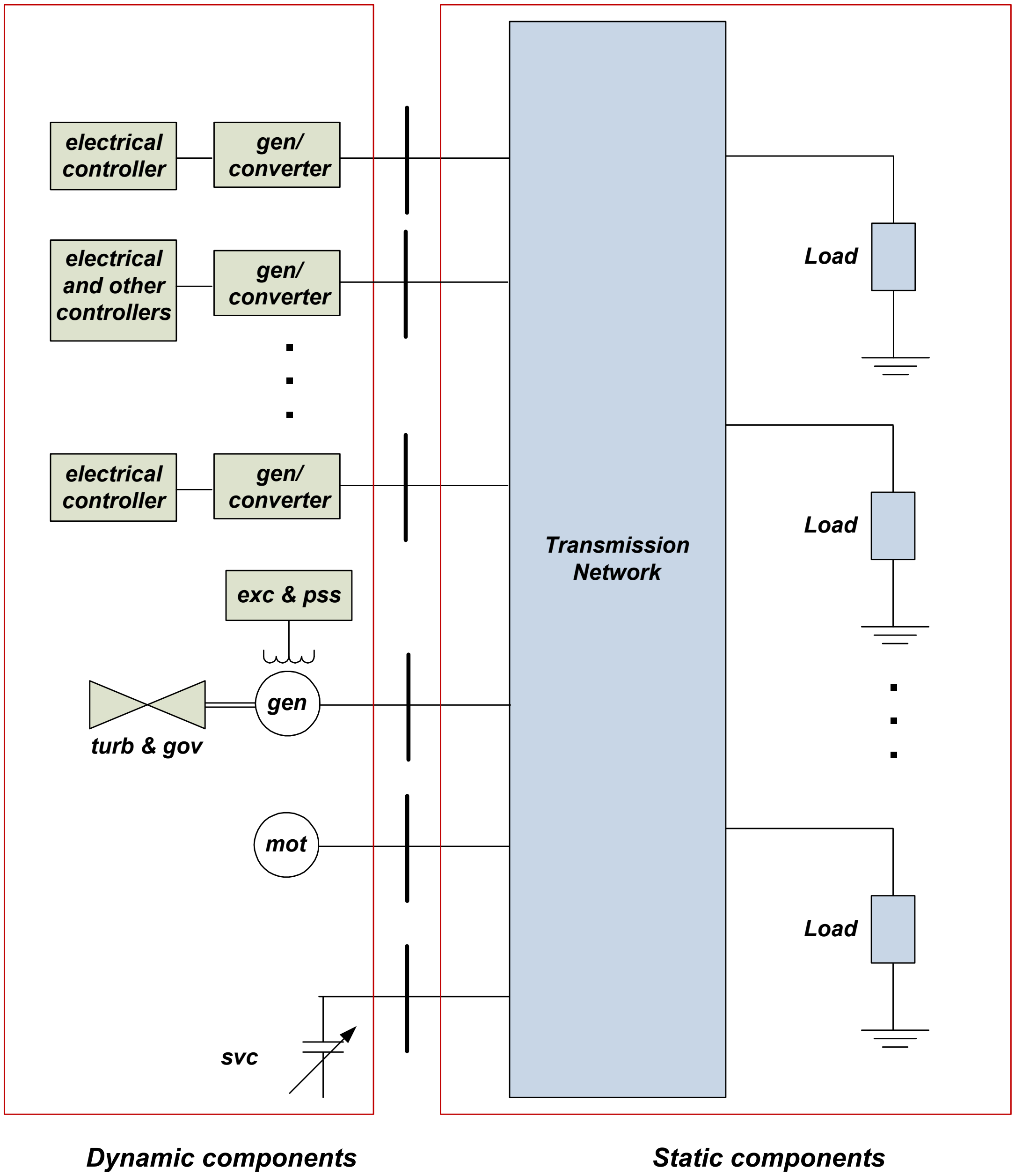


Figure 1. Schematic of a large-scale power system.

Figure 1 illustrates the typical topology of a large-scale power grid. The dynamic components on the left hand side represent fast generator dynamics including even faster IBR generation (top part of left hand side in Figure 1). The right hand side of Figure 1 represents slower time-varying dynamics on the load side of the system. Considering the system in Figure 1, we can derive power system dynamics as a set of differential-algebraic equations (DAE) of the following form:

$$\dot{x} = f(x, v) \quad (1)$$

$$0 = g(x, v) = i(x, v) - Yv \quad (2)$$

$x$ = vector of state variables

$v$ = vector of bus voltages (real and imaginary parts)

$i$ = vector of current injections (real and imaginary parts)

$Y$ = network admittance matrix

$f$ represents (primarily) the generator dynamics

$g$ represents (primarily) the bus power balance equations

Except in special cases, e.g., linear systems, an analytic solution is normally not possible – numerical methods are needed. In particular, what is needed are better numerical solvers to simulate fast & slow dynamics on longer time frames.

### Project Results and Discussion:

The primary technical results for this project include: (1) Development and demonstration of multirate methods in PowerWorld, and (2) Presentation of sensitivity analysis of parameters in variable time-step methods developed and tested in PST. The writing and submission of conference papers and a journal paper is an important aspect of disseminating project results to the wider power systems simulation community. The project team submitted a paper to the IEEE Power & Energy Society General Meeting, which is the pre-eminent conference for the power systems research community. The paper was submitted in early November 2021. The paper was accepted by the conference in January 2022. The citation for the paper appears in the Products section. An additional conference paper was submitted to the North American Power Symposium (NAPS) in Fall 2022. As of February 2022, this paper is still under review by the NAPS program committee. A journal paper is in final revision and will be submitted in March 2022 to a special issue on electric grid controls in the journal, *Energies*.

Significant progress was also made in updating models for inverters, which are the primary means by which renewable energy (including PV) are interfaced to the power grid. Two types of inverters, grid following and grid forming, have been modeled and simulated in project demonstrations. Grid following inverters track the voltage angle of the grid to control their output. This is typically accomplished through the use of phase-locked loops. Presently, the vast majority of inverters on the grid are of the grid following type. Grid forming inverters actively control their frequency output, making it possible for them to naturally support the system frequency while sharing a portion of the load change. Presently, grid forming inverters are primarily in the development phase and have not yet been implemented on the grid in any significant numbers. However, the potential for this type of inverter is very promising. Therefore, the project team believes it is essential to create models for grid forming inverters and demonstrate their behavior in the project simulation test cases.

Grid following inverters are modeled as current injection sources to the grid. This approach is useful in representing grid following inverters in extended-term simulations. The project team’s current task is getting the model incorporated into the most recent version of the PST/Matlab environment. Grid forming inverters will be modeled as voltage-behind-impedance injection sources to the grid. This approach is also useful in representing grid forming inverters in extended-term simulations. Again, the project team’s current task is getting the model incorporated into the latest PST/Matlab environment. The PST code repository for the project (link appears in Products section later in this report) will include these updated models as well as the latest code developments in PST. Both the code and the models are publicly accessible on this website.

The following technical results presented in this section have been completed by the project team during the initial 12 month period of project performance. The following subsections discuss the key components of the project: model development, model datasets, code development, numerical integration algorithm development (divided into the categories of variable time-step methods and multirate methods), and sensitivity analysis of key parameters in developed numerical algorithms.

### Model Development:

Significant progress was also made in updating models for inverters, which are the primary means by which renewable energy (including PV) are interfaced to the power grid. Two types of inverters, grid following and grid forming, will be modeled in project simulations. Grid following inverters track the voltage angle of the grid to control their output. This is typically accomplished through the use of phase-locked loops. Presently, the vast majority of inverters on the grid are of the grid following type. Grid forming inverters actively control their frequency output, making it possible for them to naturally support the system frequency while sharing a portion of the load change. Presently, grid forming inverters are primarily in the development phase and have not yet been implemented on the grid in any significant numbers. However, the potential for this type of inverter is very promising. Therefore, the project team believes it is essential to create models for grid forming inverters and demonstrate their behavior in the project simulation test cases. The following two figures illustrate the concepts the project team intends to use for modeling grid following inverters and grid forming inverters, respectively.

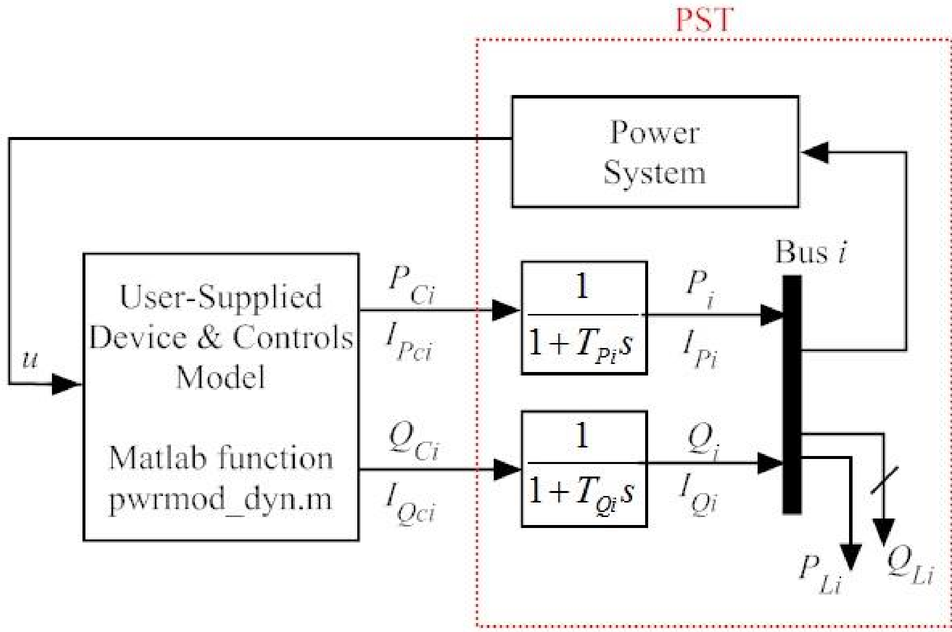


Figure 2. Grid following (e.g., current injection) model for inverters.

Figure 2 represents the block diagram details by which grid following inverters will be interfaced to the grid in simulations conducted in both the PST and PowerWorld environments. Grid following inverters will be modeled as current injection sources to the grid. This approach should prove useful in representing grid following inverters in extended-term simulations. The project team's current task is getting the model incorporated into the PST/Matlab environment.

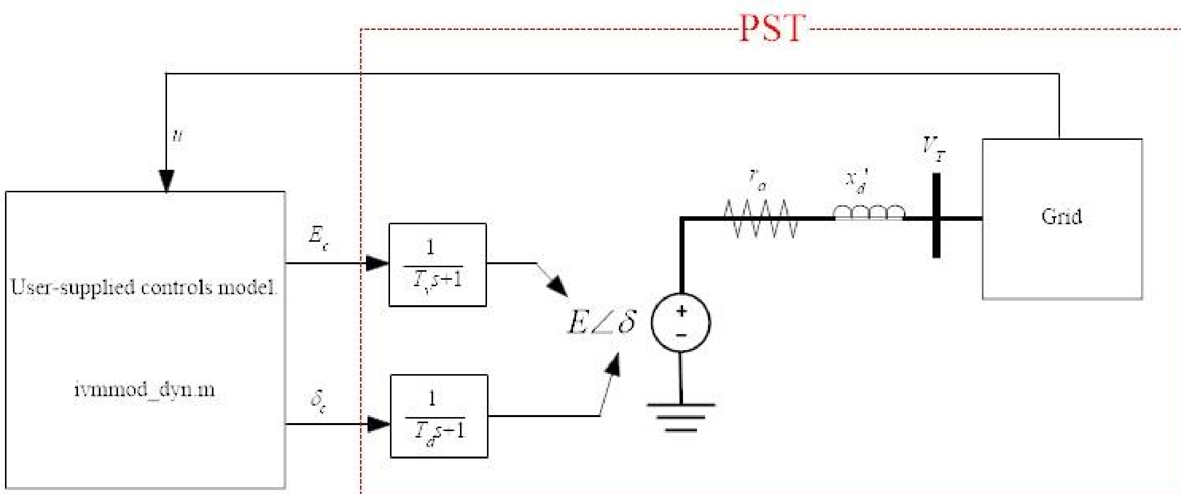


Figure 3. Grid forming (e.g., voltage injection) model for inverters.

Figure 3 represents the block diagram details by which grid forming inverters will be interfaced to the grid in simulations conducted in both the PST and PowerWorld environments. Grid forming inverters will be modeled as voltage-behind-impedance injection sources to the grid. This approach should prove useful in representing grid forming inverters in extended-term simulations. Again, the project team's current task is getting the model incorporated into the PST/Matlab environment.

### PST Code Repository with Datasets:

The milestone to develop three simulation test cases (models plus datasets) was completed by the end of this reporting period. The 3 test cases include models and data representing the following scenarios: Kundur two-area model (4 generators), IEEE 39 bus system (simplified New England model), and Mini-WECC (40 generators, 140 buses). The milestone to develop three numerical integration methods and implement them in PST has also been successfully completed. The development of integration algorithms based on multi-rate methods is nearly complete with results expected by the end of the next reporting period. Preliminary results from the variable time-step methods in PST are reported below with more formal results expected by the end of the next reporting period. New models including grid-forming inverters have also been developed and coded into PST. A website (link appears in Products section later in this report) has been created to access the latest code developments in PST. Both the code and the website are publicly accessible. The following summary results, figures, and tables are presented to illustrate the algorithm strategies, block diagrams/flowcharts, and speed-up performance results for the variable time-step methods implemented in PST.

### Variable Time-Step Results:

Summary of results for 1$^{st}$ VTS (Variable Time-Step) method implemented with SI (Simultaneous-Implicit) formulation and time-step control:

1. SI approach is adopted where differential equations are discretized using Heun's method.
2. Discretized differential equations and algebraic constraints are solved simultaneously using the Newton-Raphson method.
3. For time-step control, error estimation is estimated using the Richardson Extrapolation. See Figure 4 for flowchart of implementation strategy.
4. A simple model (see Figure 5) was simulated using variable/fixed step algorithms. Events of load disturbances were introduced at $t$ = 5 sec and $t$ = 10 $sec$ .
5. At each event occurrence, the synchronous generator inertia is also changed, which varies the dynamics between fast (small inertia) or slow (large inertia).
6. For an error tolerance, $\epsilon$ = 10−3, the total simulation time is 1.409492 sec for the variable time-step method while 19.343352 sec for the fixed time-step method. This represents a 93% improvement in simulation time.
7. Depending on changes in the dynamics, the time step varies as shown in Figure 6.

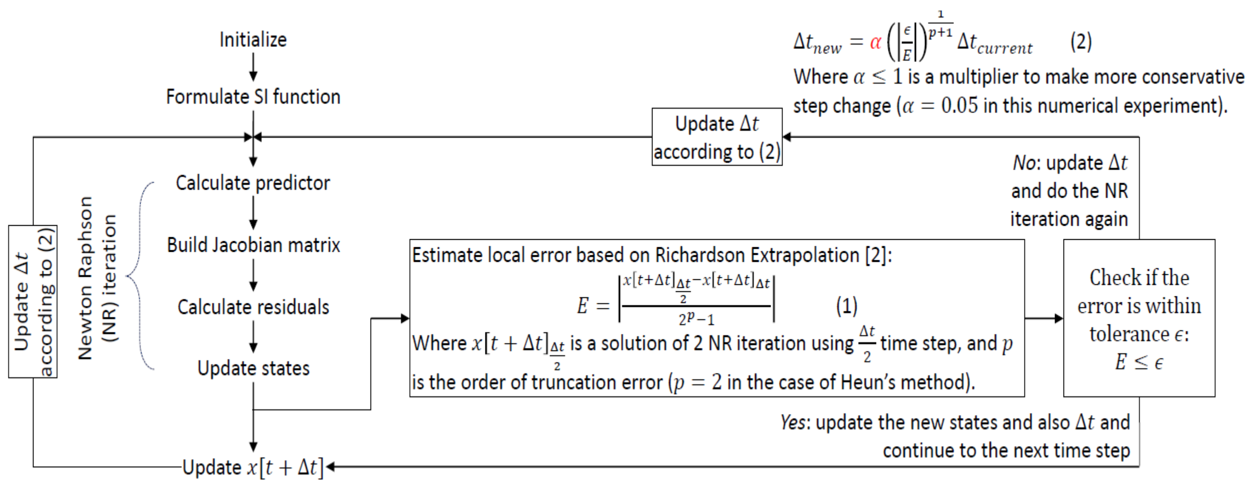


Figure 4. Flowchart of the variable-step algorithm using SI approach and time-step control.

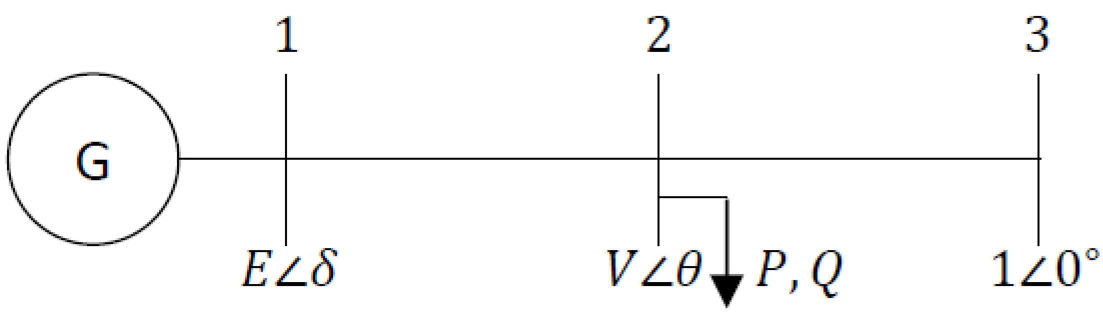


Figure 5. SMIB (Single Machine Infinite Bus) test case with synchronous generator at bus 1, PQ load at bus 2, and infinite bus at bus 3.

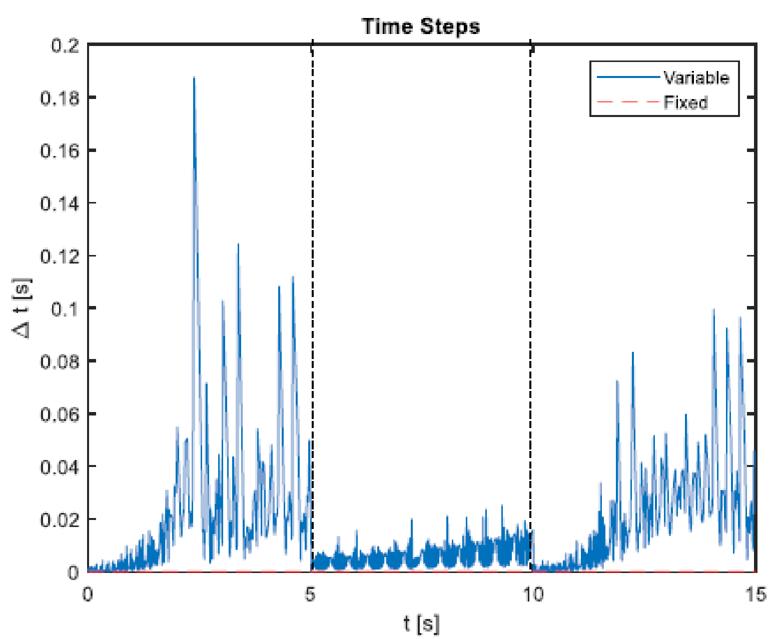


Figure 6. Time step during simulation. Note: 1) for faster dynamics, average time step is smaller, 2) time step increases as trajectory stabilizes to an equilibrium point.

Summary of results for 2nd VTS method:

1. Two baseline methods were used for comparison analysis. One is called the SETO version, which is an improved algorithm based on the other baseline method, called PST 3.1.1. The SETO version is 3.65 times faster than PST 3.1.1.
2. Using variable time steps results in a speed up of 14.84 over PST 3.1.1.
3. Results from all simulations are very similar.
4. Without creating an explicit time block at the beginning of an event, the VTS events may not occur at the exact time they are programmed but no discernable differences from the fixed time-step methods were observed.
5. VTS reduces the logged data size by approx. 4 times compared to the SETO version. Table 2 displays the performance results from this analysis. Figure 7 contains the one-line diagram of the Kundur two-area model, which was the dataset used for the results shown in Table 2. Figure 8 shows how the VTS time-step varies vs. the fixed time-step. Figure 9 depicts the number of times the network (algebraic eqs.) and dynamic system (ordinary differential eqs.) are solved for each method over the course of the simulation run time.

Table 2. Summary of results for 2nd VTS method.

| | Step Size [seconds] | | | | Solutions Per Step | | | | |
|---|---|---|---|---|---|---|---|---|---|
| PST Version | Max. | Min. | Ave. | Total Steps | Ave. | Max. | Total Slns. | Sim. Time | Speed Up |
| 3.1.1 | 4.00E-03 | 4.00E-03 | 4.00E-03 | 59,975 | 2 | 2 | 119,950 | 916.24 | 1.00 |
| SETO | 4.00E-03 | 4.00E-03 | 4.00E-03 | 59,975 | 2 | 2 | 119,950 | 250.82 | 3.65 |
| VTS | 2.32E+01 | 2.68E-04 | 2.58E-02 | 9,315 | 2 | 97 | 17,006 | 61.73 | 14.84 |

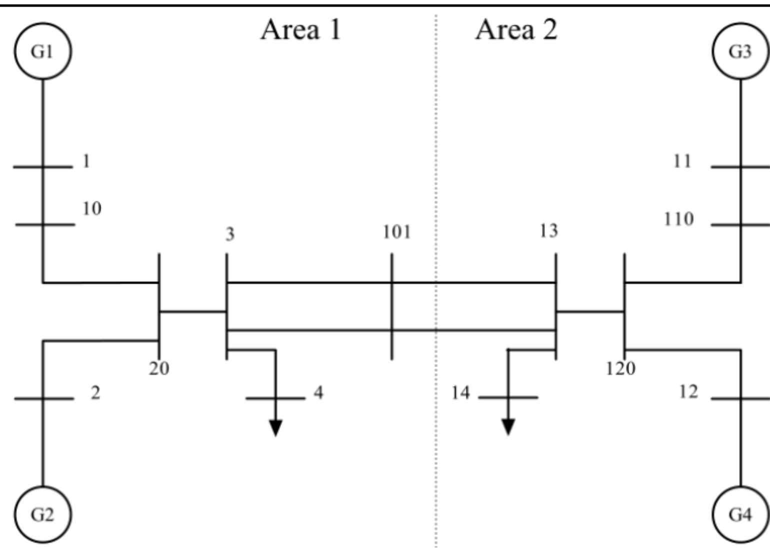


Figure 7. Kundur two-area four-machine system.

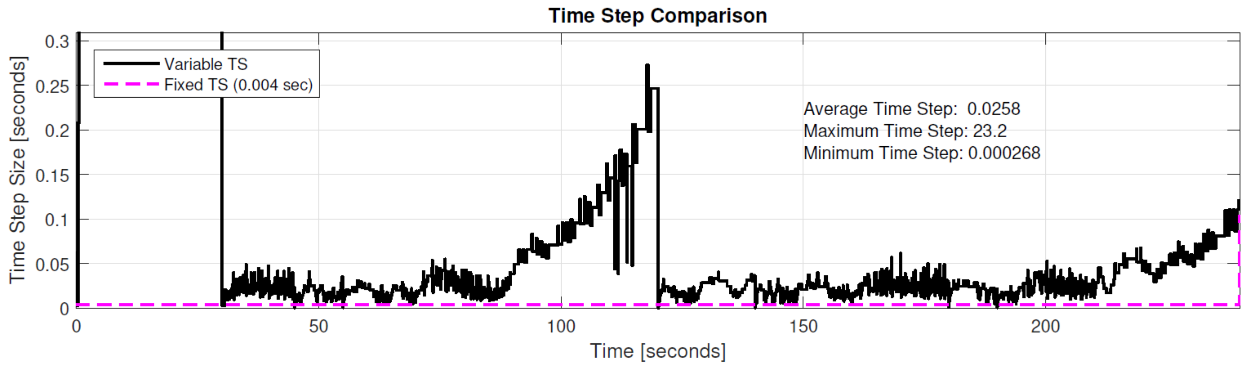


Figure 8. Comparison of time step size for variable time step and fixed time step methods.

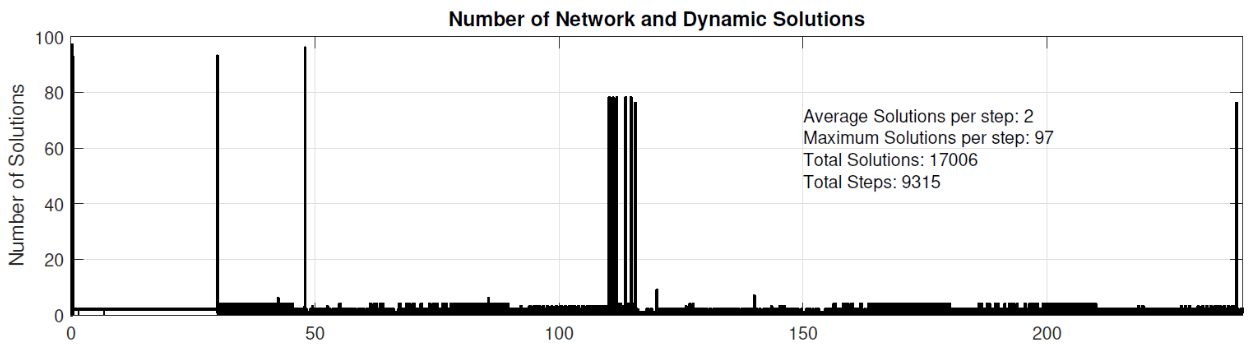


Figure 9. Plot of number of network and dynamic solutions.

Summary of results for 3rd VTS method implemented in PST: 10 minute AGC recovery of MiniWECC after 45 MW load step:

1. This VTS method was implemented on the MiniWECC model (see Figure 10 for schematic of this model).
2. The event simulated was a +435 MW load step on Bus 2 in Area 1 at t=1 sec.
3. Each area has an identical conditional AGC (Automatic Generation Control) that acts at t=40 sec and again when t=160 sec, 280 sec, 400 sec, and 520 sec (i.e. 2 minute action time).
4. The ODE solver tolerances are
    a. Relative: 1e-5
    b. Absolute: 1e-7
5. Using the VTS method (labeled ode23/ode23t in Table 3 below) provided a 9 times speed up over the baseline method, e.g., Huen's 'fixed step' method.
6. Results in Table 3 show that there were 27 times fewer steps taken using the VTS method which resulted with a saved file size that was approximately 24 times smaller than the Huen's method data file.
7. The VTS method captured fast dynamics very effectively compared to Huen's method.

8. Both the VTS and fixed time step results may ‘drift’ slightly when time steps become large. This effect can be reduced by changing the ODE solver tolerance settings.
9. Figure 11 shows how the VTS time-step varies vs. the fixed time-step. Figure 12 illustrates the number of times the network (algebraic eqs.) and dynamic system (ordinary differential eqs.) are solved for each method during the simulation run time.

Table 3. Summary of results for 3rd VTS method.

| | Step Size [seconds] | | | | Solutions Per Step | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Method | Max | Min | Ave | Total Steps | Ave | Max | Total Slns. | Sim. Time [seconds] | File Size [bytes] |
| Huen’s | 0.0083 | 8.33E-03 | 0.0083 | 72,001 | 2 | 2 | 144,002 | 483.64 | 778,259,381 |
| ode23/ ode23t | 8.6300 | 1.19E-06 | 0.0570 | 2,662 | 2 | 775 | 6,632 | 53.4 | 32,772,591 |
| ΔRatio | 0.001 | 7,000 | 0.146 | 27.05 | 1 | 0.003 | 21.71 | 9.06 | 23.75 |

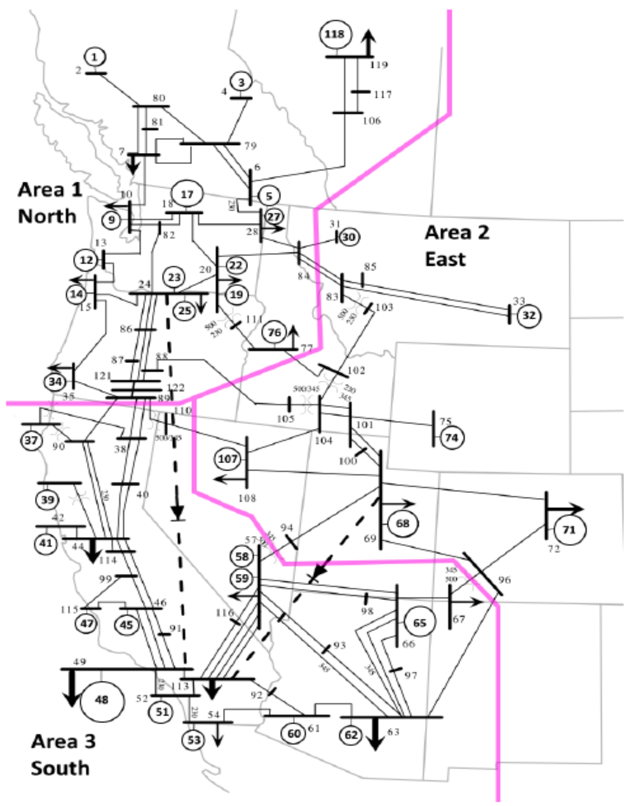


Figure 10. MiniWECC system: 122 buses, 171 lines, 88 loads, 34 generators, 623 states.

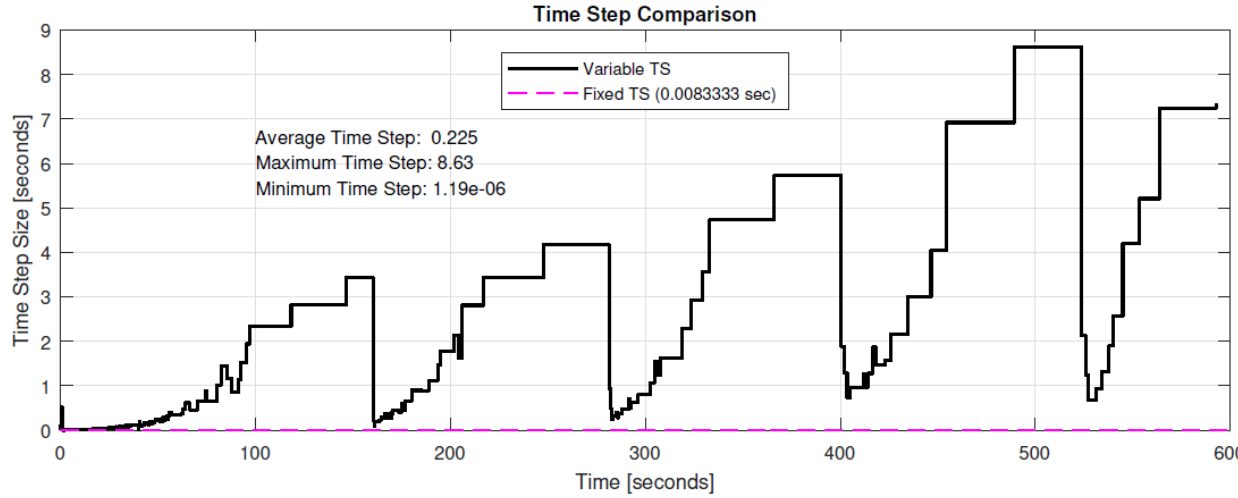


Figure 11. Comparison of time step size for variable time step and fixed time step methods.

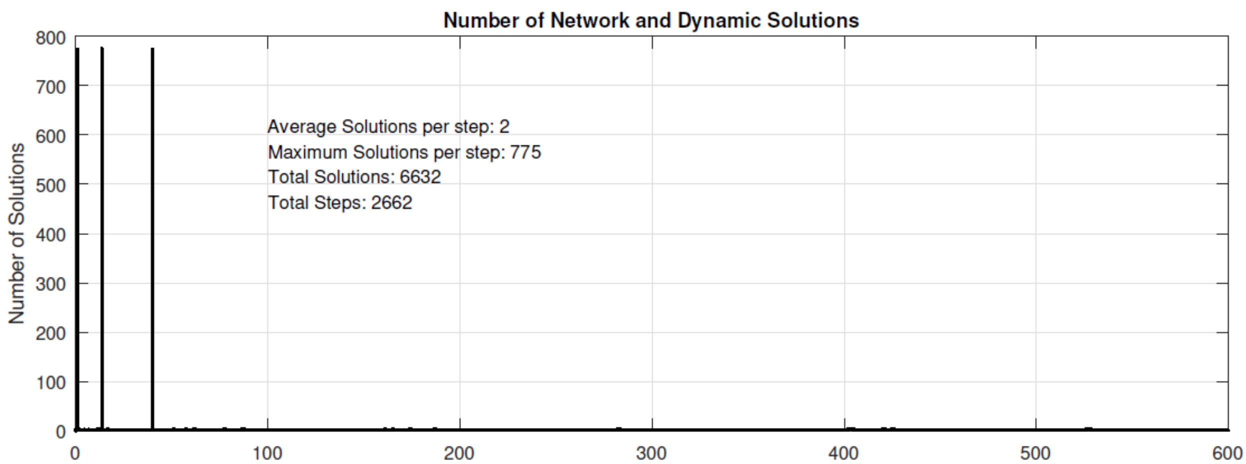


Figure 12. Plot of number of network and dynamic solutions.

## Development and Demonstration of Multirate Methods in PowerWorld:

Results using multirate methods can be viewed in more detail in the paper, “Assessment of Multirate Method for Power System Dynamics Analysis,” authored by Ju Hee Yeo, Wei C. Trinh, Wonhyeok Jang, and Thomas J. Overbye (TAMU), presented online at the North American Power Symposium, April 12, 2021.

The multirate numerical integration approach uses a unique integration step depending on dynamic characteristics of each variable. By adopting the multirate methods into dynamic simulations, maintaining numerical stability with very fast dynamics can be successfully achieved. This is because the methods allow these dynamic models to be integrated with a much smaller time step while slow variables use a longer time step. Therefore, this method aids in increasing numerical stability as well as reducing the computational burden. The basic approach in applying multirate methods can be seen in Figure 13.

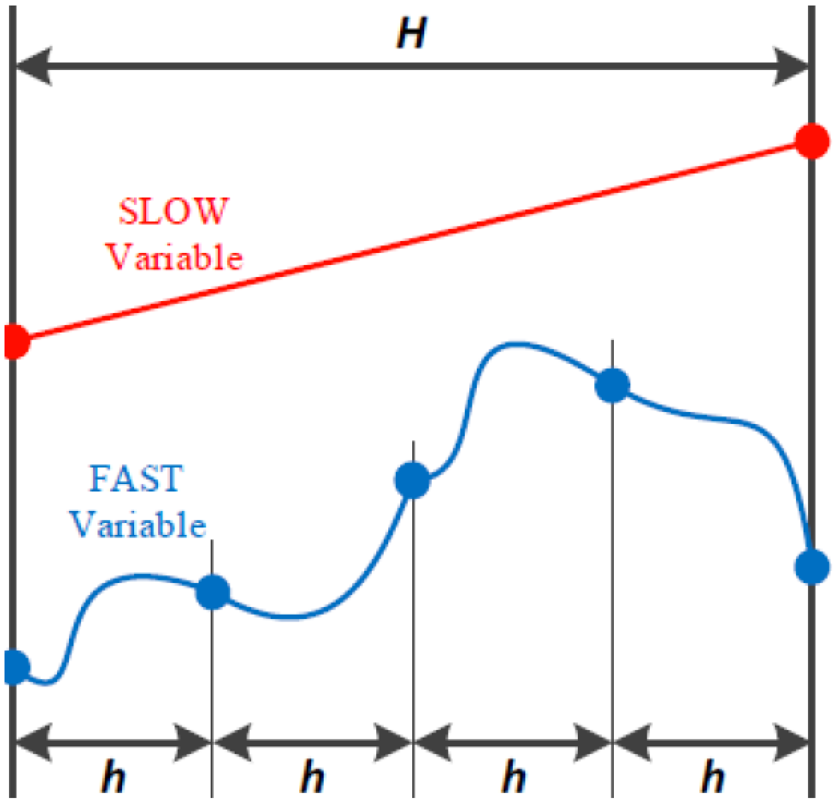


Figure 13. Multirate methods use a small timestep, h, for fast changing variables and a longer timestep, for instance, H=4h in the above, for slow changing variables.

Single rate integration methods, however, can cause numerical instability issues because their time step can sometimes be too large for fast devices. If the time step is reduced to not miss what's happening with the fast components, then slow components will also be unnecessarily updated every time step, which results in long simulations. Linear interpolation is used from slow components in order to solve the equations of each fast component. The number of subintervals (n) in the linear system can simply be obtained by computing the ratio of the main time step (T) to the time step of the fast components (t), where T = nt. This linear relationship, however, cannot be directly applied to non-linear systems and thus they require more computational burden to decide on the subinterval size.

To compare the impact of the different integration methods on power systems, three different approaches have been conducted: (1) Using the single rate method (RK-2) with a standard time step, (2) Using the single rate method (RK-2) with a greatly reduced time step, and (3) Using the multirate method with a standard time step. These three methods are applied to two synthetic grids: a 42-bus system and a 2000-bus system. These synthetic grids are publicly available test cases (available at https://electricgrids.engr.tamu.edu/). The grids are built on the footprints of central Illinois and Texas (ERCOT), respectively. They are fictitious but possess characteristics of an actual grid statistically and functionally. The first test case is the 42-bus synthetic system modeling a 345/138 kV network. The case has 14 generators and 55 loads, and includes 14 synchronous machines, exciters, and governors for each generator, but no stabilizers. The one-line diagram of the 42-bus system is illustrated in Figure 14.

The dynamics analysis results for both single rate and multirate integration can be seen in Figure 15. In particular, the focus is on the voltage of a specific bus after a three-phase solid fault is applied at that bus. The fault is applied at 1 second, and cleared at 1.01 seconds. The time step here is 0.5 cycles, and without multirate integration, the solution diverges, and the dynamics of the system are not captured. In addition, the voltage does not stay flat indicating that there is an initial condition issue with the single rate integration method with a time step of 0.5 cycles. However, by implementing multirate integration at the same time step, there are dramatic improvements in the simulation's ability to capture the dynamics of the rotor angle and the issue with the initial condition also disappears. This is compared to a single rate approach with a greatly reduced time step of 0.05 cycles, and notice that the behavior of the voltage is very similar in both cases. Tables 4 and 5 contain the simulation times and accuracies for these methods.

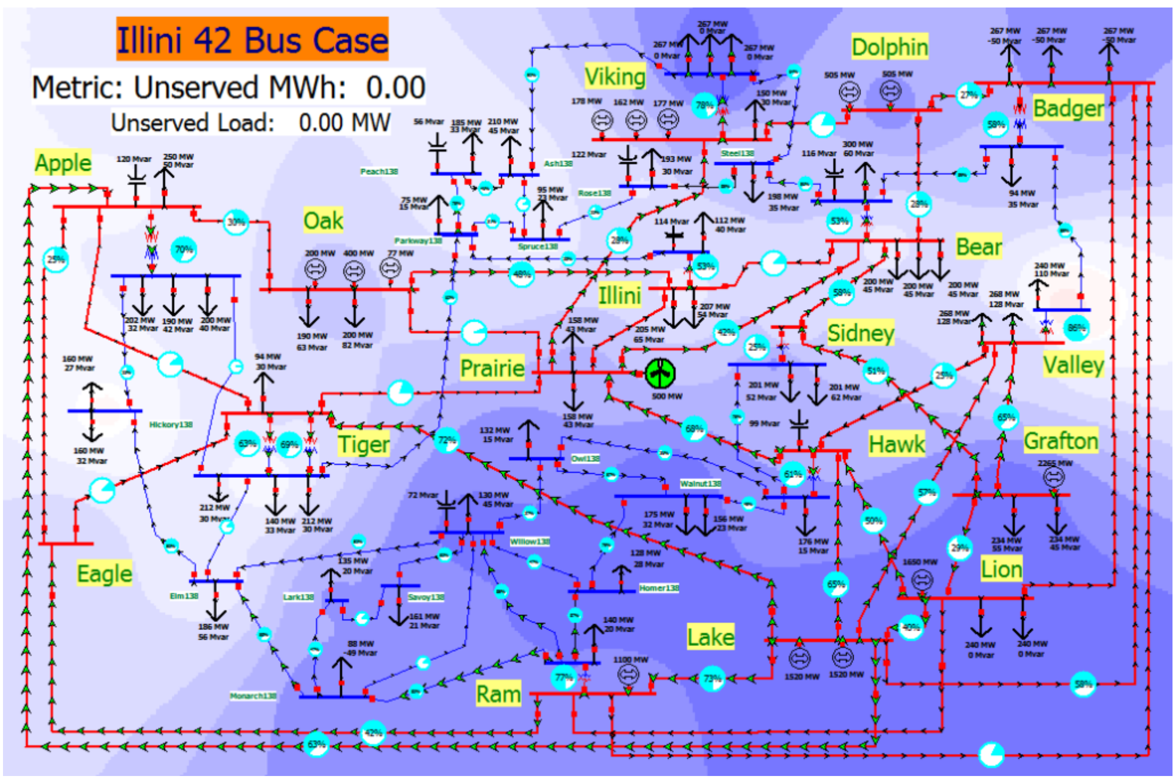


Figure 14. 42-bus synthetic grid for central Illinois.

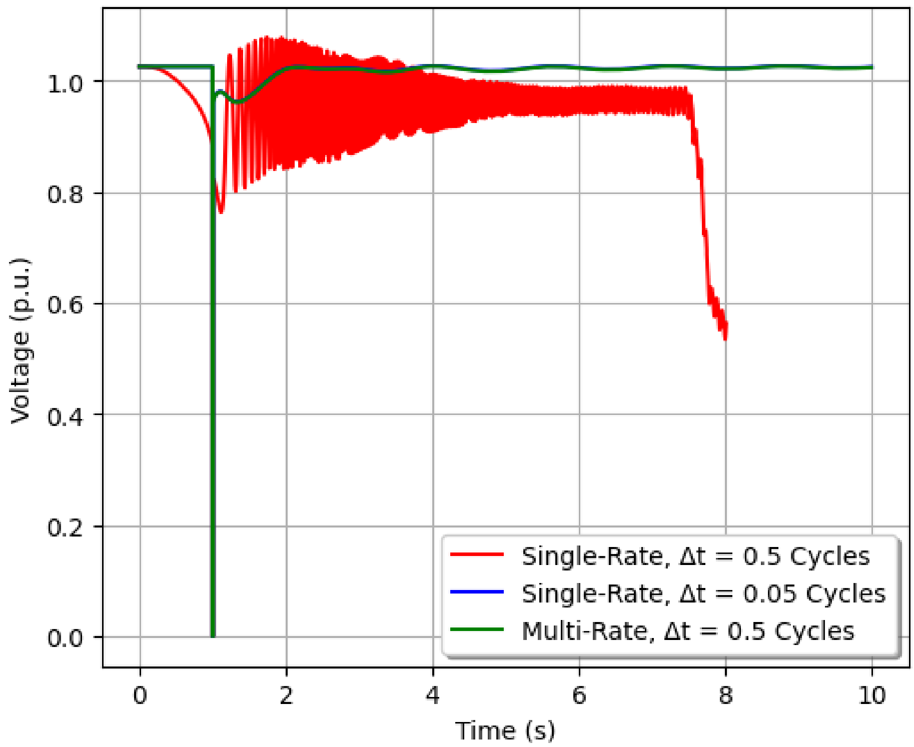


Figure 15. Bus voltages for 42-bus synthetic grid.

The second test case is a reduced-order model of ERCOT. The one-line diagram for the 2000-bus synthetic system is shown in Figure 16. There are 435 synchronous machines, 444 exciters, 435 governors, and 434 stabilizers. The total number of dynamic loads is 1350. For the voltage levels, the orange, purple and green lines in the one-line diagram denote the 500-kV 230-kV and 115-kV network in the system, respectively. The total load demand is 67 GW with 100 GW generation capacity.

The dynamics analysis results can be seen in Figures 17-19. The simulation lasts 30 seconds, with a three phase solid fault occurring at 1 second, and being cleared at 1.1 second. All measurements were taken at bus 7108, which has the largest negative eigenvalue from single machine infinite bus (SMIB) analysis. Looking at Figure 17, both the multirate approach with the larger time step of 0.5 cycles and the single rate approach with the reduced time step of 0.05 cycles converge to the same value, but the single rate approach with a larger time step does not converge. While generator outages are found by looking at properties such as rotor angle and frequency that are associated with generators being synchronized, numerical stability of the single rate approach can also be evaluated by looking at bus voltage magnitude and angle. Figures 18 and 19 show the magnitude and angle of the bus voltage, respectively. Similar to rotor angle, it can be seen that both the bus voltage magnitude and angle do not converge to a specific value when considering a single rate approach with a larger time step, indicating numerical instability. However, when using a reduced time step with the single rate approach, both the voltage magnitude and angle converge, and similar behavior is seen when using the multirate approach with the larger time step, aligning almost exactly with the single rate approach with the reduced time step.

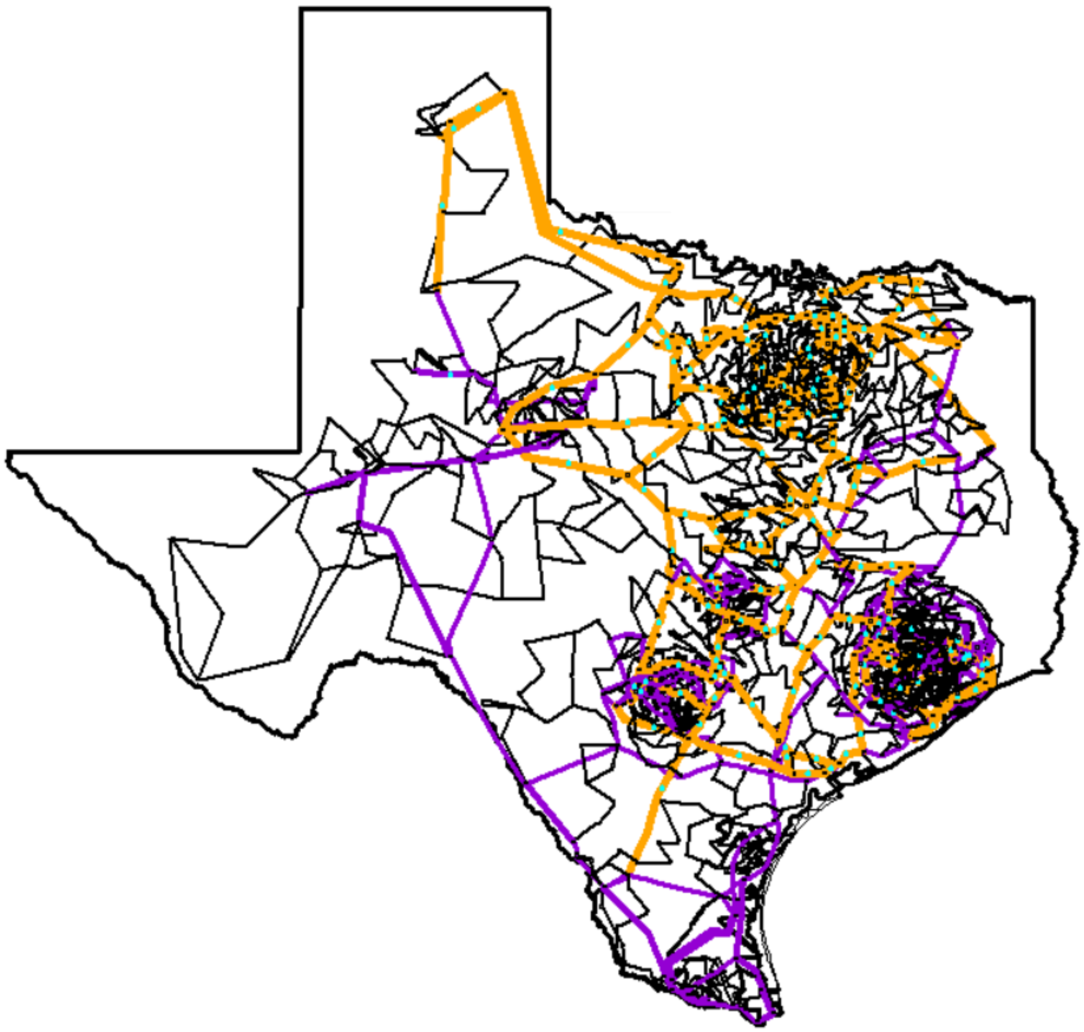

Figure 16. 2000-bus synthetic grid for ERCOT.

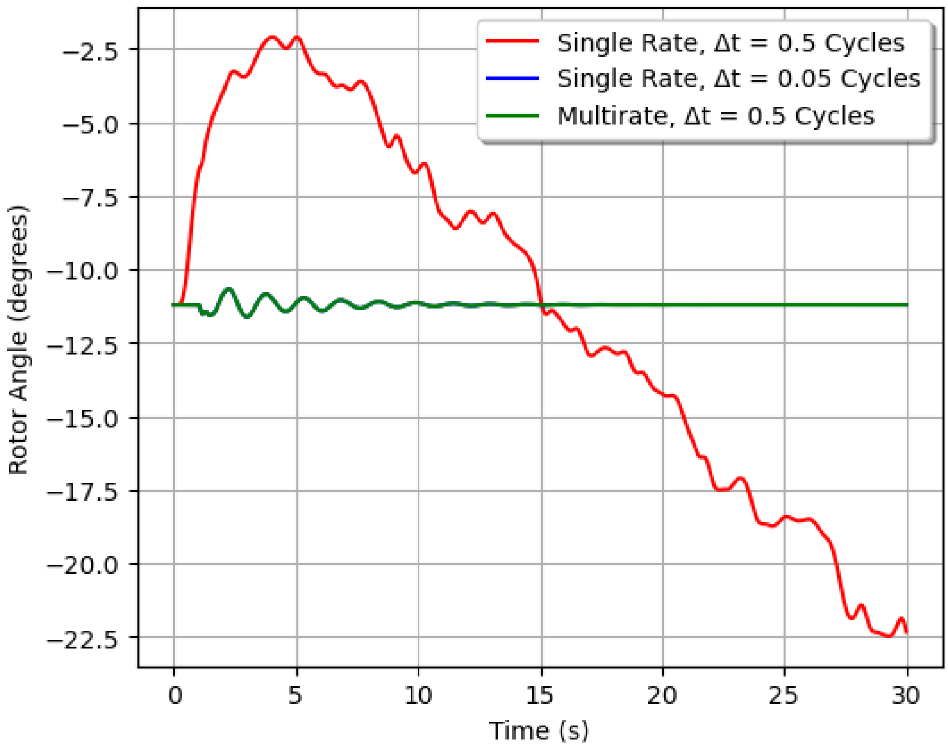


Figure 17. Bus 7108 generator rotor angle for 2000-bus system.

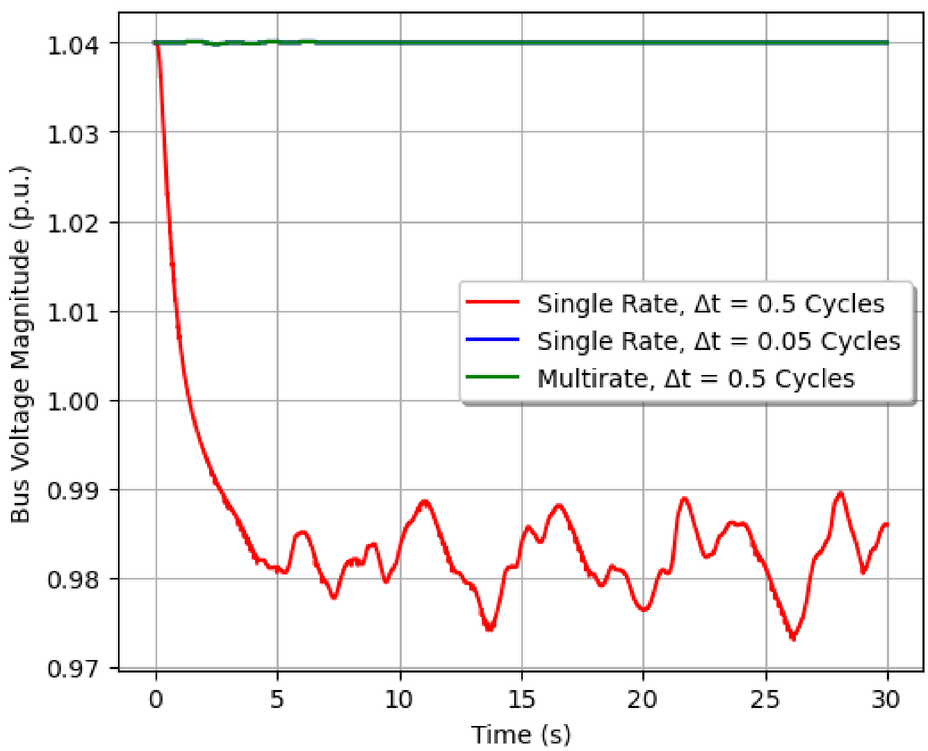


Figure 18. Bus 7108 voltage magnitude for 2000-bus system.

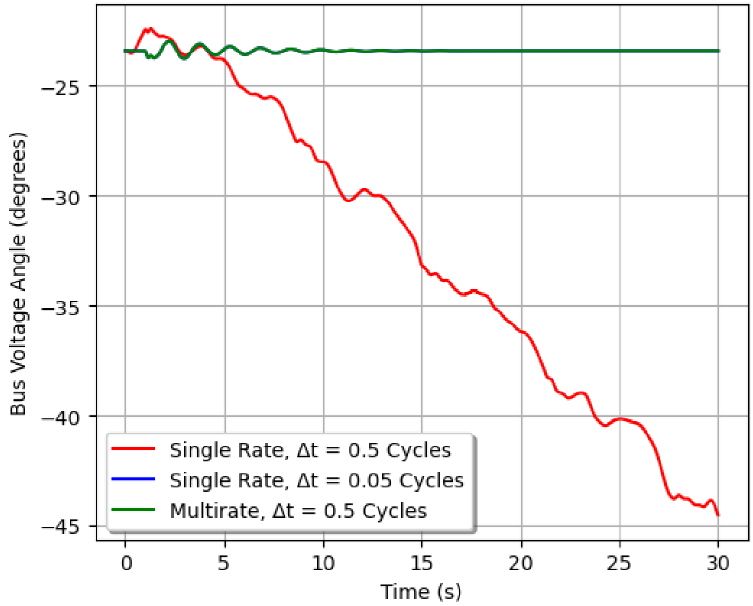


Figure 19. Bus 7108 voltage angle for 2000-bus system.

When evaluating multirate integration techniques, two primary considerations have been addressed: accuracy and computation time. Since multirate integration techniques strive to achieve equivalent results to single rate techniques, but at a larger time step for slow variables, it should be noted that multirate techniques are faster and have a higher degree of accuracy when compared to single rate techniques at the same time step.

Table 4 shows how much computation time each dynamics study took for the two different combinations of integration techniques and time steps. Looking at the computation time differences for the 42-bus system, which had a simulation run-time of 10 seconds, it is seen that using single rate integration with a reduced time step, while converging to the correct solution, takes 2.02 seconds, which is almost seven times as long as when multirate integration is used with the larger time step, which takes 0.24 seconds. When looking at the 2000-bus case, with a simulation run-time of 30 seconds, implementation of a single rate approach with a reduced time step takes over eight times as long at 147.95 seconds, when compared to multirate integration with a larger time step, which takes 17.52 seconds.

These results display one of the largest benefits of multirate integration techniques: a significant reduction in computation time. While it is entirely feasible in the context of dynamics studies to arrive at an accurate solution if you provide a small enough time step, especially for larger systems, this process can be highly inefficient in terms of time and computational load. Implementation of multirate integration methods help to circumvent these problems, enabling both fast and accurate solutions for large systems.

Table 4. Computation times by integration methods

| System | Single Rate Reduced Time Step | Multirate Larger Time Step |
|---|---|---|
| 42-Bus | 2.02 s | 0.24 s |
| 2000-Bus | 147.95 s | 17.52 s |

Table 5 shows the accuracy of the different combinations of integration techniques. In this instance, the single rate integration approach with a greatly reduced time step of 0.05 cycles is used as the ”true” data, as multi-integration techniques are looking to achieve equivalent results in less time. Mean squared error (MSE) is used as the metric to determine accuracy. For MSE, the error is the difference between the ”true” data mentioned above, and the data we are comparing against, generated from either a single rate or multirate integration technique at the time step of 0.5 cycles.

For the 42-bus system, the single rate integration approach with a larger time step does not converge to a solution. Combining that knowledge with the computation times indicated in Table 4, it can be concluded that multirate integration achieves relatively accurate results with significant time saved for smaller systems. When looking at larger systems, the accuracy results are looked at through the different bus measurements. Starting with rotor angle, it is noted that there is a significant difference between the single rate and multirate approaches at the same time step. This difference of over 8 orders of magnitude is attributed to the divergence of the single rate approach. Due to smaller discrepancies, in terms of the numerical difference in values, the single rate approach and the multirate approach differ by a smaller amount for voltage magnitude. However, MSE calculations indicate that the multirate approach perfectly matches the results from the single rate approach at a reduced time step for voltage magnitude. Finally, when examining the differences between the approaches for voltage angle, it is seen in Figure 19 that the voltage angle does not converge, whereas the multirate approach does. Similar to rotor angle, due to divergence, the MSE difference between the single rate and multirate approach is over 8 orders of magnitude. In all instances, irrespective of system size, it is seen that the multirate approach is always significantly better than the single rate approach when it comes to accuracy. This, in conjunction with reductions in computation time, as seen in Table 4, we re-affirm that a multirate integration approach is ideal when considering fast dynamics.

Table 5. Mean squared error estimates by integration methods

| System | Single Rate Larger Time Step | Multirate Larger Time Step |
|---|---|---|
| 42-Bus | Does Not Converge | 7.60E-7 |
| 2000-Bus Rotor Angle | 39.27 | 2.98E-7 |
| 2000-Bus Voltage Mag. | 0.003 | 0 |
| 2000-Bus Voltage Angle | 130.86 | 2.14E-7 |

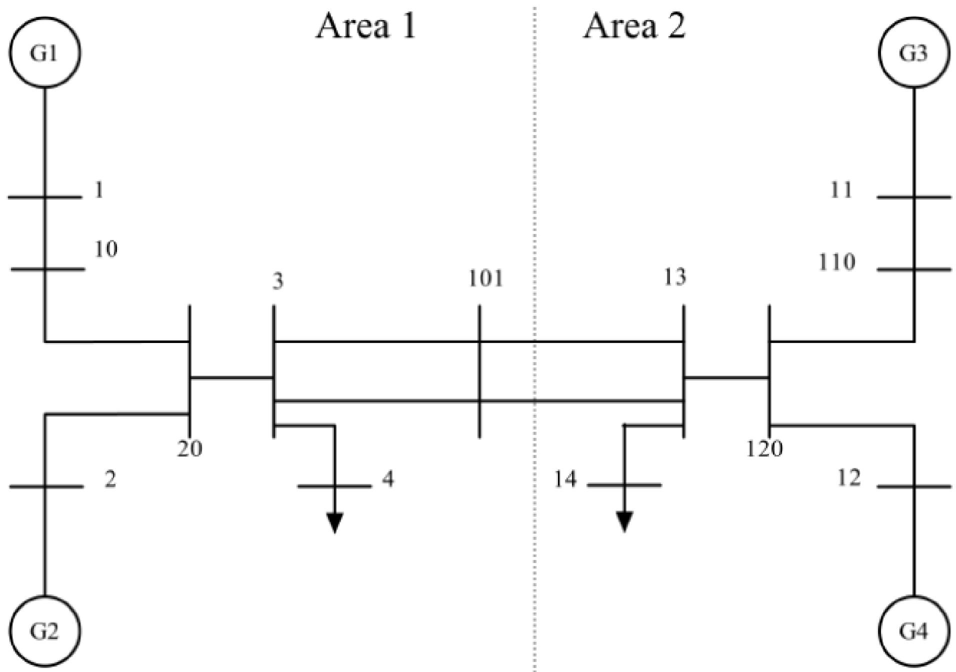


Figure 20. Kundur two-area four-machine system.

## Sensitivity analysis of parameters in variable time-step methods:

This section discusses results from sensitivity analysis of variable time-step methods simulated in PST on the Kundur two-area four-machine system, as shown in Figure 20. The sensitivity analysis is conducted by varying the parameters of initial step sizes, error tolerance, and type of ODE solvers.

The scenario simulated on the Kundur two-area system is to perturb the governors by mimicking a solar variation due to cloud cover. PST version 4 is used for both fixed time step (FTS) and variable time step (VTS) methods. The base case for VTS: ode23t solver, RelTol/AbsTol = $10^{-7}$, and initial step size = $10^{-3}$. Table 6 summarizes the sensitivity analysis results for the FTS and VTS methods.

General observations from the sensitivity analysis are as follows:

1. Sensitivity to initial step size choice is marginal:

Simulations with different initial step sizes ranging from 1e-1 to 1e-5 show no significant difference in terms of accuracy, step size, computation time, and number of solutions.

2. Different error tolerance values have a large impact on computation time while the impact on accuracy is marginal:

Computation time is significantly reduced for larger error tolerance values while the accuracy is not deteriorated to a large degree except for the largest disturbance interval (90~150 [s]). This is primarily due to a larger number of solutions required for smaller error tolerance while not changing minimum/maximum time steps significantly.

3. Different ODE solvers significantly affect both computation time and accuracy:

non-stiff solvers (ode113, ode23) are slower than stiff solvers (ode23t, ode15s) while non-stiff solvers produce more accurate solutions.

Table 6. Summary of sensitivity analysis results for FTS and VTS methods

| | FTS | VTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Base Case | Initial Step Size | | | Rel./Abs. Tolerance | | | ODE Solvers | | |
| | | | $10^{-5}$ | $10^{-2}$ | $10^{-1}$ | $10^{-3}$ | $10^{-4}$ | $10^{-5}$ | ode15s | ode113 | ode23 |
| Avg Error [%] | 0.0 | 3.4e-3 | 7.4e-4 | 4.5e-4 | 3.0e-3 | 1.0e-2 | 7.3e-3 | 3.5e-3 | 3.1e-4 | 5.5e-5 | 2.7e-5 |
| Total Comp Time [s] | 333.5 | 176.5 | 187.0 | 173.4 | 169.4 | 16.5 | 30.2 | 92.6 | 117.4 | 263.9 | 280.3 |
| Avg Time Step [s] | 0.004 | 0.010 | 0.010 | 0.001 | 0.010 | 0.229 | 0.078 | 0.025 | 0.014 | 0.008 | 0.007 |
| Max Time Step [s] | 0.004 | 21.900 | 19.900 | 14.100 | 23.400 | 21.900 | 21.900 | 21.900 | 10.000 | 0.156 | 0.128 |
| Min Time Step [s] | 4e-3 | 1.6e-5 | 1.0e-5 | 1.6e-5 | 1.6e-5 | 3.9e-4 | 1.2e-4 | 4.2e-5 | 3.9e-5 | 5.8e-5 | 8.8e-6 |
| Avg Sol per Step | N/A | 2 | 2 | 2 | 2 | 4 | 3 | 2 | 2 | 3 | 2 |
| Max Sol per Step | N/A | 100 | 96 | 96 | 96 | 104 | 100 | 100 | 96 | 27 | 8 |
| Total Sols | N/A | 48075 | 48738 | 50566 | 47570 | 3722 | 7906 | 20984 | 30956 | 87794 | 77082 |
| Total Steps | N/A | 23644 | 23849 | 24251 | 23629 | 1049 | 3087 | 9553 | 17734 | 29150 | 35632 |

NOTE: Error was computed by $\frac{1}{T}\left(\sum_{t=1}^{T}\frac{VTS(t)-FTS(t)}{FTS}\times 100\right)$ [%] corresponding to the machine 1 speed. To calculate the error at each time $t$, FTS was interpolated on VTS using MATLAB command 'interp1'.

## Impact:

The findings from this project will make an impact to the field through the following process. The primary outcome of the project is the development, implementation, and demonstration of numerical integration algorithms enabling extended-term dynamic simulations of power systems with high penetration of PV generation. This outcome has resulted in a computational framework to support high fidelity dynamic models that are being brought closer to market through demonstrations, industry outreach, and stakeholder engagement. The primary beneficiaries of the project outcome are the wider power systems community that needs to understand the impact of high PV penetration in power grids. This includes grid planning departments at electric utilities and Independent System Operators (ISOs), dynamic simulation software vendors, university power system research groups, grid reliability organizations (e.g., regulatory commissions, reliability coordinators, standards organizations), power system consulting companies, and non-university research labs.

The impact of the project outcome is the availability of improved simulation tools that lead to a more accurate understanding of power system behavior when generation consists of high penetration of PV power. This will enable improved grid planning resulting in a reduction of barriers to high PV penetration. Algorithm development and simulation results have already been made widely available through peer-reviewed conference publications, industry meeting presentations, and public webinars. Further, the project team has engaged with the power system community at industry forums including the IEEE Power and Energy Society Work Group Meeting, the Joint Synchronized Information Subcommittee (JSIS) of the Western Electricity Coordinating Council (WECC), the North American Synchrophasor Initiative (NASPI) work group meeting, and outreach to power system experts such as those from the North American

Electric Reliability Corporation (NERC), WECC, and the Bonneville Power Administration (BPA).

## Plans for Next Reporting Period:

This is the final report for the project.

## Changes/Problems:

To accommodate the additional deliverables to Milestone #6, the project end date was changed from 3/31/2021 to 11/30/2021.

## Products:

A paper submitted by the project team to the IEEE PES General Meeting in November 2021 was accepted by the conference program committee in January 2022. The citation for the paper is: Thad Haines, Matt Donnelly, and Dan Trudnowski, "Power System Toolbox Updates to Enable Long-Term Variable Time-Step Dynamic Simulation," to be presented at the 2022 IEEE Power & Energy Society General Meeting, July 17-21, 2022. An additional conference paper was submitted to the North American Power Symposium (NAPS) to be held in Fall 2022. As of February 2022, this paper is still under review by the NAPS program committee. A journal paper is currently in final revision and will be submitted in March 2022 to a special issue on electric grid controls in the journal, *Energies*.

A project website has been created: https://github.com/thadhaines/MT-Tech-SETO. This website is a Github public repository for PST code being used by the project for the simulation analysis involving the variable time-step algorithms vs. the baseline method.

The project PI, Dr. David Schoenwald, presented a talk titled, "Improving Simulation Tools to Better Understand Impact of High PV Penetration in Power Grids," as part of a panel session on Solar Photovoltaic System Design and Grid Interconnection for the 2020 IEEE PES General Meeting. The panel session was held online on Wednesday, August 5, 2020.

Two conference presentations and a public webinar were delivered by the project PI during April and May. The conferences were both well-known electric utility meetings, North American SynchroPhasor Initiative (NASPI) Virtual Work Group Meeting on April 13, 2021 and the Joint Synchronized Information Subcommittee (JSIS) Meeting of the Western Electricity Coordinating Council (WECC) on May 13, 2021. The public webinar was hosted by Sigma Xi, IEEE, and the University of New Mexico on April 15, 2021. Prof. Tom Overbye presented a public webinar on multiple subjects which included project results on Feb. 24, 2021. This seminar also included a discussion of the ERCOT situation in Texas. The full citations and URL addresses for these presentations are listed on the accomplishments tab (Tab VI) in the Excel file of the RPPR2-21Q2 report.

A user manual for PST, written by Thad Haines (MTU), contains information on the variable time-step methods, simulation test cases, and improved inverter & AGC models developed in this project. It is publicly available in the project repository for PST code at: https://github.com/thadhaines/MT-Tech-SETO/blob/master/PST/literature/PST4UserManual-1.0.0.pdf.

The multi-rate method development and simulation results were presented at the North American Power Symposium on April 12, 2021. The citation for the paper is: Ju Hee Yeo, Wei C. Trinh, Wonhyeok Jang, and Thomas J. Overbye, "Assessment of Multirate Method for Power System Dynamics Analysis," North American Power Symposium (online), April 12, 2021.

### Participants & Collaborators:

Montana Technological University, led by Prof. Matt Donnelly, has developed, and tested the code for PST, which includes three new variable time-step methods as well as the test cases for demonstration. MTU has also created a new model for inverter-based resources including PV. MTU has also developed an improved model for AGC. All of the code and data for the MTU contribution can be found at the project website: https://github.com/thadhaines/MT-Tech-SETO. Texas A&M University, led by Prof. Tom Overbye, has developed a numerical integration algorithm based on multi-rate methods. This has been implemented and demonstrated on two large grid examples in PowerWorld. PowerWorld, led by Dr. Mark Laufenberg, has deployed the simulation test cases, new models, and integration algorithms into PowerWorld software, which has been rolled out to the power systems simulation community.

### Special Reporting Requirements:

N.A.

### Budget Information:

The project budget has been completely costed with the full amount of cost share provided by the cost share-providing recipients, Montana Technological University and Texas A&M University.