CERTS Project
Voltage Stability Applications using Synchrophasor Data

Report 6
Perform Voltage Stability Analysis
Report 7
Development of Network Models for Wind Generation Sites
Report 8
Real-Time Application Strategies

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Introduction

This is a combined report for Tasks 6, 7, and 8. The discussion will follow in the order of Task 7, Task 6, and then Task 8.

1. Task 7: Develop network models for wind generation sites

The objective of Task 7 is to describe the wind generation site and the network model. We were able to work with BPA to study the Jones Canyon wind turbine site (Figure 1) [1].

In this system, 6 wind farms are connected to the 230 kV Jones Canyon substation. The wind farms are all rated at about 100 MVA. Four wind farms are of Type 2 (induction generator) and the other two are of Type 3 (Doubly-Fed Asynchronous Generator, DFAG). The reactive power of the generators is supplemented by switched shunt capacitors of relatively small ratings. One of the Type-2 wind farm has a STATCOM rated at +/- 15 MVar. The (P,Q) flow output of each wind farm is measured. The statuses of the shunt capacitor banks are not known, and have to be estimated. The Jones Canyon substation is also equipped with two shunt capacitor banks with higher ratings.

The Jones Canyon substation is connected to the east via a relatively short line to the McNary 230 kV substation (East Bus), which is connected to the McNary 500 kV substation through a step-up transformer. The Jones Canyon substation is also connected to the west via a relatively long line to the Santiam substation (West Bus), which is connected to a 500 kV substation via a step-up transformer.

The intent of the study is to use a minimal set of measurements to enable the voltage stability analysis. The rationale is that if the measurements of the entire system is available, the problem would become a voltage stability analysis for the energy management system for the control center. Here the data requirements are:

1. Voltage and (P,Q) flow measurements of the individual wind farms and the East and West Buses. No measurements beyond the East and West Buses are used.
2. Line parameters of the network shown in Figure 1.

Because no measurements beyond the East and West Buses are used, it is assumed that they each are connected to a stiff bus via an impedance. Thus we have to develop a Thevenin equivalent at the West Bus, and one at the East Bus, as indicated in Figure 1. A least-squares procedure is used to estimate the Thevenin voltage at the stiff bus and the Thevenin impedance, as described in [2].

In the voltage stability analysis procedure in which the total output power of the wind farms is increased until a voltage collapse point is reached, the incremental wind power is divided 50-50 going to the East and West Buses.

In this setting, the AQ-bus method is applied to this wind hub system to determine the voltage stability limits for the wind farm outputs.

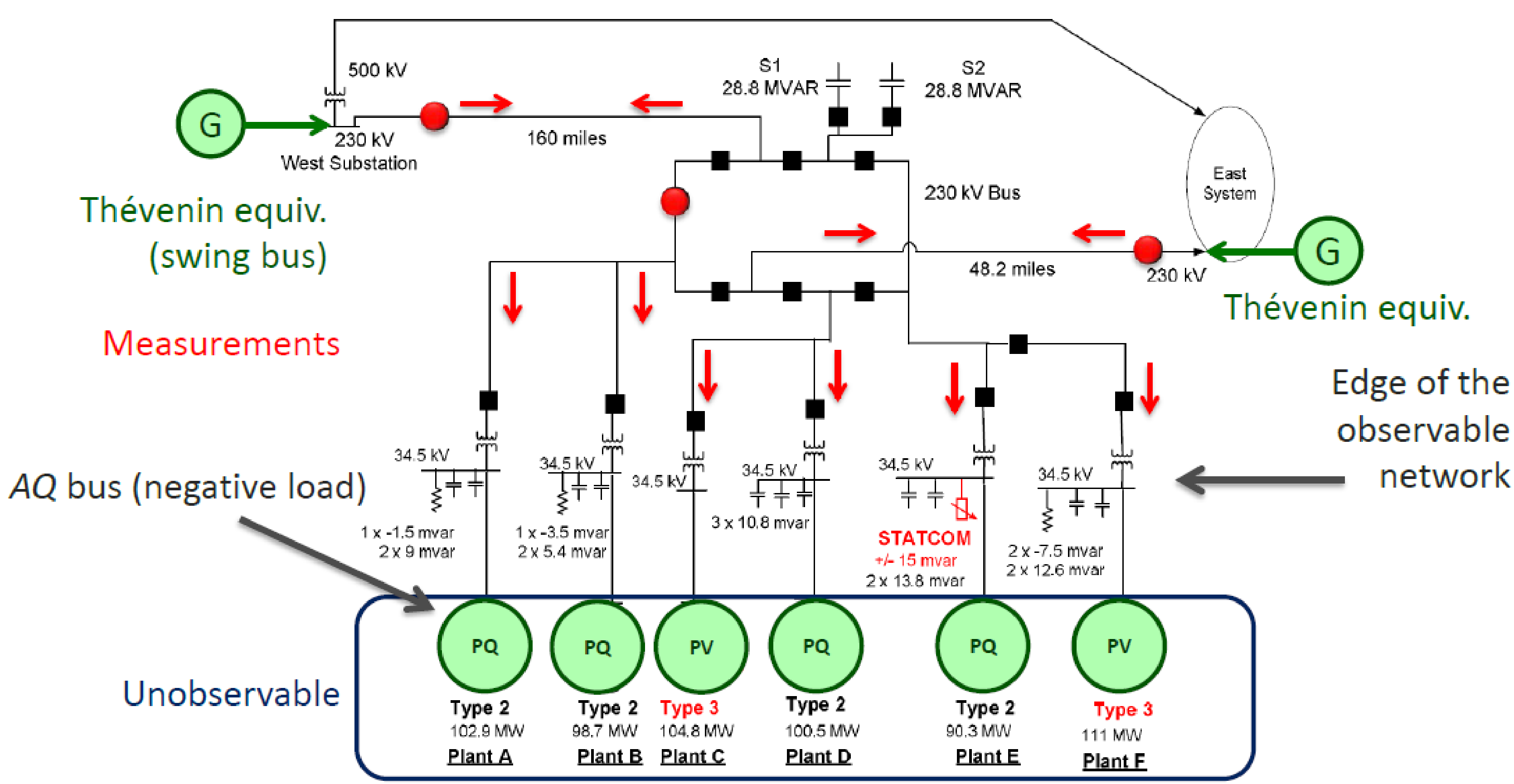

Figure 1. Connection diagram of the Jones Canyon wind site.

2. Task 6: Perform voltage stability analysis

The objective of Task 6 is to perform voltage stability analysis using the BPA wind hub network model and the Thevenin equivalents to compute the voltage stability margins for the wind hub.

It is important that the approach taken meets the expectation of the user. On June 2, 2014, the RPI project team (Joe Chow and Scott Ghiocel) met with BPA engineer Tony Faris, who is in Dr. Dmitry Kosterev's group. It was decided that for a demonstration of the approach, it would be applied to historical data, so that the results could be considered carefully before proceeding to a potential real-time application. The plan was for BPA to supply a week's worth of 24-hour data set containing all the required voltage and flow measurements at the wind hub system. As the PMU at Jones Canyon had not been installed yet, 2-sec SCADA data would be used. Furthermore, the voltage stability margin would be computed every 5 minutes, using the SCADA data for the last 5 minutes.

Thus computer code written in MATLAB was developed to perform these 5-minute VS calculation for the whole 24-hour record. The computation procedure is as follows:

1. For each 5 minutes, compute new Thevenin equivalents for the East and West Buses.
2. Increase the wind farm power output and use the AQ-bus method to compute the PV curves of at all three buses (which are computed simultaneously). The power margin is from the current operating condition to the point of voltage collapse.[1]

The results of this set of 24-hour analysis are shown in Figures 2 to 7. These figures were generated by the graphical user interface. The 3 plots on the top left show the power delivered over time to the West Bus, the power generated by the wind hub, and the power delivered to the East Bus. The two plots in the middle left are the wind hub output power plotted against the maximum power output limit, and the voltage stability margin, that is, additional power that can be delivered by the wind hub. The three plots on the bottom left are the PV curves for the West Bus, the wind hub, and the East Bus. Note that the voltage at the wind hub is most sensitive to the power output. Note also that there are two curves in the PV curve plot: the red line is the short-term curve (that is, no capacitor switching) and the black line is the long-term curve (that is, shunt capacitors will switch when the voltage reaches a threshold).

Currently, a 24-hour analysis would require about 15-20 minutes of elapsed time on a laptop that is a couple of years old.

The right most column contains three plots. The top one is the measured voltages at the three buses. The lower two plots are the Thevenin voltages and impedances at the East and West buses.

Also note that no stability margin is computed if the output of the wind hub is zero. The assumption is that the wind turbines are off line.

[1] In some VS programs, voltage stability is defined by a low voltage threshold, which is not the same as the true collapse point voltage. This option can be applied here also.

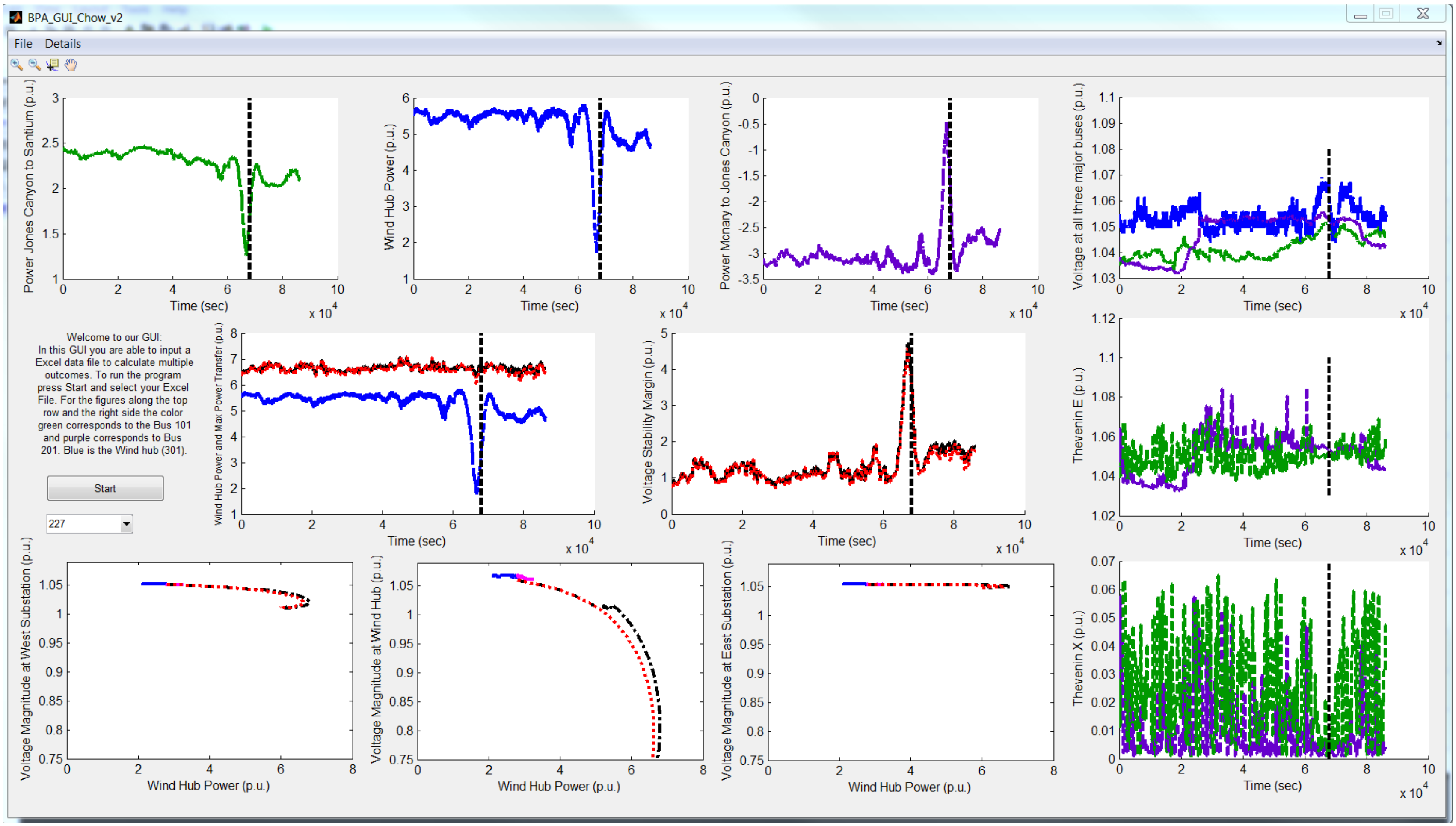

Figure 2. One-day voltage stability analysis for June 16, 2014

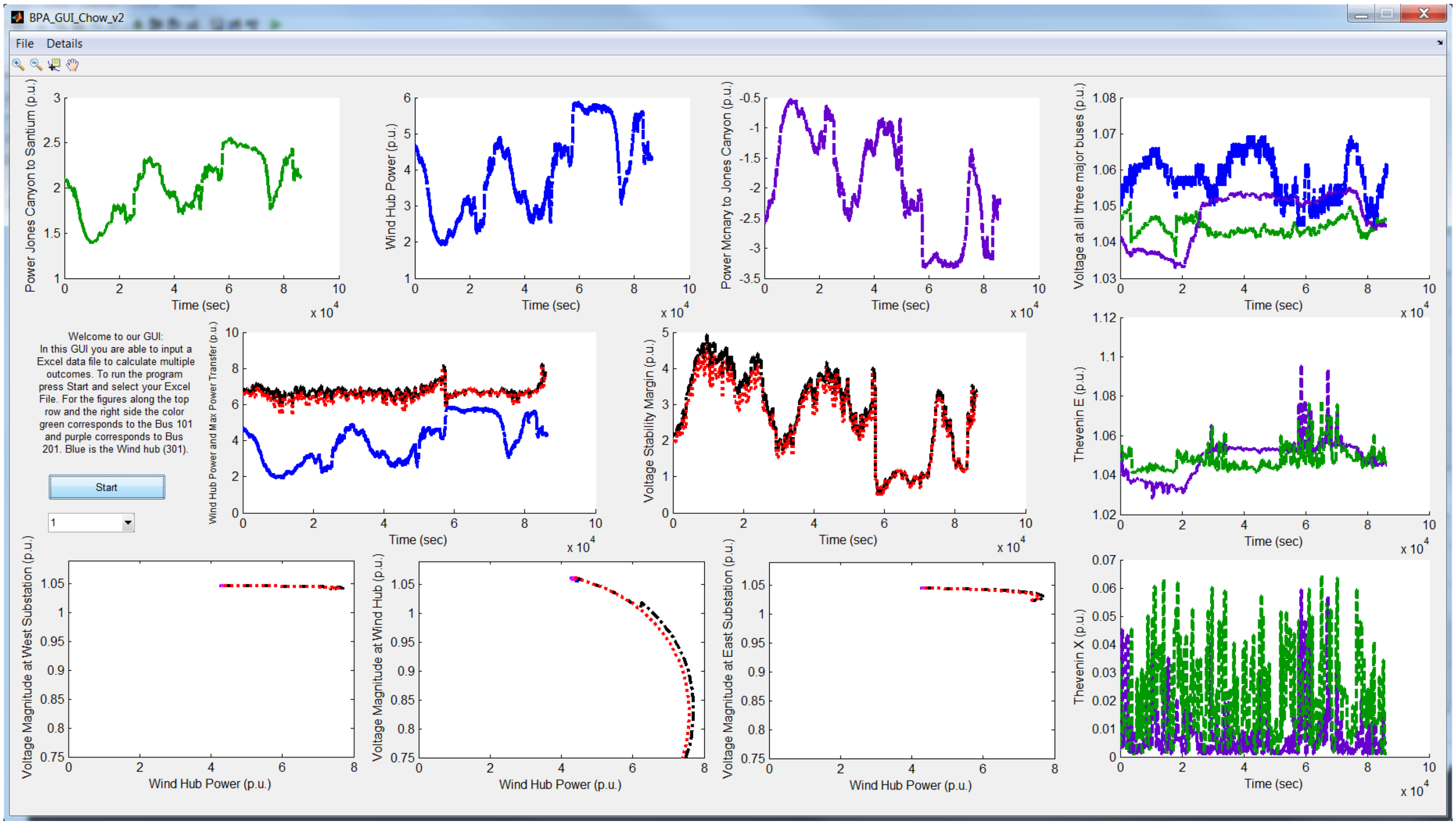

Figure 3. One-day voltage stability analysis for June 17, 2014

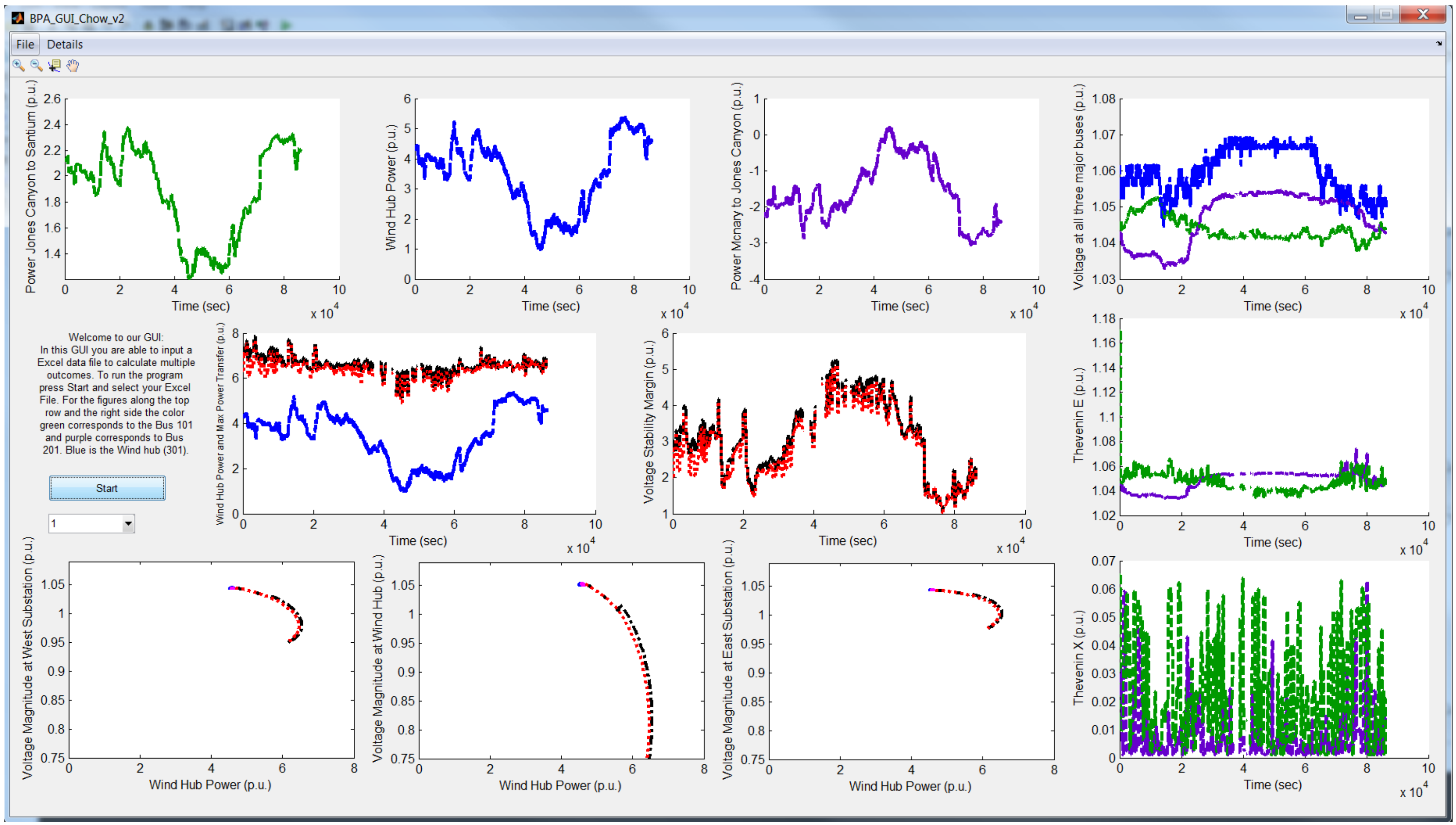

Figure 4. One-day voltage stability analysis for June 18, 2014

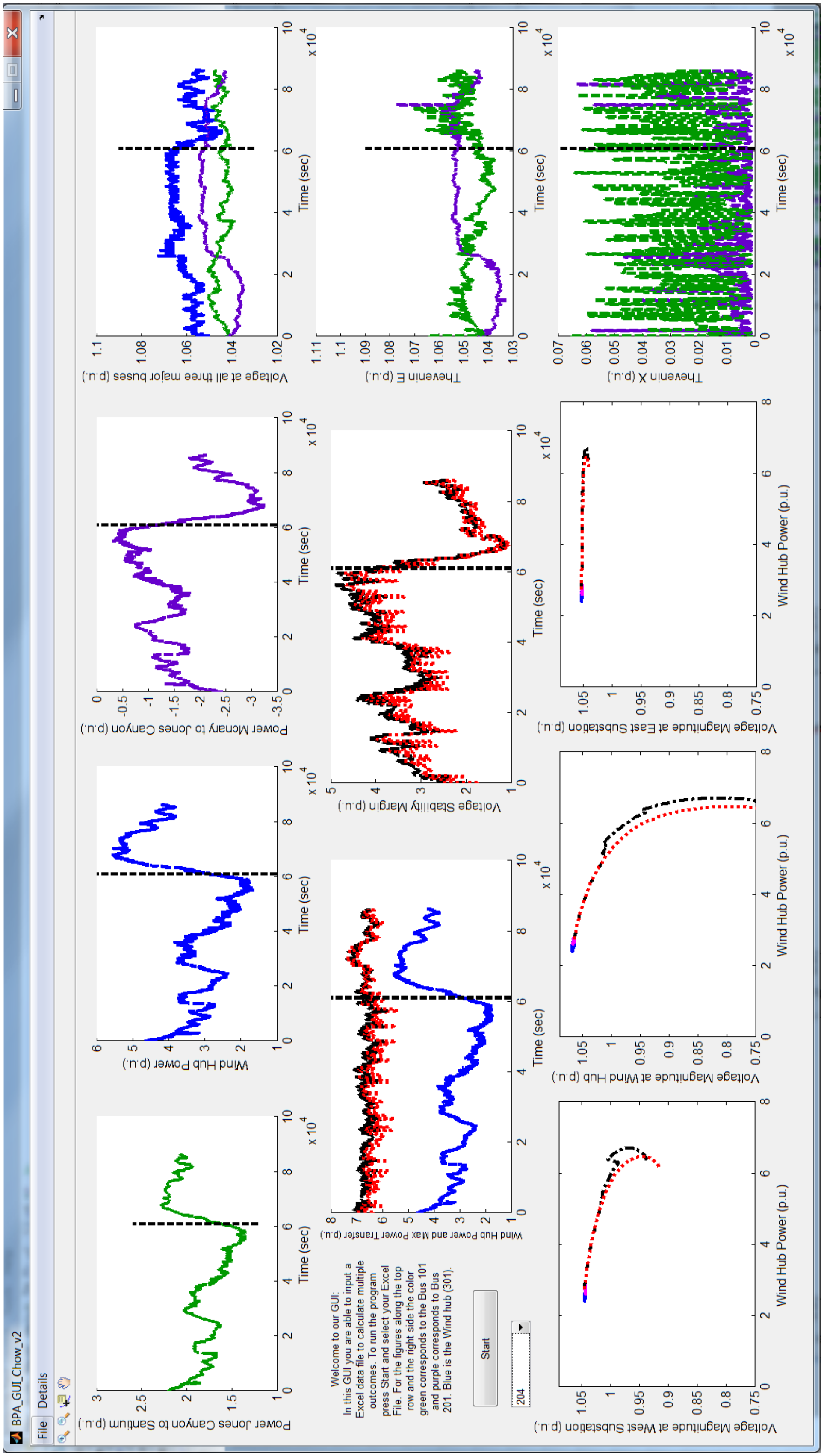

Figure 5. One-day voltage stability analysis for June 19, 2014

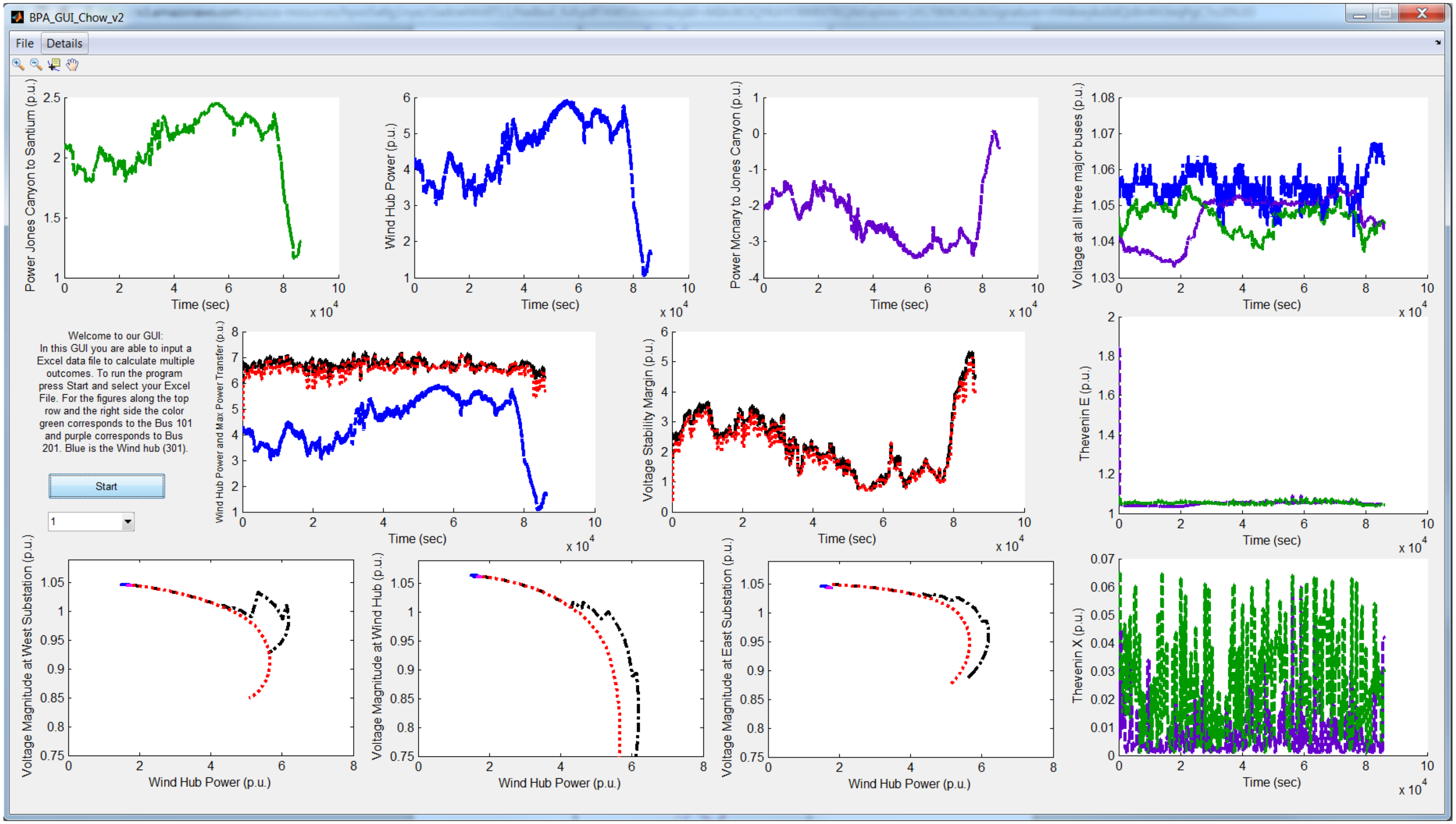

Figure 6. One-day voltage stability analysis for June 20, 2014

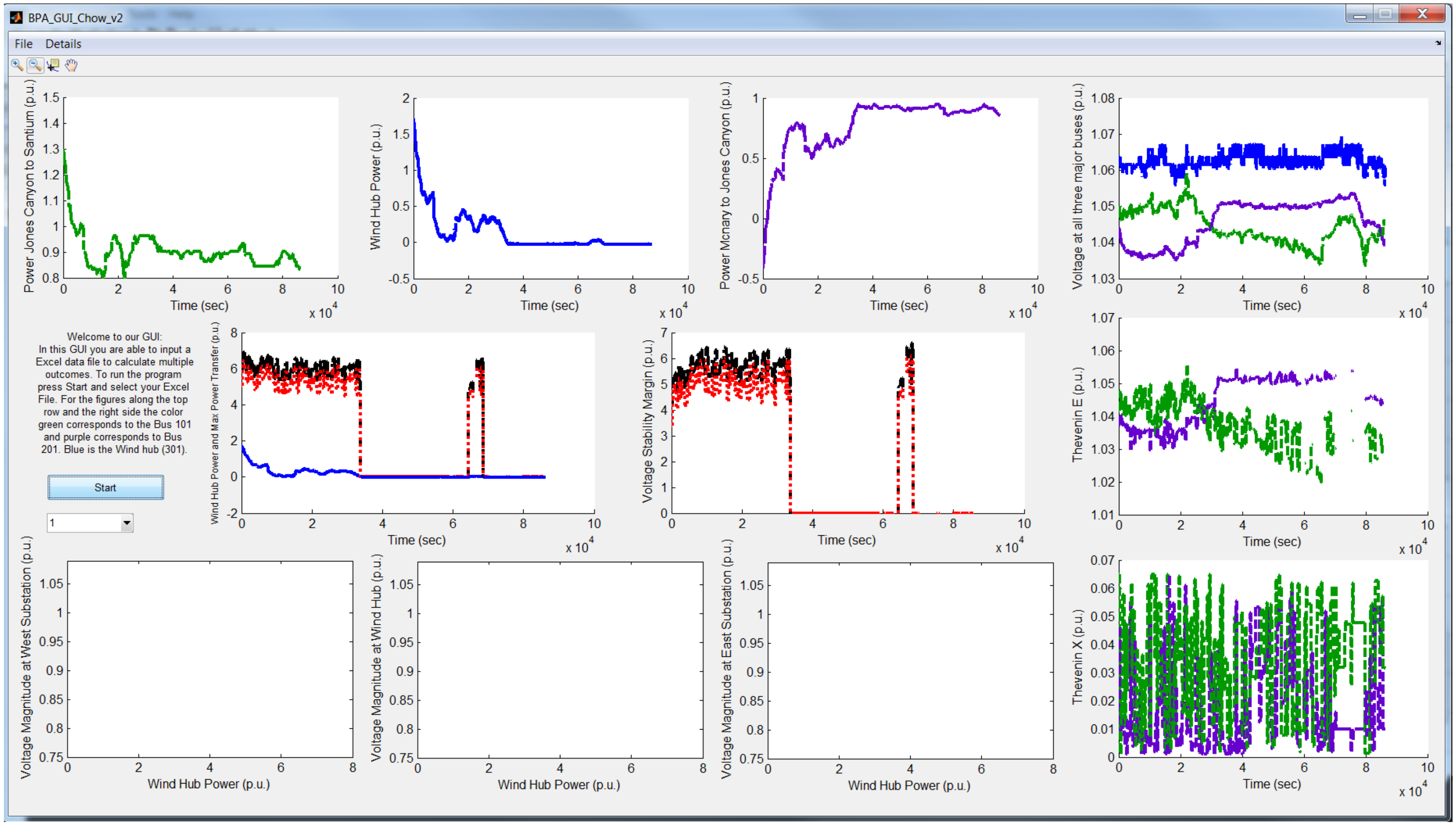

Figure 7. One-day voltage stability analysis for June 21, 2014

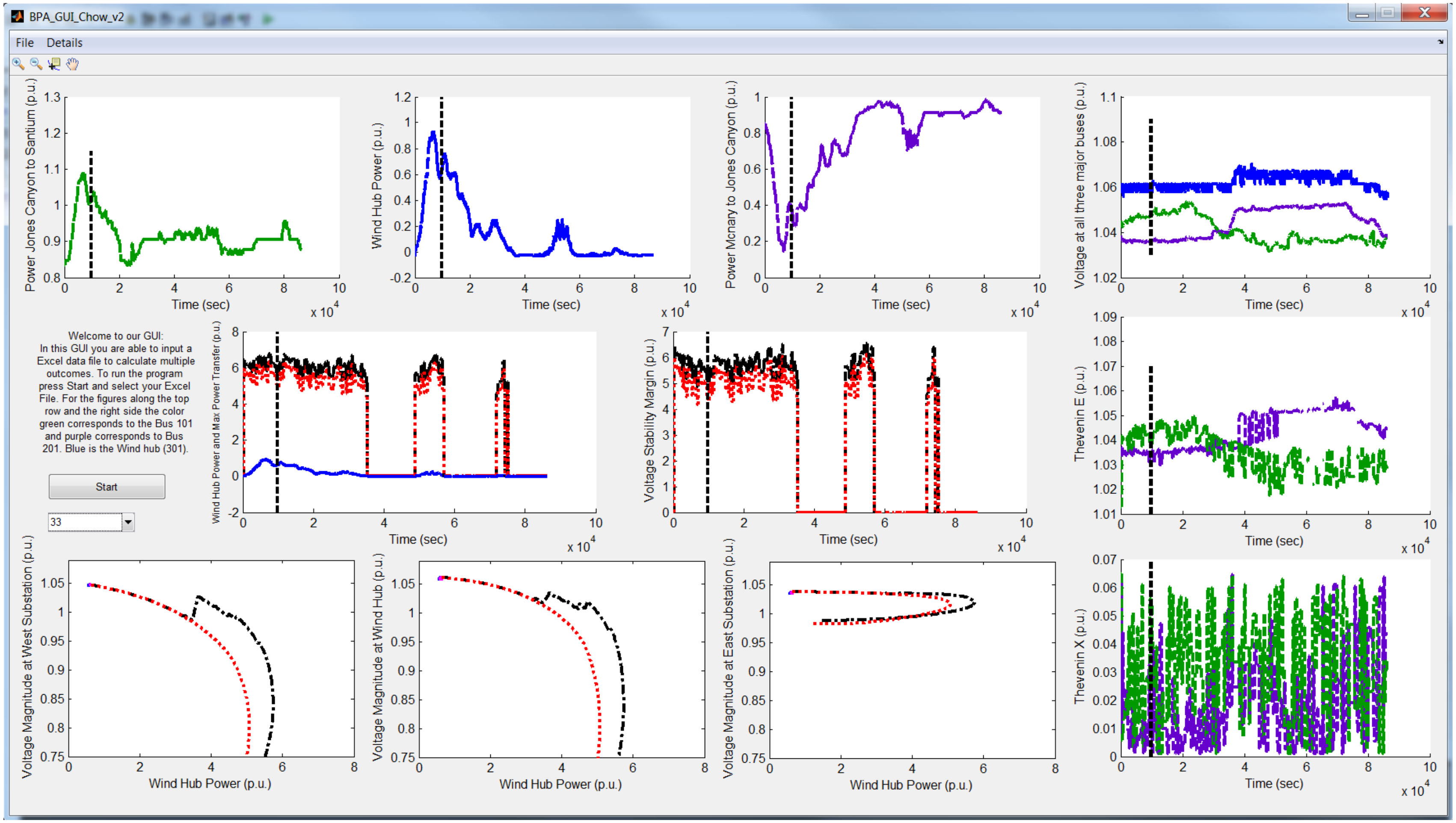

Figure 8. One-day voltage stability analysis for June 22, 2014

2.1 Observations on the Analysis Results

The VS analysis results seem to be quite reliable. The maximum power that can be delivered from the wind hub is about 650 MW, regardless of the loading condition on the two lines connecting to the East and West Buses.

The Thevenin equivalent voltage value tends to be quite steady, varying by one or two percent, but the Thevenin impedances tend to vary quite a bit. However, the impedance values are still quite a bit smaller than the impedances of the lines from the wind hub to the East Bus and the West Bus. The reasons for the time varying nature of the impedances are mostly due to:

1. Measurement noise, including quantization error in the wind hub voltage measurement
2. Steady voltage and power flow values that make it difficult to obtain sensitivities
3. Fast varying voltage and power flow values that induce nonlinear system behaviors, including wind turbine control systems and shunt capacitor bank switching.

Even though the Thevenin impedance value computed by the least-squares method shows significant variations, the analysis results still seem to be valid. In the future, it would be interesting to investigate more sophisticated algorithms such as the one proposed in [3].

3. Task 8: Real-time application strategies

The objective of Task 8 is to develop strategies for using the proposed voltage stability method in a real-time setting using PMU data collected by phasor data concentrator (PDC).

As mentioned earlier, the wind hub VS software (MATLAB code) will be provided to BPA for evaluation, which will be done on an off-line basis. The software has been applied to multiple days of the wind hub operation. Thus we expect the BPA engineer will be able to execute it without difficulties (like software crashes). We are committed to support the software during this evaluation phase, which may last beyond the completion date of the current project, as the graduate students who contributed to this effort are still studying for their PhD degrees.

Once the software has matured to the point that BPA would be interested to host it in real time, the following strategies can be considered:

1. Using streaming PMU data from the wind hub: In the BPA configuration, only data from Jones Canyon would be needed. Thus it would not require the use of a PDC, which collects PMU data from multiple substations. However, it is still convenient to host the real-time software on a PDC, as other similar types of wind hub operation may require additional PMU data other than the wind hub. In terms of the development effort, the VS software needs some input data streaming code.
2. Frequency of VS calculation: Currently the VS margin is calculated every 5 minutes. It is straightforward to change this time duration. The margin can be calculated more frequently, like every minute. The amount of data of for the Thevenin equivalent calculation can also be varied. For example, although the margin is calculated every minute, the Thevenin equivalent can be based on the most recent 5-minute data (or longer). The process can even be made adaptive, allowing the algorithm to use as much data as needed to obtain a consistent set of Thevenin voltage and impedance.

3. System status: The accuracy of the method can be improved if the shunt capacitor statuses are provided, which will help in the computation of the Thevenin equivalent.
4. Wind turbine control systems: It is contemplated that the VS margin can be made more accurate if some information of the wind turbine active and reactive power control modules are available.

4. Conclusions

In this combined report of 3 tasks, we have shown the results of applying a reliable method of computing the voltage stability related to a wind hub installed on the 230 kV BPA system. The software will be delivered to BPA shortly for evaluation on an off-line basis. This wind hub location is not unique to BPA. There are many other locations in the US power grid with wind hubs in median-level transmission systems. For the remaining part of the project, we will investigate a wind hub in the Southern California Edison service area. ERCOT also has shown an interest to work with us on voltage stability analysis.

References

[1] E. Heredia, D. Kosterev, and M. Donnelly, "Wind Hub Reactive Resource Coordination and Voltage Control Study by Sequence Power Flow," *2013 IEEE PES General Meeting*, July 2013.
[2] S. G. Ghiocel, J. H. Chow, R. Quint, D. Kosterev, and D. J. Sobajic, "Computing Measurement-Based Voltage Stability Margins for a Wind Power Hub using the *AQ*-Bus Method," presented at the Power and Energy Conference at Illinois (PECI), 2014.
[3] S. Corsi and G. N. Taranto, "A Real-Time Voltage Instability Identification Algorithm based on Local Phasor Measurements," *IEEE Transactions on Power Systems*, vol. 23, pp. 1271-1279, 2008.