SINGLE USER REAL-TIME DYNAMIC GEOMAGNETIC DISTURBANCE SIMULATIONS OF POWER SYSTEMS

A Thesis

by

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ABSTRACT

This thesis documents the process by which a single-user geomagnetic disturbance simulation scenario was designed. This includes modifications to the user interface designed to decrease human error factors such as change blindness and make the controls as intuitive and accessible as possible. It also shows the tools provided to the user during the simulation to help them operate the system such as frequency and voltage plots as well as voltage contours. Additions to the generator dynamics models including minimum power outputs and over-excitation limiters that are designed to make the case as realistic as possible are also discussed. The e-field inputs used to simulate the geomagnetic storm were taken directly from the North American Electric Reliability Corporation geomagnetic benchmark file. Finally, this thesis details the formulation of key performance metrics used to evaluate user performance, as well as associated visual representations. Some of these metrics are derived from the operational guide of the Electric Reliability Corporation of Texas and utilize the time series data of the system frequency and bus voltages. Other metrics include unserved load and generator MVAR reserve capacity. Finally, an evaluation from three different simulation runs, including a base case and an experienced operator case are included in the appendix along with the exact script used to calculate these metrics. As expected, the experienced operator had significantly better scores that the base case in which no control actions are taken before or during the geomagnetic disturbance event.

DEDICATION

I would like to dedicate this thesis to my grandparents, without whom I surely would not be here today. Thank you for advocating for me to go straight to a 4-year university, specifically Texas A&M, encouraging me to never settle and even to continue into a graduate program.

ACKNOWLEDGEMENTS

First, I would like to thank my committee members, Dr. K Davis, Dr. T. Davis, and Dr. Nevels for agreeing to be on my committee. I know everyone has busy schedules and I greatly appreciate your time.

Secondly, I would like to thank Komal Shetye for being the driving force behind the “rides” research group, as well as for providing the fundamental base 39-bus island case that I was able to build off of. I would also like to thank the other members of our research group for various guidance, and I would specifically like to thank Yijing Liu for her work on the TSR decoder that helps evaluate user performance.

Finally, and most importantly, I would like to thank my committee chair, Dr. Overbye for giving me this opportunity to join his group, it was a fantastic opportunity to continue working in the same area as my undergraduate thesis. This has been a great experience and much more fulfilling than the masters of engineering I was originally considering. I appreciate being given the flexibility to work on a less traditional thesis by working on these “ride” simulations. Hopefully they will continue to be used well into the future both for training data sets as well as inspiring the next generation of power system engineers and giving engineers a more “hands-on” experience than previously possible. This experience has taught me how to work with very diverse groups, greatly deepened my knowledge of power systems, as well as even given me some additional industry and life experience I never would have had otherwise and for that I am eternally grateful.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Tom Overbye, Professor Kate Davis, and Professor Robert Nevels of the Department of Electrical and Computer Engineering and Professor Tim Davis of the Department of Computer Science.

The base 42-bus case was provided by Komal Shetye and the software tools and support were provided by PowerWorld Corp and Professsor Tom Overbye. Geomagnetic Disturbance benchmark e-field directions and magnitudes were provided by the North American Reliability Corporation.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

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NOMENCLATURE

A	Amp
AC	Alternating Current
DC	Direct Current
DS	PowerWorld Dynamic Studio
E-field	Electric Field
GIC	Geomagnetically Induced Current
GMD	Geomagnetic Disturbance
NERC	North American Electric Reliability Corporation
PC	Personal Computer
PF	Power Factor
p.u.	per unit
RMSD	Root Mean Squared Deviation
RVC	Rapid Voltage Changes
SCADA	Supervisory Control and Data Acquisition
TSR	Transient Stability Results (file)
V	Volts
V/km	Volts per Kilometer

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1. INTRODUCTION

Geomagnetic disturbances (GMD's), which are often caused by solar flares, have the potential to create large quasi-DC currents in today's power systems. These currents especially impact transformers where they can cause excessive heating, as well as half cycle core saturation which can increase reactive losses [1]. While large GMD events are rare, studying them has become a major area of power system research, and regulations now require that utility companies study the effects such an event would have on their system [2]. Some utilities have procedural documents describing pre-emptive measures to take in the event of a GMD warning but very few people have ever gotten to experience operating a power system in real-time during a significant GMD event.

To solve this problem, a GMD scenario has now been developed for use in PowerWorld Dynamics Studio (DS). This will allow power engineers, students, and operators among others to get hands-on experience with GMD's. Using this fully dynamic simulation allows users to take actions in real-time during the event and then using logs of the simulation we can evaluate their performance after the fact. This allows us to compare their performance to previous runs to gauge learning curves and measure the effectiveness of new tools such as visual aids. Users implementing the pre-emptive actions described in untouched emergency procedures and reacting to voltage fluctuations and GIC current measurements during the event itself will give us valuable insight into what can be expected of human-in-the-loop systems during such an event.

In addition to the benefits for researchers, this simulation will help give users an intuitive feel for the controls available to them as well as the speed with which GMD's occur. Ideally with future implementations, this experience and intuition would help pull operator responses out of rule and knowledge-based behavior and perhaps more into the skill-based domain. While extensive training for these events may sound unrealistic given the infrequency of significant GMD's, with the help of space weather forecasts, targeted training sessions could make a real difference for operators if such a rare event were to occur.

The scenario developed here is not meant to model any real-world power system, nor is it intended to emulate any particular SCADA control system. Rather this case in particular is meant purely for informational, experimental, and educational purposes to expose first time users to all the control actions available to them in a typical power system. It is designed in such a way that anyone should be able to effectively interact with the system with minimal training on the software package itself.

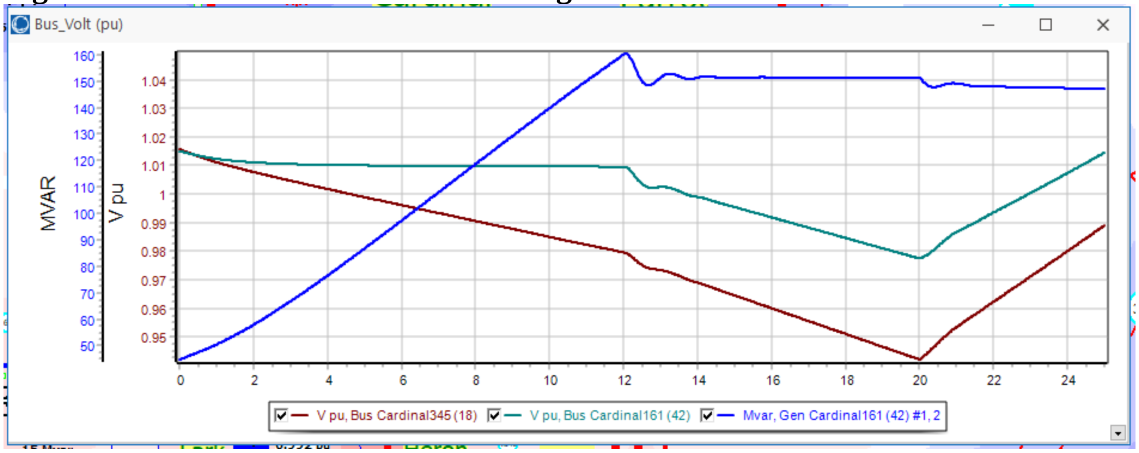
2. 39-BUS ISLAND CASE AND CONTROLS

The case used in this scenario is based off of a 39-bus “Island” case originally developed by Komal Shetye. The smaller size allows the simulation to run smoothly on most PC’s even those with relatively limited resources and can also be opened using the educational version of PowerWorld. To ensure realistic dynamic responses to the GMD scenario, over excitation limiters as well as more governor limits were added to the case. Additionally, to make this simulator as user friendly as possible and prevent the effects of change blindness associated with having to open a dialog box, more controls were added directly to the one-line. These include controls for transformer tap ratios, generator MW setpoints, as well as generator voltage setpoints. Finally, a series capacitor was added on one transmission line to demonstrate how these devices behave in a GMD event.

2.1. Governor and Over Excitation Limits

One of the main goals of this simulation is for the user to gain a better understanding of the issues that arise during a GMD event and how the pre-emptive measures can help mitigate those problems before they arise. A major one of these issues is the potential for a voltage collapse. In real life, system generators have upper limits to the reactive power they can supply, this limits their ability to regulate terminal voltages during a severe GMD event. This is demonstrated in Figure 2-1 using the Cardinal generator. In this case the limit was set at 150 MVAR, and for demonstration purposes a short time delay was used so the limit would be more strictly enforced. Approximately one second after the 150 MVAR limit is hit, the over-excitation limiter cuts in, this causes the bus voltage to eventually drop to 0.98 pu. Without these limiters in place the generator would produce unlimited MVAR’s and keep the terminal voltage constant under any severity of GMD event which is inaccurate. To prevent this, over excitation limiters were added to this dynamics case to emulate those limits set in PowerWorld and create limited reactive power reserves, these limits are also later used in the evaluation stage when calculating MVAR reserve capacity.

Figure 2-1: Cardinal Generator Reaching MVAR Limit



As mentioned earlier, part of the recommended preemptive actions for a GMD is bringing equipment that is out of service online if at all possible. In the case used here, the generator at Crow is initially offline for a “scheduled outage”. As part of the experience the user should put this generator into service to provide additional reactive power support/reserves. In practice many generators would never be run purely for reactive power support, rather they would have some minimum MW rating. These lower limits were already provided in the PowerWorld case, however these minimum ratings had not been accounted for in the dynamics system. To make the process of bringing generators on-line more realistic and make the PowerWorld and DS limits match up, min gate openings were added to the governors of these generators. Before these settings were added, closing the circuit breaker on a generator would bring that generator online but the MW output would stay at 0, now with the minimum gate values added, the DS will automatically ramp up the real power output of the generator to the minimum limit regardless of the MW setpoint. In practice, this means that the user will need to redispatch other units when bringing new units online to balance out load and generation to keep the system frequency in check. This helps to create a more realistic simulation and deepens the user experience significantly. It is important to note that droop control is enabled so the system will stay stable no matter what, however, frequency drift is accounted for in the user evaluation at the end so it is still important. Table 2-1 below lists all the generators in the system along with their min/max MW/MVAR setting in both PowerWorld and DS as well as their initial setpoints.

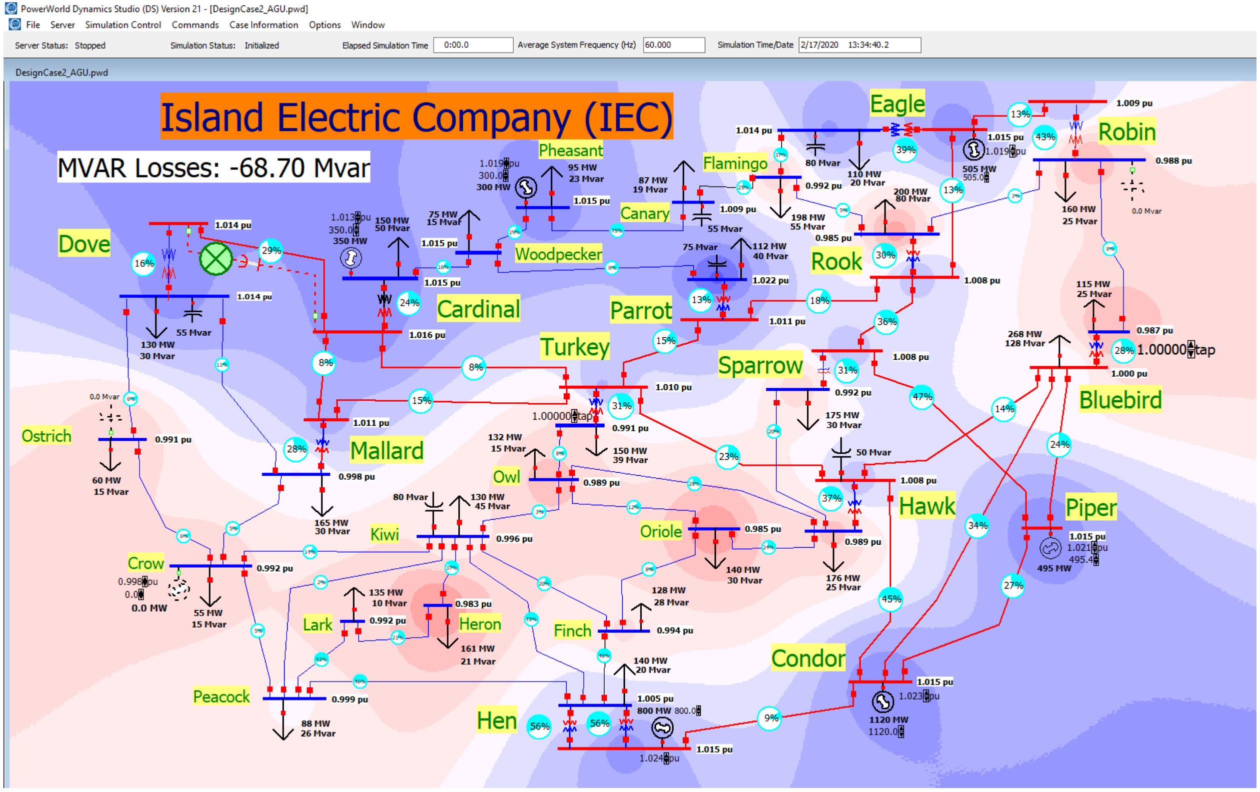
Table 2-1: Generator Properties

Generator:	**Crow**	**Hen**	**Condor**	**Piper**	**Eagle**	**Pheasant**	**Cardinal**
PW MW Max	800	800	1300	1350	700	450	350
DS MW Max	800	800	1400	1350	800	350	400
PW MW Min	300	300	300	0	0	0	0
DS MW Min	300	300	323	0	0	0	0
PW MVAR Max	350	350	600	600	250	180	150
DS MVAR Max	350	350	600	600	250	180	150
PW MVAR MIN	-250	-250	-300	-400	-280	-130	-198
Voltage Setpoint	N/A	1.024	1.023	1.021	1.019	1.019	1.013
MW Setpoint	0	800	1120	495	505	300	350
Initial State	Offline	Online	Online	Online	Online	Online	Online

2.2. User Controls

During the ride, the user has a wide range of controls available to them, both those that work as well as those that don't. These include: line switching, transformer switching, transformer tap changes, bringing generators on/off line, shunt switching, generator voltage and power set points, and the ability to shed load among others. Given the smaller size of this power system, all of these controls are available to the operator on the oneline, and for standard screen sizes no scrolling or zooming is required. This is important for two reasons. First, it makes controlling the case very intuitive, even to people that have never used PowerWorld. This allows people to focus on the task at hand rather than using significant cognitive resources just navigating the dialog boxes. Second and perhaps most importantly, putting all the controls on the oneline removes the potential for change blindness. Change blindness occurs when there is a disruption in the visual field causing large changes to go unnoticed. This is exactly what happens when a generator dialog box must be opened to adjust the voltage/MW set point or a table must be referenced to switch a shunt. Putting these controls on the oneline allows the users visual field to be uninterrupted during the control action and therefore it is easier for them to detect the effect of their control input on something like a voltage contour. The exact oneline used for this case is shown below.

Figure 2-2: Oneline with Initial Conditions



PowerWorld Dynamics Studio (DS) Version 21 - [DesignCase2_AGU.pwd]

Server Status: Stopped

Simulation Status: Initialized

Elapsed Simulation Time 0:00.0

Average System Frequency (Hz) 60.000

Simulation Time/Date 2/17/2020 13:34:40.2

DesignCase2_AGU.pwd

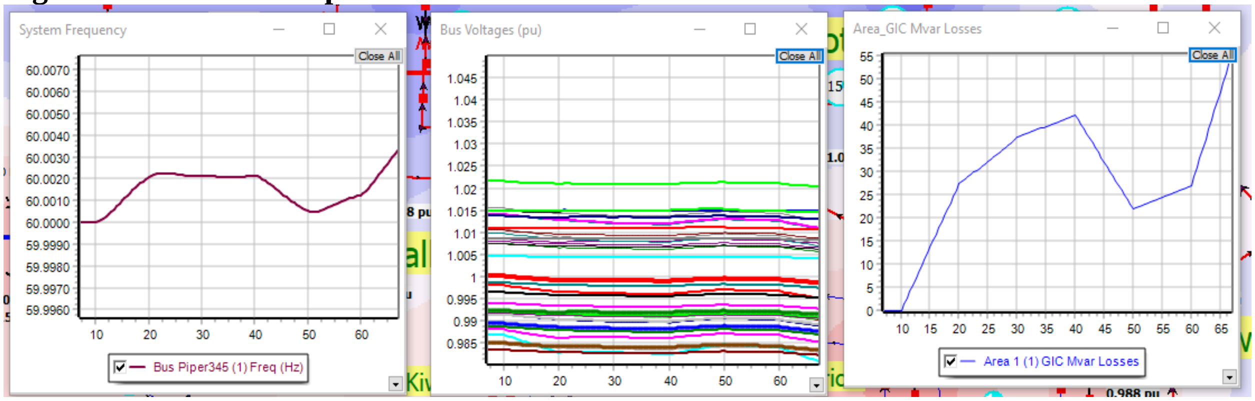
Island Electric Company (IEC)

MVAR Losses: -68.70 Mvar

2.3. User Tools

The default tools given to the user to operate this system consist primarily of the voltage contour seen in above in Figure 2-2, animated arrows showing the GICS flowing on the transmission lines/transformers and finally the three strip charts shown below in Figure 2-3. These strip charts show the system frequency, voltage profile of all the busses and the GIC related losses.

Figure 2-3: Default Strip Charts



The chart on the left, system frequency, should be used to balance system generation and load to keep the frequency near 60 Hz. Because there are no load changes (unless the user sheds load) this will primarily be used when generators are taken on or offline. The middle chart is a graph of all the bus voltages with the line thickness weighted proportionally from 1-4 based on the size of the load present at that bus. This is useful because in some of the final performance evaluations this load weighting is also taken into account. Finally, the chart of the right depicts the MVAR Losses associated with GIC's. This helps the user see the impact of various control elements, such as line switching, on these losses. More advanced users can access additional information such as individual generator MVAR output if they so choose and in the future additional graphic displays can be developed and their effectiveness evaluated using this case.

3. GEOMAGNETIC DISTURBANCE SCENARIO

The geomagnetic disturbance input in this scenario is modeled using a time varying series of voltage inputs. These were generated using the geographical coordinates of all the busses assuming a uniform electric field across the entire system. Given the size of this system this isn't a wild assumption, however if this is to be expanded to larger systems more complex modeling may be required. The magnitude and direction of the electric field used is taken directly from a contiguous segment of the NERC benchmark GMD scenario [2]. The simulation was designed to run for 16 minutes real time and includes the peak intensity from the benchmark scenario. For the purposes of this simulation the exact magnitude of the e-field in V/m was scaled somewhat from an 8 V/km peak to 13 V/km from the benchmark file but it remains a realistic example of how fast GMD's change both magnitude and direction. The magnitude and direction profile can be seen in Figures 3-1 and 3-2 below. Note linear interpolation is used between points.

Figure 3-1: GMD E-Field Voltage Magnitude

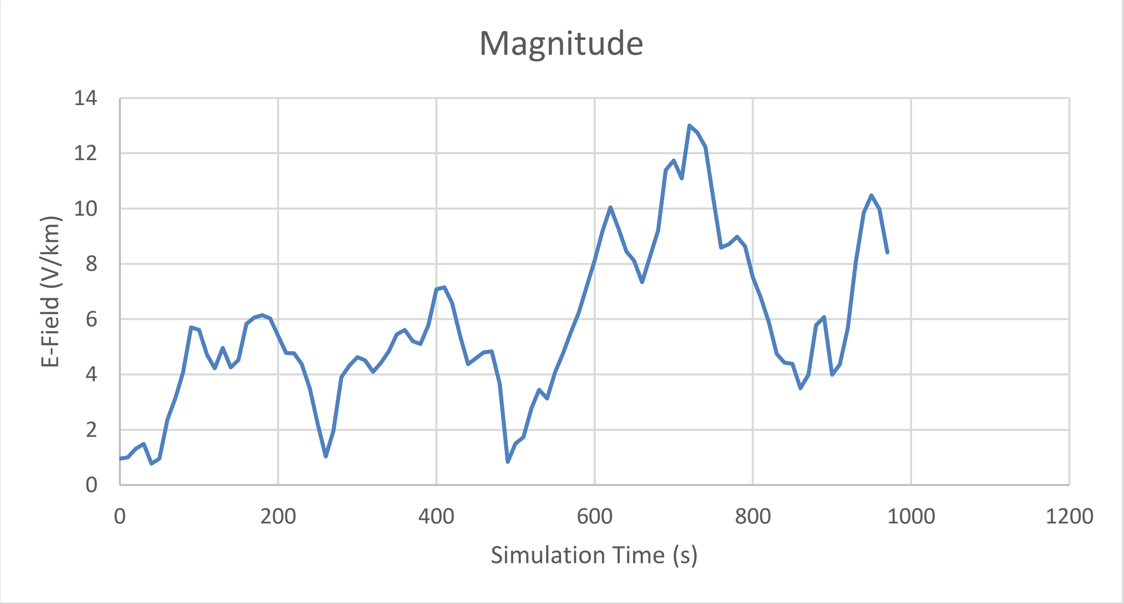
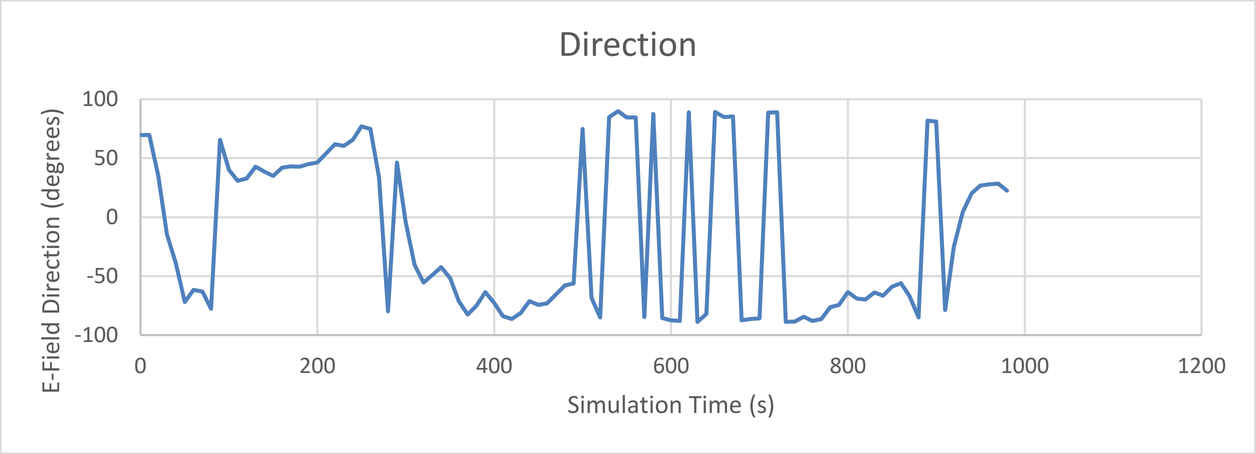


Figure 3-2: GMD E-Field Orientation



Figures 3-3 and 3-4 below show the case with and without any line switching at peak e-field intensity. In this case, switching one line reduced GIC losses by 72.73 MVAR.

Figure 3-3: Peak E-Field Voltage Contour without/with Line Switch

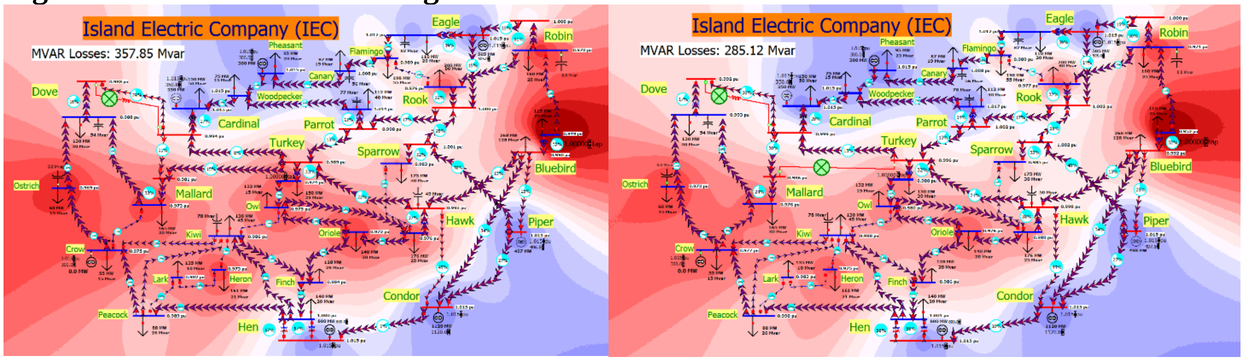
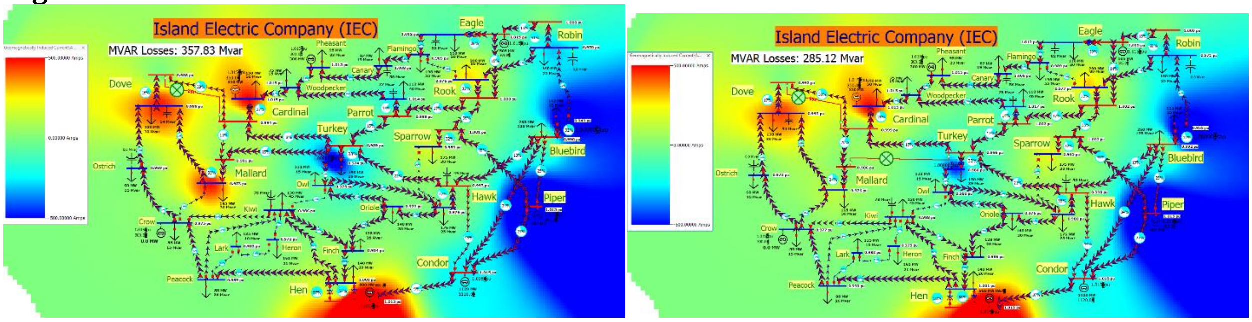


Figure 3-4: Peak E-Field GIC Contour without/with Line Switch



4. PERFORMANCE EVALUATION METRICS

4.1. Overview

Performance evaluation is a key part of this scenario. While in some cases the system may “blackout”, this only happened once during testing thus far. However just because a system did not blackout does not mean the user could not have done a “better” job of managing the system during the simulation. Luckily, PowerWorld allows the logging of system states throughout the simulation into a TSR file. In this case, the states are logged every 6 time steps or every 0.025 seconds of simulation time. These states can then be input into an algorithm designed to condense that information down into either one overall score or several specific scores such as an aggregate voltage profile. These metrics give the users a more accurate idea of how they performed compared to their peers as well as their own previous runs. These can also help when evaluating the effectiveness of any new operator tools or visual aids. Following the findings of Don Morrow, some of these metrics can be assessed using a penalty factor [3]. This penalty factor can be compared to other runs on the same case to give the user a more meaningful score such was which percentile of users they fall within. In this section, methods of evaluating different aspects of performance are discussed as well as other visual interpretations of that data that can be useful to the user.

4.2. Key Metrics

The key metrics that will be evaluated are things like: system frequency, bus/load voltage, MVAR reserves, and load shedding if applicable. Weighting these metrics appropriately as well quantitating the frequency of switching related ‘flicker’ or rapid voltage changes will also be evaluated. In addition to these, one metric that isn’t captured in the TSR file is whether the system is N-1 reliable. This becomes important because in some cases, disconnecting one transformer can drastically reduce system losses and improve the voltage profile, but depending on the generator dispatch this may create a system that is no longer N-1 reliable. To test this a contingency analysis can be run in PowerWorld with all the elements in their final state, but continuous evaluation of reliably will be left for future work.

4.2.1. System Frequency Metrics

The simplest metric to evaluate is the system frequency so we will start here. Since this system is relatively small, we are using the frequency of one of the central busses as an approximation of the average system frequency. From this we develop three metrics stemming from the ERCOT Nodal Operating Guide [4].

4.2.1.1.1. Time in Violation

The first metric focuses on the extreme frequency deviations outside of the designated operating range known as violations. For this metric, we really don't care what the exact frequency is, but rather the length of time it is outside of this acceptable range. Based on the ERCOT guide, 59.7 is the lowest frequency which Responsive Reserve Providers can set their under-frequency relays to drop load and 60.6 is the lowest allowable setting for automatic generator tripping [4]. Therefore 59.7-60.6 was chosen as the acceptable frequency range.

$$FrequencyTimeInViolation = (\#\ Frequency\ Samples < 59.7\ or > 60.6) * (0.025\ sec.)$$

4.2.1.1.2. Frequency Root Mean Squared Deviation

The second metric offers a more quantitative measure of the user's performance by accounting for all frequency deviations, even if they are not a violation. The nominal system voltage is 60 Hz and the RMSD formula is shown below. The RMSD will likely never be 0 in a GMD scenario, but the closer to 0 the better the user performed. Additionally, for more granularity the a FrequencyErrorSquared penalty factor is also calculated, however this is not normalized to the length of the simulation. It will be more useful when calculating performance percentile rankings for a specific scenario.

$$FrequencyRMSD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(60 - Frequency(i))^2}$$

$$FrequencyErrorSquared = \sum_{i=1}^{N}(60 - Frequency(i))^2$$

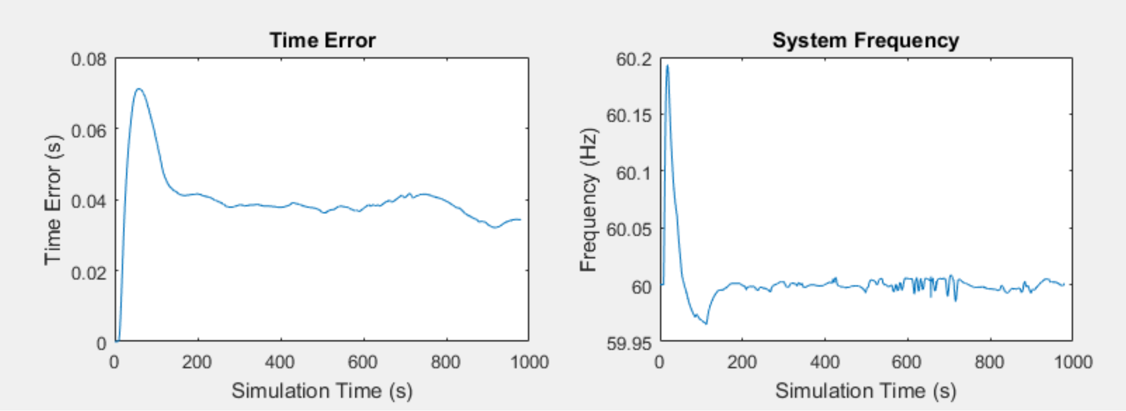
4.2.1.1.3. Time Error

The final frequency metric calculated is time error and is based on Section 2.2.9.1 of the ERCOT operational guide [4]. In practice it is integral of the frequency deviation and is equivalent to the time error that would occur on an analog clock connected to the power system in question. The limit of time error before ERCOT would make a correction is 30 secs [4]. This limit would never be reached in a 16-minute scenario like this one, however it still offers insight into how the user performed.

$$TimeError = \sum_{i=1}^{N}\frac{(Frequency(i) - 60)}{60} * 0.025 \ \ (seconds)$$

To give the user a visual feel for their frequency performance a plot of the frequency as well as the time error throughout the simulation is provided and can be seen in Figure 4-1 below.

Figure 4-1: Time Error and Frequency Plots Example



4.2.2. Bus Voltage Metrics

The metrics calculations on bus voltage deviations are similar to system frequency. However, since voltage magnitudes can vary significantly from bus to bus, not only must the algorithm iterate through the length of the simulation but also through each bus at every timestep to get an accurate picture of the system performance as a whole. Additionally, in one of the voltage deviation metrics the penalty factor is weighted by the amount of load at that bus. This takes into account of the customer impact of poor service quality.

4.2.2.1.1. Time in Violation

The first metric focuses on the extreme bus voltage violations which are outside of the designated operating range. For this metric, we really don't care what the exact voltage is, but rather the length of time it is outside of this acceptable range. Based on the ERCOT guide, Section 2.7.3 the typical voltage limits are 0.95 to 1.05 per unit [4]. The time in violation calculates the total time of violations in bus-seconds. In other words, if two busses our outside of their limit for 1 second the time in violation is 2 seconds. Again, in most cases there should be no violations.

$$VoltageTimeInViolation = (\#Bus\ Voltage\ Samples < 0.95\ or > 1.05) * (0.025\ sec.)$$

4.2.2.1.2. Voltage Root Mean Squared Deviation

The second metric offers a more quantitative measure of the user's performance by accounting for all voltage deviations, even if they are not a violation. The nominal system voltage is 1 pu and the RMSD formula is shown below. The RMSD will likely never be 0, but the closer to 0 the better the user performed. Additionally, for more granularity the WeightedVoltageErrorSquared penalty factor is also calculated. It factors in the amount of load at the bus when determining the bus voltage deviation penalty. This weighting factor ranges from 1-4 depending on the real power delivered at that bus. This metric is also not normalized and will be more useful when calculating performance percentile rankings for a specific scenario.

$$VoltageRMSD = \sqrt{\frac{1}{39 * N} \sum_{bus=1}^{39} \sum_{time=1}^{N} (1 - Voltage(bus, time))^2}$$

$$WeightedVoltageErrorSquared = \sum_{bus=1}^{39} \sum_{time=1}^{N} WeightFactor(bus, time) * (1 - Voltage(bus, time))^2$$

4.2.2.1.3. Voltage Flicker Metrics

The third voltage metric considered is called voltage flicker. This is a metric that can be used to evaluate the frequency of control inputs that cause rapid voltage changes (RVC's) such as the switching of transmission lines, transformers, and shunts. This is useful for a few reasons. First, frequent switching can decrease the life of system components and increase the probability of a fault or failure, so a good operator would minimize switching as much as possible. Secondly, and perhaps most visibly is the power quality concerns for customers. The ideal utility would always provide 1.0 pu voltage but beyond that most would agree that consistency is also important so a steady 1.02 is better than switching from 0.98 to 1.02 every two minutes. The larger the RVC the lower the acceptable frequency of such a change is and this can be seen in Figure 4-2 below taken from IEEE Std 1453-2015 which was originally developed by GE [5]. This standard also includes "Indicative planning levels for rapid voltage changes" which states the acceptable frequency of RVC's given their magnitude and can also be seen below in Table 4-1.

Figure 4-2: GE Flicker Curve [5]

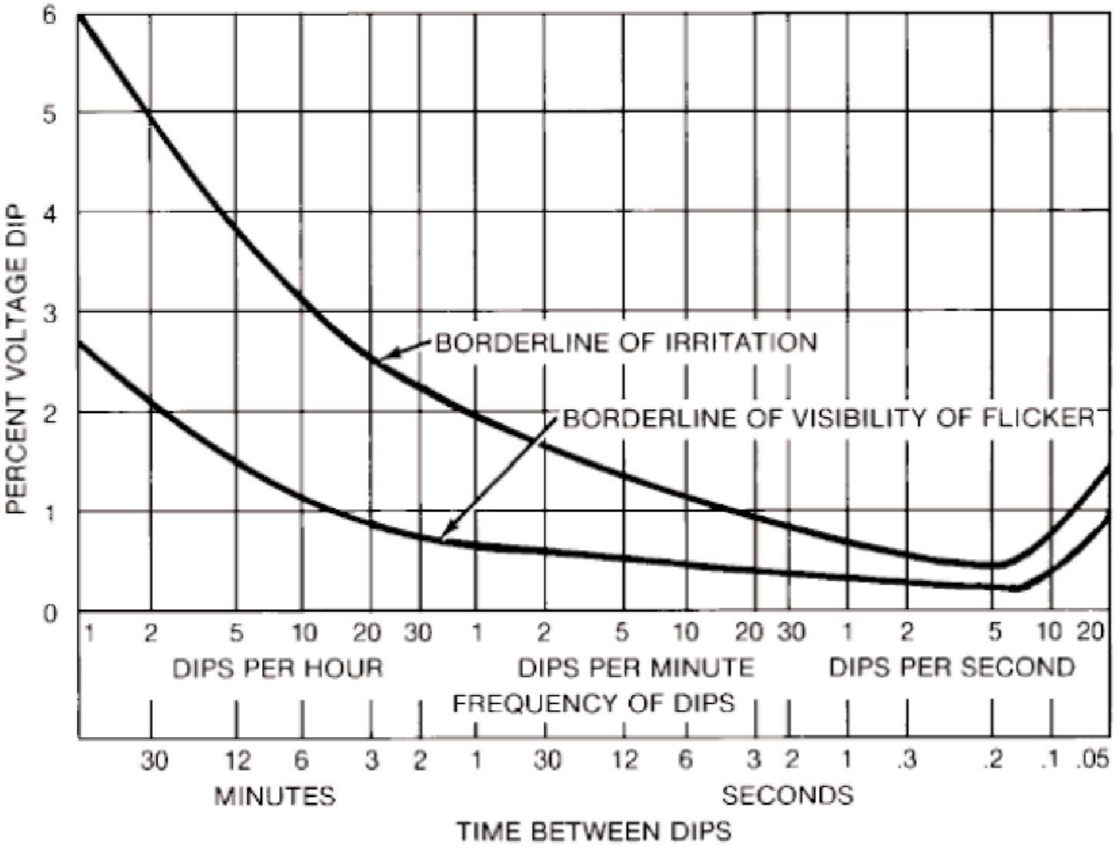


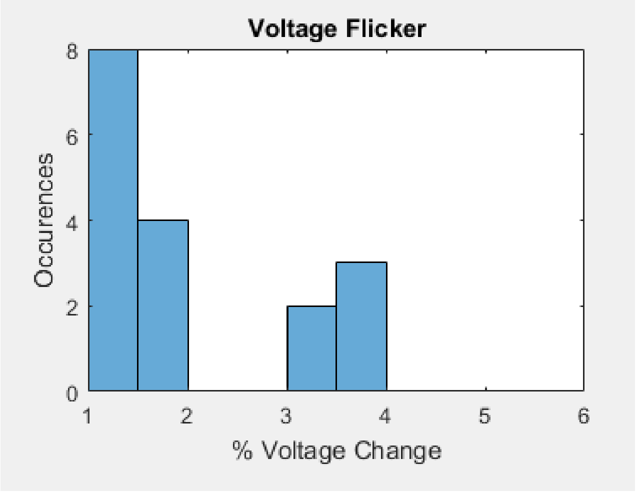
Table 4-1: Indicative Planning Levels for Rapid Voltage Changes (IEC 61000-3-7) [5]

Number of changes, N	ΔV/Vr (%)	
	MV	HV-EHV
N ≤ 4 per day	5–6	3–5
N ≤ 2 per hour	4	3
2 < N ≤ 10 per hour	3	2.5

To evaluate this flicker, each bus voltage measurement is compared to the last saved value, and if their difference (ΔV) is more than 1% it is logged. This data is then plot into a histogram to sort them by magnitude and act as a visual representation of how often they occurred. An example of this histogram can be seen below in Figure 4-3.

$$\Delta V = Voltage(bus, time) - Voltage(bus, time - 1)$$

Figure 4-3: Voltage Flicker Histogram Example



4.2.3. Load Shedding Metrics

This metric is relatively simple and should not be used all that often but is required to prevent the user from solving all their voltage problems by simply shedding load. This looks at the bus load status throughout the simulation and calculates the total load that goes unserved in kWh. In most cases this should be 0 because load shedding should always be a last resort.

$$UnservedLoad\ (kWh) = \sum_{i=1}^{N} OpenLoadAmountMW(i) * 0.025 \frac{1000}{60 * 60}$$

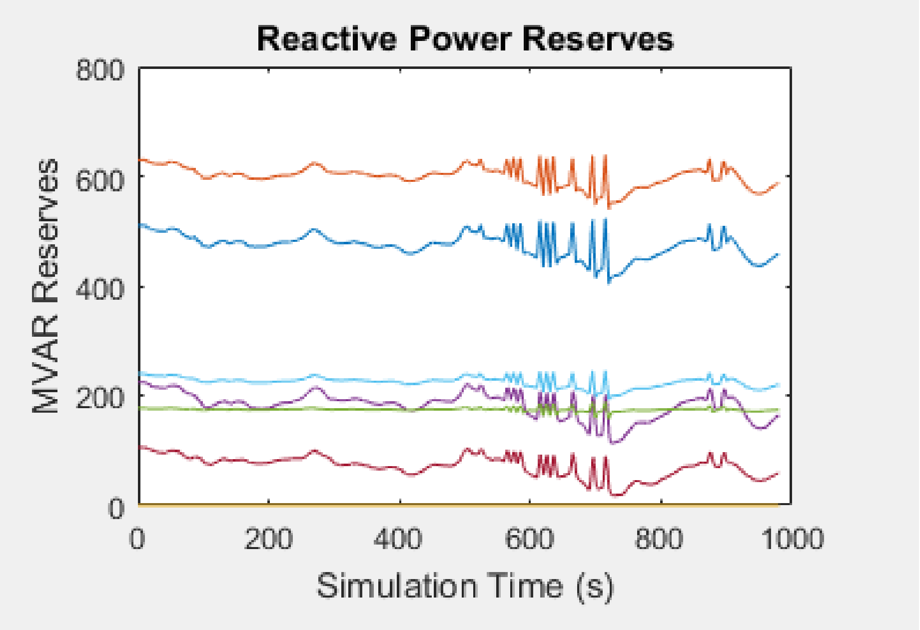
4.2.4. Generator MVAR Reserve Metrics

The final metric discussed here is the generator MVAR reserves. As seen earlier in Figure 2-1, when a generator hits it’s MVAR limits, it loses its ability to regulate its terminal voltage. Ideally a generator would not come near this limit, however, because of the increased MVAR losses during GMD’s this can become an issue if operators do not take the necessary preemptive measures such as bringing additional generation online and switching in additional capacitors. To evaluate this, the MVAR reserves of each generator are calculated throughout the simulation and eventually plotted as seen in Figure 4-4. In addition, a MVARTimeInViolation is also calculated, similar to what was done for frequency and voltage. This serves as an easy way to tell if and for how long the generators were operating within 15% of their MVAR limits.

$$\begin{aligned} GenMVARReserve \\ &= GenStatus(gen, time) * GenMVARLimit(gen) \\ &- GenMVAROutput(gen, time) \end{aligned}$$

$$MVARTimeInViolation = (\#of\ GenMVARReserves < 15\%\ of\ limit) * (0.025\ sec.)$$

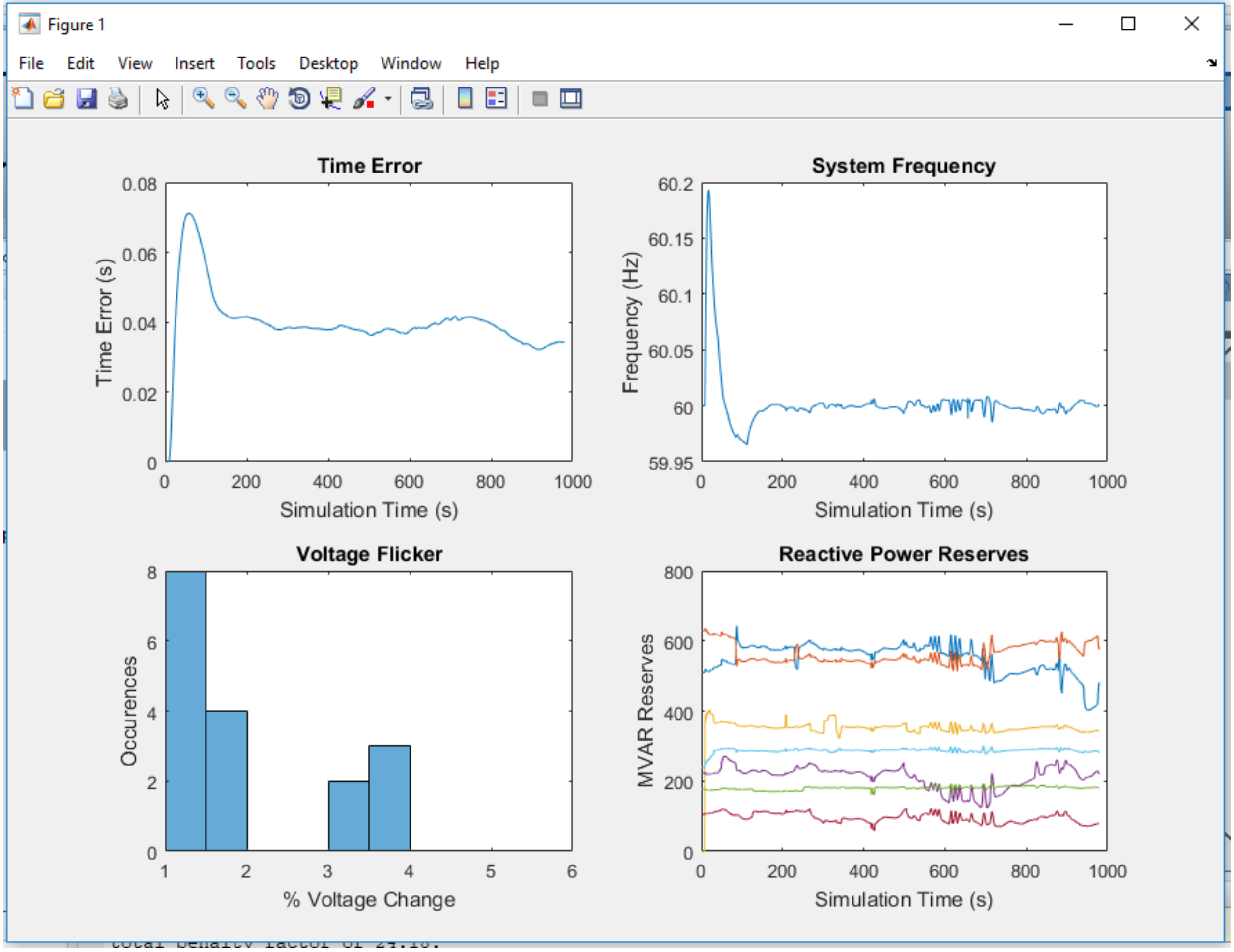
Figure 4-4: Generator Reactive Power Reserves Example (with violation)



4.2.5. Metrics Conclusion

These are the metrics that are currently used to evaluate user performance. Some will only be meaningful when compared to other users scores, while others, such as the violations, provide instant feedback as a rough gauge of how well a first-time user may have performed. In addition to the numerical metrics mentioned, some of the qualities can provide meaningful plots and examples of these can be seen in Figure 4-5 below. The MatLab code used to produce these metrics is included in Appendix A. As mentioned earlier, one final test that can be run is a contingency analysis of the system in its final state to test for N-1 reliability. This will help the user understand if any of their line switching actions that appeared to have helped actually made the system less reliable.

Figure 4-5: Evaluation Metric Graphs Example



5. EVALUATION METRIC RESULTS

Testing these evaluation metrics was done using three TSR files. The first is the Baseline results if no user action is taken, the second is an example of a typical “experienced operator”, in this case the author, and the last example is a test case that shows what happens if the only action taken is some load shedding early on in the simulation. A summary of these results is shown in Table 5-1 below. The exact output script can be seen in Appendix B through D.

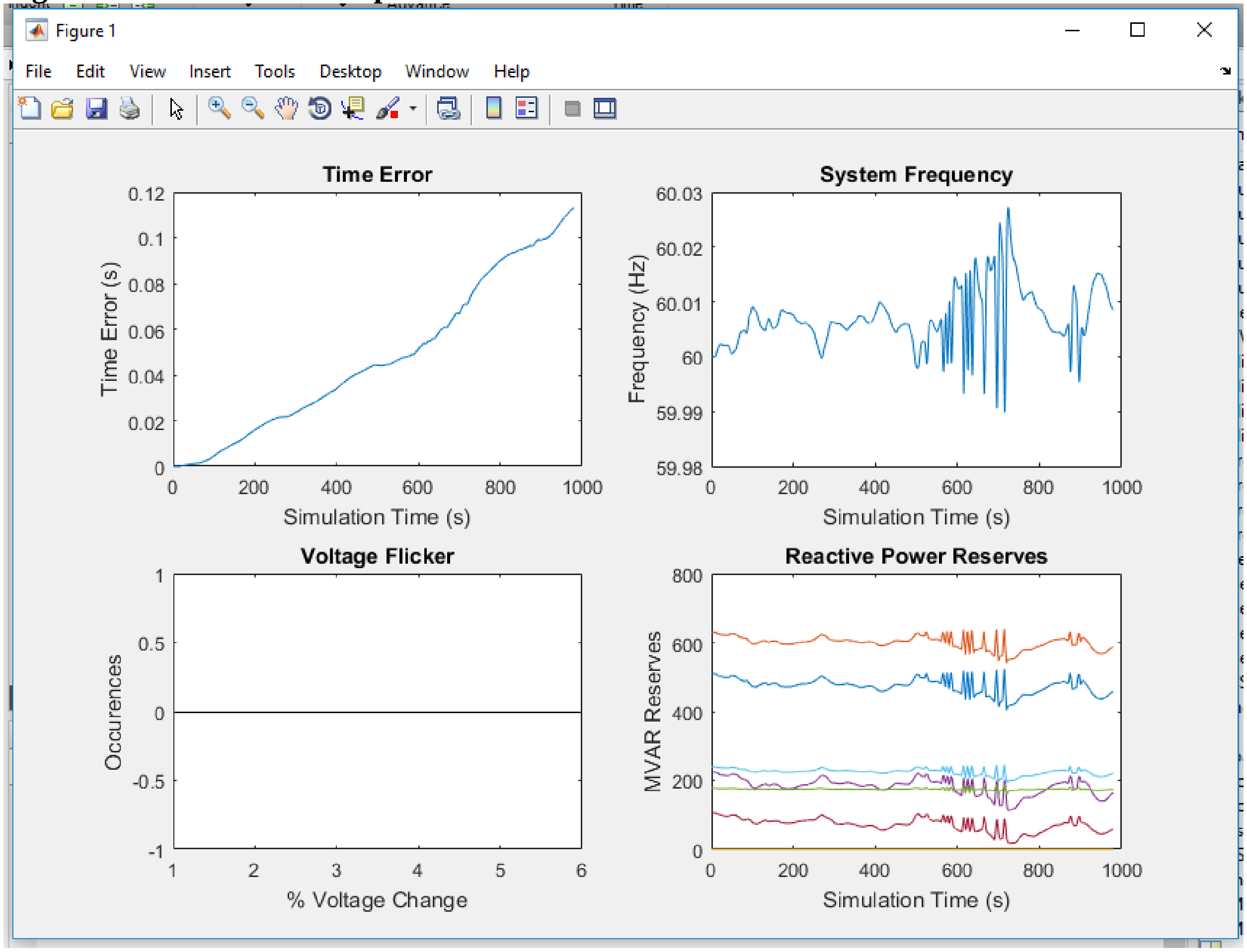
Table 5-1: Evaluation Metrics Results Summary

Metric	Baseline	Experienced Operator	Load Shedding
Frequency RMSD (Hz)	0.01	0.02	0.14
Frequency Penalty	2.94	24.18	780.85
Frequency Violations (secs)	0	0	0
Time Error	0.11	0.04	2.2
Bus Voltage RMSD (pu)	0.01	0.01	0.01
Load-Weighted Bus Voltage Penalty	559.14	252.88	456.68
Voltage Violations (secs)	67.23	0	29.25
Total Voltage Flicker	0	17	9
Unserved Load (kWh)	0	0	53,792
MVAR Limit Violations (secs)	20.90	0	19.27

5.1. Baseline Results

As expected, the bus voltage penalty for the baseline case in which no control actions were performed is the highest of the three files. Additionally, there are both voltage violations and MVAR limit violations. These are beneficial because they prove that control actions must be taken during the simulation to avoid these violations. Additionally, this is the only case in which no switching-related RVC’s or flicker events were recorded. This makes sense because no control actions were taken so all voltage changes would’ve been gradual from the GMD event and not met the criteria to be counted in the voltage flicker histogram shown in Figure 5-1.

Figure 5-1: Evaluation Graphs Baseline

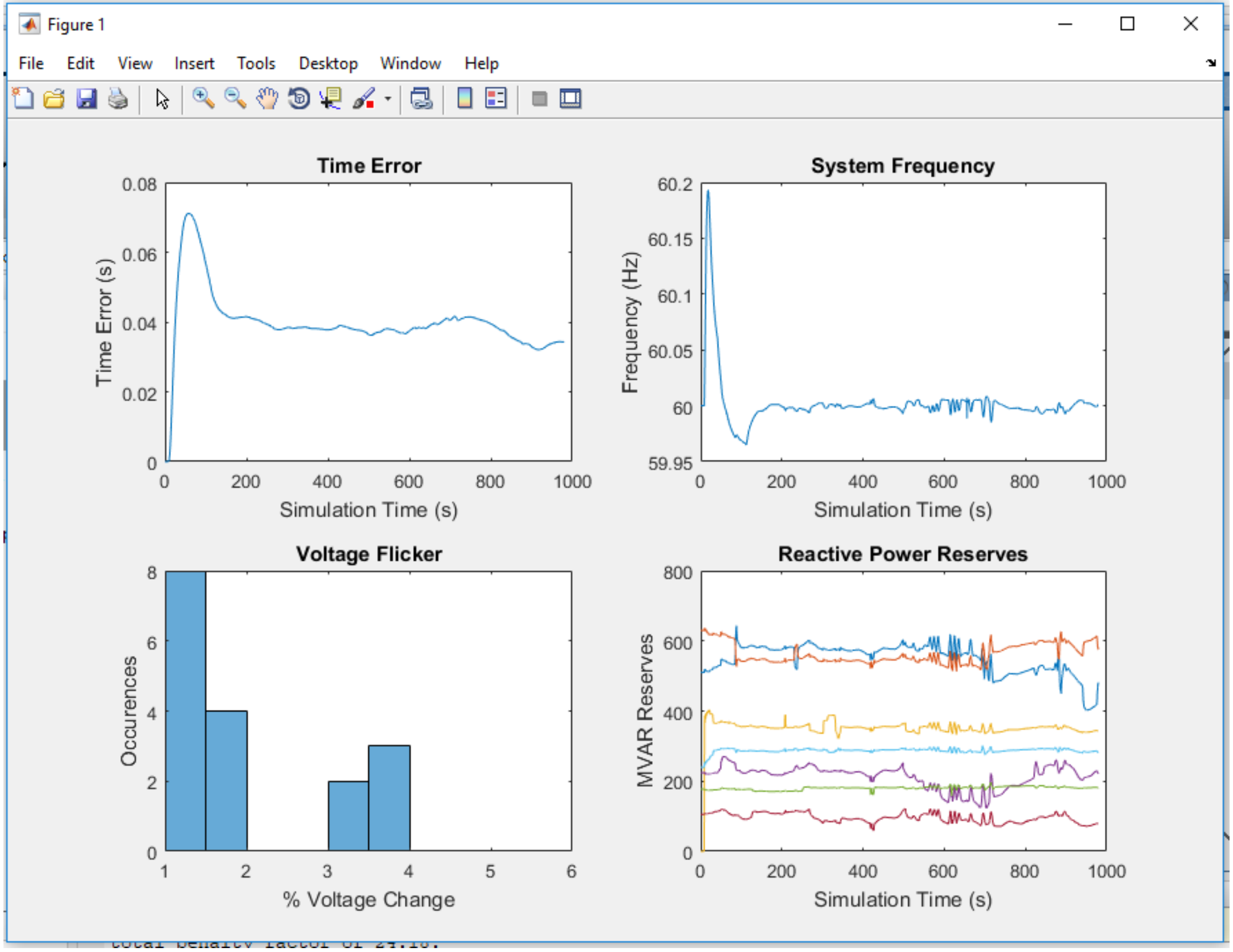


It can also be seen why there are MVAR violations. It is clear that one of the generators reactive power reserves nears 0 around 700 seconds and this is near the peak of the GMD storm. The Reactive Power Reserves graph is very useful, and while not currently possible, a similar graph updating in real-time throughout the simulation experience would likely be very beneficial to the operator as an added visual aid.

5.2. Experienced Operator Results

The experienced operator results are also very pleasing. In this case there were no violations which proves this is an attainable goal. Additionally, the voltage penalty factor was reduced by over 50%. This was all done without shedding any load which can be seen from the Unserved Load statistic. This case also provides a good example of what the voltage flicker histogram would typically look like and can be seen in Figure 5-2.

Figure 5-2: Evaluation Graphs Experienced Operator

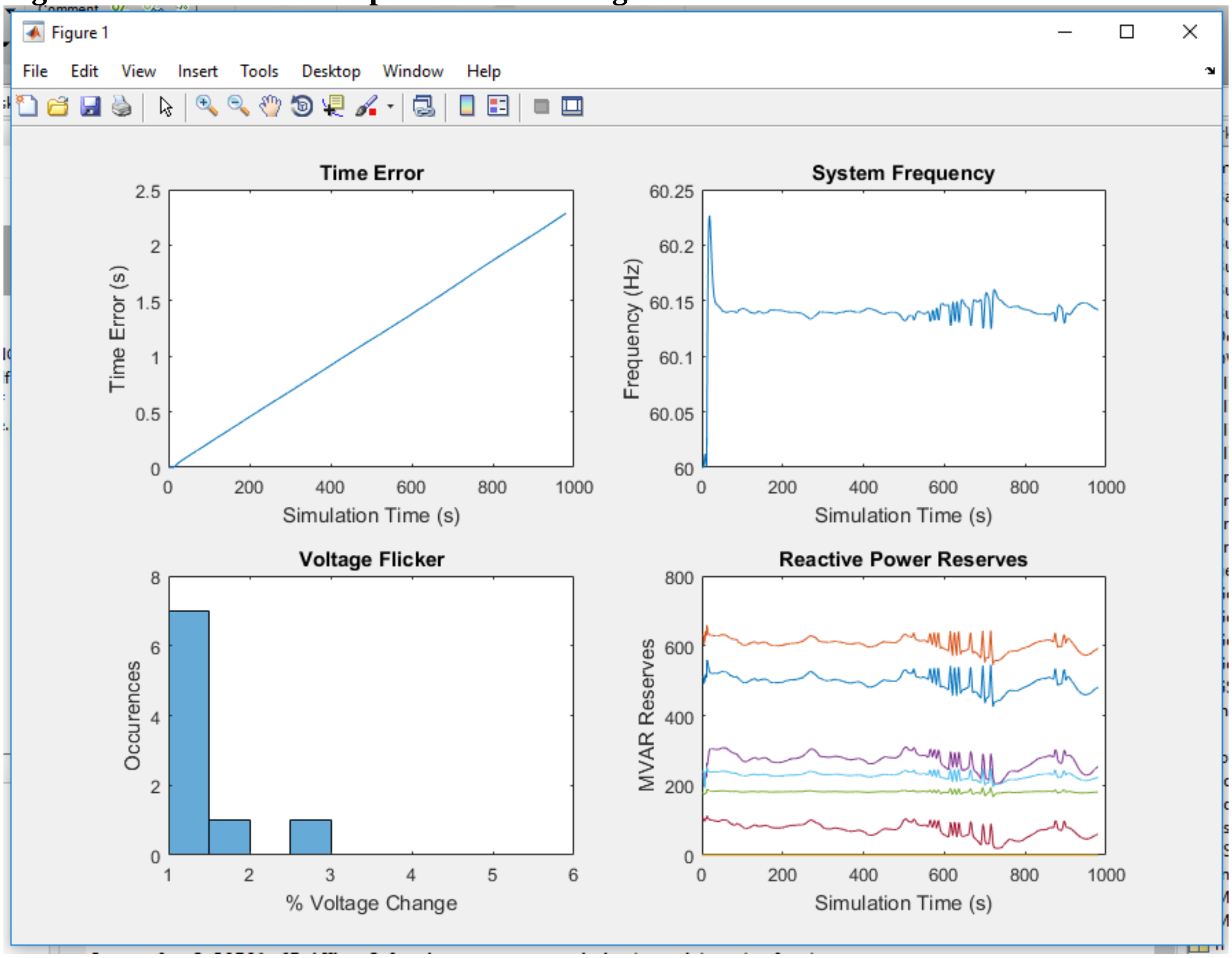


The initial spike in system frequency was the result of bringing one of the offline generators online, but this was corrected by adjusting the setpoints of the other generators. The reactive support provided by this additional generator is seen in yellow. These additional reserves are what help prevent the MVAR violations seen in the baseline results above.

5.3. Load Shedding Results

The final TSR file evaluated was a case in which 200 MW of load was shed early on in the simulation with very few other control actions. As expected, this significantly reduced the voltage violations, however it makes this the only case to have unserved load, approximately 50MWh in this case. This is also the case with the largest frequency penalty and this is due to there being no generator re-dispatch after the load is shed. This causes the frequency to settle to a higher value once droop control takes effect. This can be seen below in Figure 5-3. The total flicker is also lower because throughout most of the simulation no control actions are taken.

Figure 5-3: Evaluation Graphs Load Shedding



5.4. Percentile Ranking

While the goal of having no violations is a good goal for first time users, distinguishing between violation free results is more challenging. Effectively comparing these results is what will allow us to evaluate learning curves as well as quantitate the effectiveness of new operator displays and tools. Once we get a substantial library of TSR files, we can add additional metrics such as performance percentile rank similar to what is used on SAT scores. This will give users and researchers a better feel for how someone performed in relation to their peers. This percentile rankings could also be divided into categories such as first-time operators, experienced operators, and all operators to allow for a fair evaluation. Analyzing the apparent trade-off between the different penalty factors and metrics like voltage flicker will make it easier to develop a single overall user performance score later on that is an aggregate of the current metrics.

6. CONCLUSION

This scenario gives users the one-of-a-kind experience of operating a power system during a GMD event that even most real-life operators will likely never get to experience. It allows users to get a more intuitive feel for all the controls available to them and learn for themselves what works and what doesn’t via the innately human method of trial and error. It also gives them a chance to gain familiarity with procedural documentation including what pre-emptive measures to take in the event of an advanced GMD warning. They can see for themselves what all is involved in implementing those changes and what can happen if those measures are not taken in advance.

The evaluation metrics provide a good source of feedback to the user. These metrics can be used to effectively compare the system performance between multiple runs. This allows users to “compete” against themselves and other users making the simulation more engaging and interactive. In addition, perhaps the most valuable usage of these performance metrics will be to evaluate the effectiveness of changes to the user interface as well as the tools provided to them.

The ultimate goal would be to expand these simulations to larger systems which would allow for multi-user scenarios. This would help better explore and study the fast communication and coordination required during a real-life large GMD event. Other things to consider for longer more realistic simulations would be non-uniform electric fields and earth resistivity models as well as the addition of time varying loads and more accurate load dynamics models.

REFERENCES

[1] V. D. Albertson, J. M. Thorson, Jr., R. E. Clayton, and S. C. Tripathy, “Solar-induced-currents in power systems: Cause and effects,” IEEE Trans. Power App. Syst., vol. PAS-92, no. 2, pp. 471–477, Mar./Apr. 1973.

[2] *Transmission System Planned Performance for Geomagnetic Disturbance Events*, North American Electric Reliability Corporation TPL-007-1, 2020.

[3] D. J. Morrow, “Use of Penalty Factors to assess Reliability-Related Performance when Simulating Power Systems”, 2020.

[4] *ERCOT Nodal Operating Guide*, 2019.

[5] *IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems*, IEEE Std 1453-2015, 2015.

APPENDIX A

MATLAB TSR EVALUATION CODE

```
%Matthew Gaskamp
%TSR GMD Ride Evaluation Metrics
%39-Bus Island Case
clc; clear all;

%Import Data from CSV File
BaseLineData = csvread('GMD Ride_BaseCase.csv', 2,4);
[m,n]= size(BaseLineData);

%Frequency Control Evaluation
FrequencyTimeInViolation=0;
FrequencyErrorSquared=0;
FrequencyRMSD=0;
TimeErrorSeconds=0;
Time=0.025:0.025:980;

    %Pull Central Bus (#43) Frequency Data
    SystemFrequency=BaseLineData(537,:);

    %Iterate through File
    for x=1:(length(SystemFrequency)-1)
        Frequency=SystemFrequency(x);

        %Count Violations
        if (Frequency <= 59.7 || Frequency >= 60.3)
            FrequencyTimeInViolation=FrequencyTimeInViolation+0.025;
        end

        %Sum Of Error Squared and RMS

        FrequencyErrorSquared = FrequencyErrorSquared
+(Frequency-60)^2;
        FrequencyRMSD= FrequencyRMSD + ((Frequency-60)^2);

        %Time Error
        TimeErrorSeconds=TimeErrorSeconds+((Frequency-60)/60*0.025);
        TimeErrorPlot(x)=TimeErrorSeconds;

    end

    %Calculate and Print Frequency RMSD
    FrequencyRMSD=sqrt(FrequencyRMSD/(length(SystemFrequency)-1));
    fprintf('The Frequency Root Mean Squared Deviation was
 %2.2f with a \ntotal penalty factor of %2.2f.\n',FrequencyRMSD,
 FrequencyErrorSquared)

    %Print Frequency Violations
    if FrequencyTimeInViolation==0
            fprintf('No Frequency Violations, Well Done \n')
        else fprintf('System Frequency was in violation for %2.2f
 seconds.\n',FrequencyTimeInViolation);
    end
```

```
    %Format and Display Plots
    subplot(2,2,1)
    plot(Time,TimeErrorPlot(1:39200))
    xlabel('Simulation Time (s)');
    ylabel('Time Error (s)');
    title('Time Error');
    subplot(2,2,2)
    plot(Time, SystemFrequency(1:39200))
    xlabel('Simulation Time (s)');
    ylabel('Frequency (Hz)');
    title('System Frequency');


%Voltage Deviations
    BusV=0;
    BusVoltages=0;
    BusWeights=0;
    BusWeight=0;
    x=1;

    %Iterate Through File
    for bus=154:10:534
        if x==1
            BusVoltages=BaseLineData(bus,:);
            BusWeights=BaseLineData(bus+6,:)+1;
        else
            BusV= BaseLineData(bus,:);
            BusVoltages=vertcat(BusVoltages, BusV);
            BusWeight=BaseLineData(bus+6,:)+1;
            BusWeights=vertcat(BusWeights, BusWeight);
        end
    x=x+1;
    end

    VoltageTimeInViolation=0;
    WeightedVoltageErrorSquared=0;
    VoltageErrorSquared=0;
    Flicker1to2=0;
    Flicker2to3=0;
    Flicker3to4=0;
    Flicker4=0;
    index=1;
    DV=0;
    DeltaV=0;
    for bus=1:39
        for time=1:length(BusV)-1
  %Weighted Time of Violations
     if (BusVoltages(bus,time) <= 0.95 || BusVoltages(bus,time) >=
 1.05)
            VoltageTimeInViolation=VoltageTimeInViolation
+BusWeights(bus,time)*0.025;
     end
  %Summation of Weighted Square Error
```

```
  WeightedVoltageErrorSquared= WeightedVoltageErrorSquared+((1-
BusVoltages(bus,time))^2)*BusWeights(bus,time);
  VoltageErrorSquared=VoltageErrorSquared+(1-BusVoltages(bus,time))^2;

  % Voltage Flicker Assesment
  if (time > 1)
      DV=(BusVoltages(bus,time)-BusVoltages(bus,time-1));

       if DV >0.01 && DV<0.02
          Flicker1to2=Flicker1to2+1;
        end
       if DV >0.02 && DV<0.03
          Flicker2to3=Flicker2to3+1;
       end
       if DV >0.03 && DV<0.04
          Flicker3to4=Flicker3to4+1;
       end
       if DV >0.04
          Flicker4=Flicker4+1;
       end

      if DV> 0.005
      DeltaV(index)=DV;
      index=index+1;
      end

  end
        end
    end

    %Calculate and Print Voltage RMSD and Total Weighted Voltage
 Penalty
    VoltageRMSD=sqrt(VoltageErrorSquared/((length(BusV)-1)*39));
    fprintf('\nThe Bus Voltage Root Mean Squared Deviation was %2.2f
 with a \ntotal load-weighted penalty factor of %2.2f.\n',VoltageRMSD,
 WeightedVoltageErrorSquared)


 %Create Histogram of Step Voltage Changes by %
 DeltaV=DeltaV*100;
    subplot(2,2,3)
    histogram(DeltaV,[1,1.5,2,2.5,3,3.5,4,4.5,5,5.5,6]);
    ylabel('Occurences')
    xlabel('% Voltage Change')
    title('Voltage Flicker')

    if VoltageTimeInViolation==0
            fprintf('No Voltage Violations, Well Done \n\n')
        else fprintf('The system had voltage violations for %2.2f bus-
seconds.\n\n',VoltageTimeInViolation);
        end

   % Load Shedding Metrics
   LoadStatus=0;
```

```
   Load=0;
   x=1;
   L=0;
   Ls=0;
    for load=554:9:779
        if x==1
            Load=BaseLineData(load,:);
            LoadStatus=BaseLineData(load+6,:);
         else
            L= BaseLineData(load,:);
            Load=vertcat(Load, L);
            LS=BaseLineData(load+6,:);
            LoadStatus=vertcat(LoadStatus, LS);
        end
       x=x+1;
    end
UnservedLoadkWh=0;
%Calculate Unserved Load
 for load=1:26
        for time=1:length(L)-1
    if LoadStatus(load,time)== 0

        UnservedLoadkWh=UnservedLoadkWh+Load(load,1)*0.025/
(60*60)*100*1000;
    end
        end
 end
 %Print Unserved Load Metrics
   if UnservedLoadkWh==0
            fprintf('No Load was shed during this simulation., Well
 Done \n')
        else fprintf('A total of %2.2f kWh of load went unserved
 during this simulation.\n',UnservedLoadkWh);
        end


 %MVAR Reserves
 GenMVARLimits=[6;6;3.5;2.5;1.8;3.5;1.5];
 gen=0;
 GenMVAR=0;
 GenStatus=0;
 x=1;

 %Pull Generator MVAR Output Data
  for gen=7:19:121
        if x==1
            GenMVAR=BaseLineData(gen,:);
            GenStatus=BaseLineData(gen+9,:);
         else
            MVAR= BaseLineData(gen,:);
            GenMVAR=vertcat(GenMVAR, MVAR);
            GS=BaseLineData(gen+9,:);
            GenStatus=vertcat(GenStatus, GS);
        end
```

```
       x=x+1;
  end
  % Calculate MVAR Reserves at Each Generator
  for time=1:length(GS)-1
       for gen=1:7
               if time ==1

              if GenStatus(gen,time) == 1 %Check to see if generator
 is on-line
  GenMVARReserve(gen,time)=(GenMVARLimits(gen)-GenMVAR(gen,time));
              else
                  GenMVARReserve(gen,time)=0;
              end


               else
          if GenStatus(gen,time)==1 %Check to see if generator is on-
line
          GenMVARReserve(gen,time)=(GenMVARLimits(gen) -
 GenMVAR(gen,time));
          else
              GenMVARReserve(gen,time)=0;
          end
      end
     end
  end

  %Plot MVAR reserves at each generator for duration of simulation
  GenMVARReserve=GenMVARReserve*100;
   subplot(2,2,4)
    plot(Time, GenMVARReserve(:,1:39200));
    ylabel('MVAR Reserves')
    xlabel('Simulation Time (s)')
    title('Reactive Power Reserves')

  violationpercentage=15;
  percentMVAR=GenMVARLimits*100*violationpercentage/100;
  MVARTimeInViolation=0;
  %Time in MVAR Violations
  for gen=1:7
        for time=1:length(GS)-1
            if GenStatus(gen,time)==1
     if (GenMVARReserve(gen,time) < percentMVAR(gen))
            MVARTimeInViolation=MVARTimeInViolation+0.025;
     end
            end
        end
  end

  %Print MVAR Violation Time
  fprintf('\nGenerators were within %2.0f percent of their
 MVAR limits for %2.2f Generator-Seconds',violationpercentage,
 MVARTimeInViolation);
```

APPENDIX B

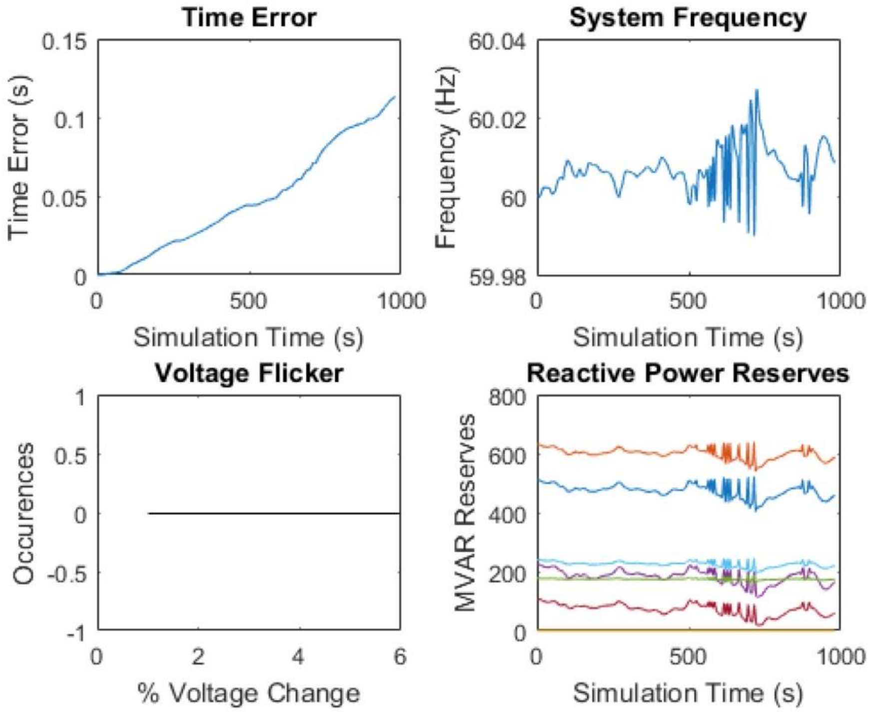
BASELINE EVALUATION RESULTS

```
The Frequency Root Mean Squared Deviation was 0.01 with a
total penalty factor of 2.94.
No Frequency Violations, Well Done

The Bus Voltage Root Mean Squared Deviation was 0.01 with a
total load-weighted penalty factor of 559.14.
The system had voltage violations for 67.23 bus-seconds.

No Load was shed during this simulation., Well Done

Generators were within 15 percent of their MVAR limits for 20.90
 Generator-Seconds
```



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APPENDIX C

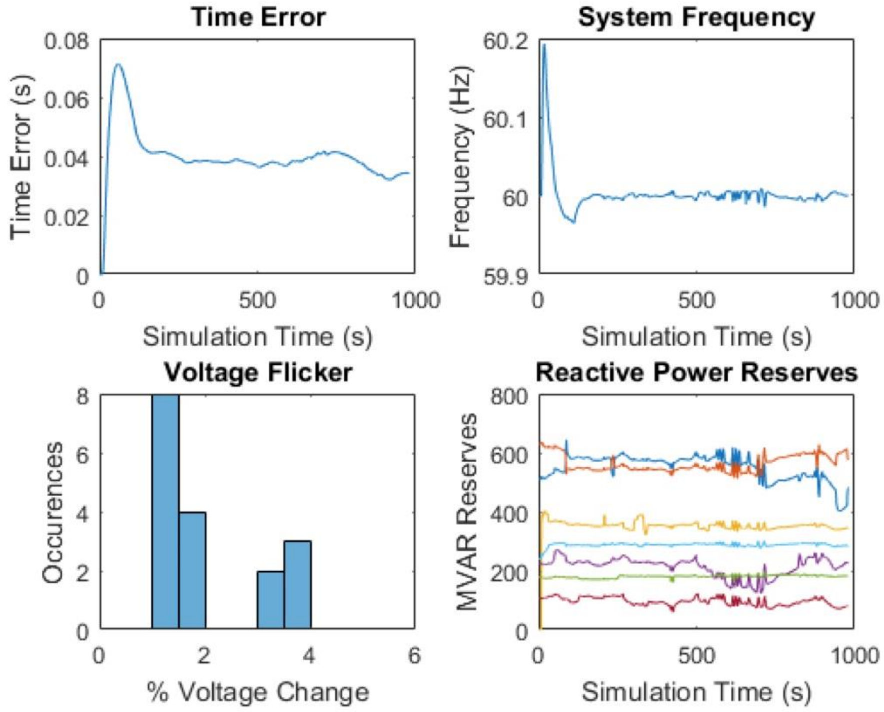
TYPICAL EXPERIENCED OPERATOR EVALUATION RESULTS

```
The Frequency Root Mean Squared Deviation was 0.02 with a
total penalty factor of 24.18.
No Frequency Violations, Well Done

The Bus Voltage Root Mean Squared Deviation was 0.01 with a
total load-weighted penalty factor of 252.88.
No Voltage Violations, Well Done

No Load was shed during this simulation., Well Done

Generators were within 15 percent of their MVAR limits for 0.00
 Generator-Seconds
```



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APPENDIX D

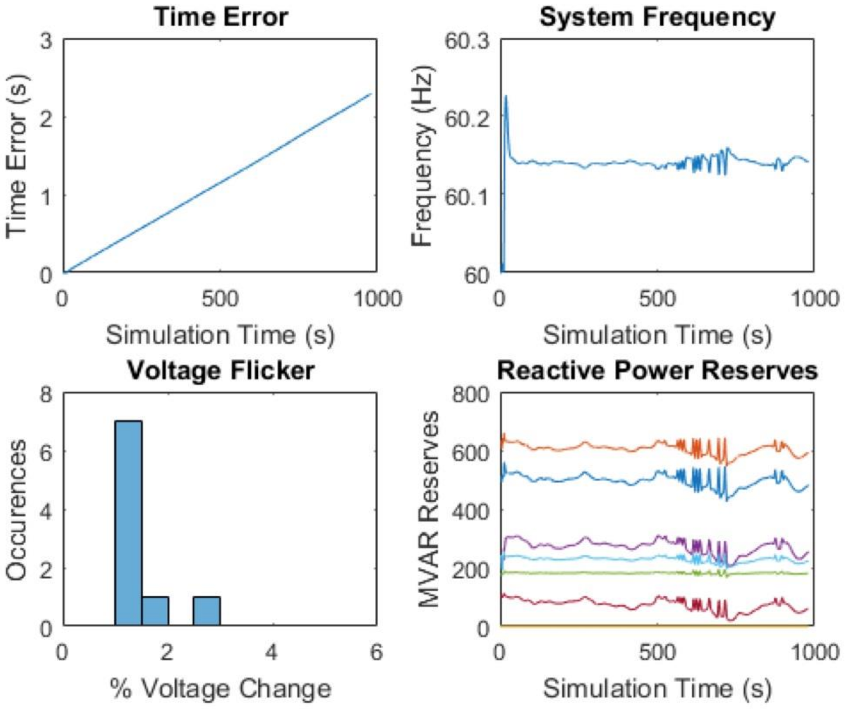
LOAD SHED EXAMPLE EVALUATION RESULTS

```
The Frequency Root Mean Squared Deviation was 0.14 with a
total penalty factor of 780.85.
No Frequency Violations, Well Done

The Bus Voltage Root Mean Squared Deviation was 0.01 with a
total load-weighted penalty factor of 456.68.
The system had voltage violations for 29.25 bus-seconds.

A total of 53791.67 kWh of load went unserved during this simulation.

Generators were within 15 percent of their MVAR limits for 19.27
 Generator-Seconds
```



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