

REAL-TIME VALIDATION OF POWER SYSTEM TRANSIENT STABILITY
SIMULATION RESULTS

BY

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THESIS

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Abstract

Performing transient stability study using simulation software is crucial to determining the threshold amount of disturbance a system can handle before losing synchronism. These disturbances include events such as loss of generation, loss of a large load, or fault on transmission facilities. Currently, there are state estimator models used in simulating the transient stability response of large systems in the U.S. to disturbances.

This research project studies the transient stability models used in simulating a disturbance on the system, with a focus on generator modeling. The objective of this research project is to achieve a more optimized transmission grid, by facilitating better planning studies and operational enhancements. Real time state estimator cases do not have any generator or load models in them. A procedure has been developed to automatically load generator model data from the planning case into the real time case and troubleshoot the incorrect models to get the case ready for a transient stability run. With real-time PMU data, it will be possible to simulate the same contingency in commercial software, compare it with the recorded PMU data, and make modifications to the current model accordingly. In this work the preparation procedure will be discussed, as well as the comparison and interpretation of simulated and real-time data.

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1. Introduction

This section explores the background information related to this research project. Particularly, it introduces the definition, causes and influencing factors of power system transient stability, as well as the motivation and objectives of this research project. The purpose of this section is to offer an initial understanding of the problem before going into the more technical details and methodologies in later sections of this paper.

1.1 Overview of Power System Transient Stability

Power system transient stability is the ability of the power system to maintain synchronism. Transient stability issues arise in power systems when a severe disturbance occurs, such as a loss of generation, loss of a large load, or a fault on transmission facilities [1]. This creates an imbalance between the input power supplied to the synchronous generators and their electric power outputs [2]. When these disturbances are large enough, the power system will experience significant variations in the generator rotor angles, power flows, bus voltages and other system variables [3]. The result is that the system will be unable to maintain synchronism in the process.

Unlike power flow studies, which are conducted when the system is in steady state conditions, transient stability analysis focuses on the dynamic response of a system after steady state operating conditions have been disturbed by a contingency. When conducting a transient stability analysis, we are interested in whether the system is able to recover from the disturbance and return to a steady state operation. The time frame of interest for transient stability ranges from a few seconds up to dozens of seconds, depending on the size of the system.

The effect of the disturbances on a power system varies with several factors. First of all, certain generators that are electrically closer to the fault location experience a greater influence than others that are more remote to the fault location.

Second, the duration of the disturbance also makes a difference. A power system might be able to recover if the disturbance lasts a very short time. The duration of the fault that would create a large enough disturbance on the system for it to lose synchronism and subsequently result in transient instability is called the critical clearing time. This is the time required to clear the fault by either protective equipment or operating personnel interference to aid the system in recovery before instability occurs.

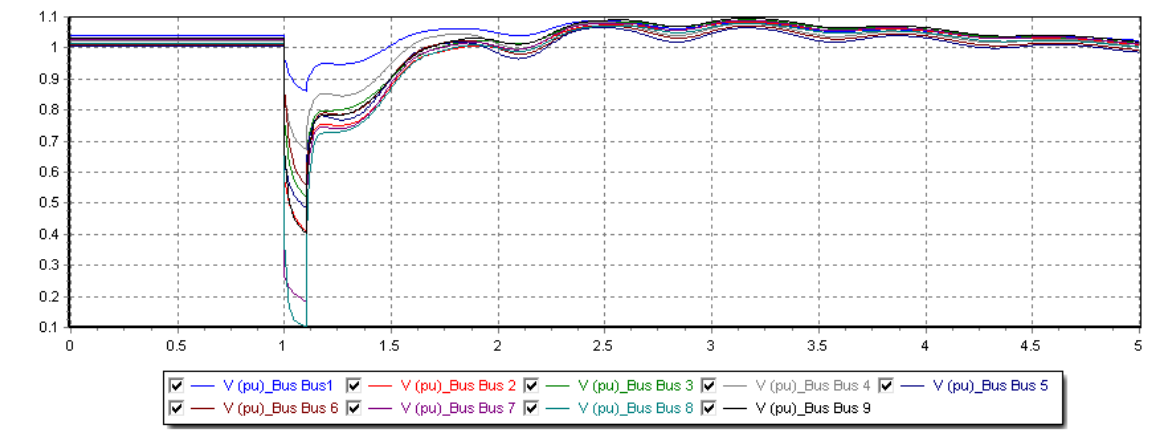


Figure 1 Results from an example of transient stability simulation in a 9-bus system with fault duration of 0.1 seconds.

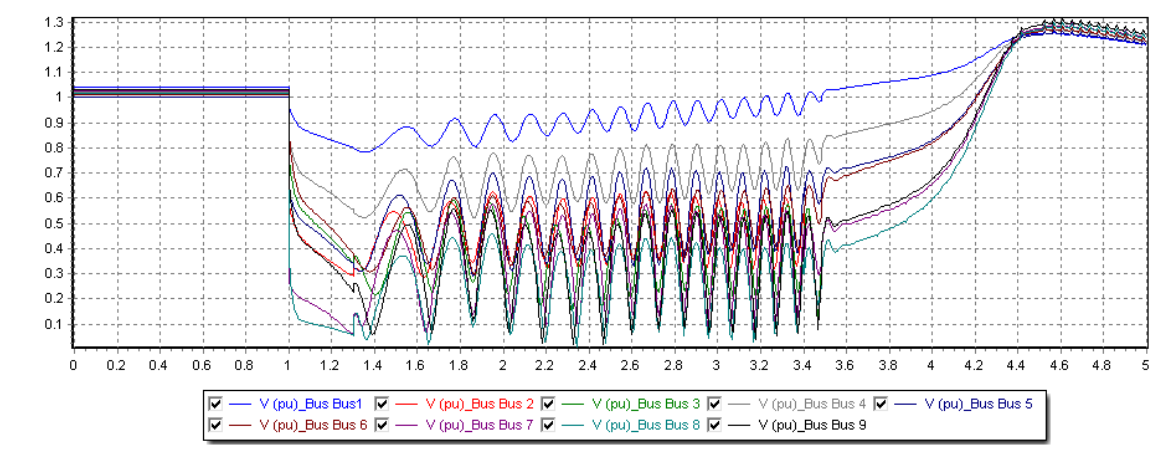


Figure 2 Results from an example of transient stability simulation in a 9-bus system with fault duration of 0.3 seconds.

Figure 1 and Figure 2 are good demonstrations of the concept critical clearing time. This simulation is conducted in a small case of only 9 buses. Although this is unrealistic because in a real-world situation

the system would be much larger, it is a good starting point in trying to understand what transient stability is. The figures show the per unit voltage at different buses plotted against time in seconds. The simulations in both cases are run for a total of 5 seconds. During time period from 0 to 1 second, the system is in steady state, illustrated by the constant voltage level at all the buses. At 1 second, a contingency is applied. The difference between Figure 1 and Figure 2 is that in the scenario of Figure 1, the duration of the fault is only 0.1 seconds, while Figure 2 shows the response after the fault is applied for 0.3 seconds. Figure 1 shows that after the clearing of the fault at 1.1 seconds, the system recovered from the disturbance, returning to a steady-state operation. However, we can see in Figure 2 that when the fault is cleared at 1.3 seconds, it has caused sufficient damage to the system that it is unable to recover and return to synchronism. In this case, the critical clearing time is somewhere between 0.1 and 0.3 seconds.

Figure 3 shows the one-line diagram of the system used in the transient stability simulations. As illustrated, Buses 1, 2 and 3 are generator buses; Buses 5, 6 and 8 have loads, while the rest of the buses are used in the transmission of power. When a fault happens anywhere on the system, the interconnected buses will all be affected, especially in a small system like this one.

The third factor that has an impact on transient stability of a system is the magnitude of the fault. This is perhaps the most important factor in power system transient stability analysis. Determining what the threshold amount of disturbance a power system can handle would help us better understand and operate the system to prevent catastrophic incidents.

When performing transient stability studies, commercial software packages are usually used to model the system, including generation, load and transmission infrastructure. At least one dynamic model is required before a simulation can be run.

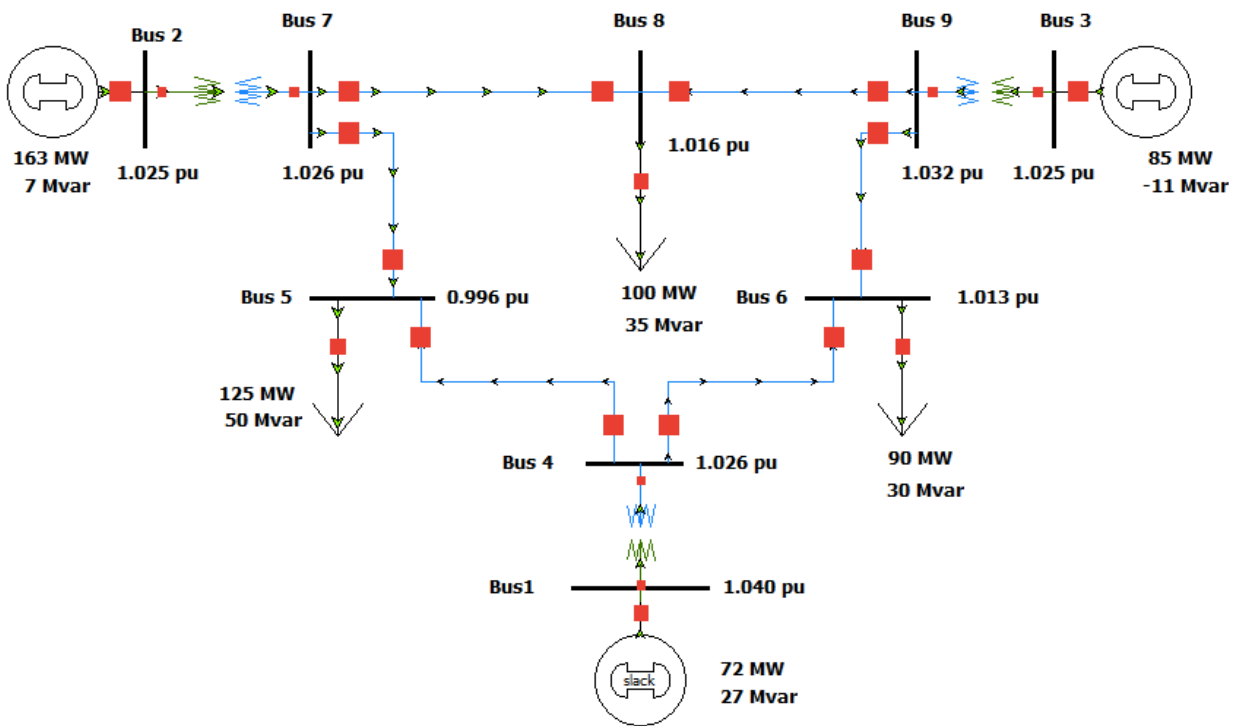


Figure 3 One-line diagram of nine-bus system used in simulation studies.

Figure 4 shows the different components' models used in a power system transient stability analysis.

These are very complex systems with several or sometimes thousands of buses interconnected together, each with its own transient stability model.

Commercial software packages used in transient stability simulations have dynamic models built-in that can be selected for each machine and load. Each model has parameters that most of the time need to be changed from the default value in order to match the realistic behavior of the machine or load.

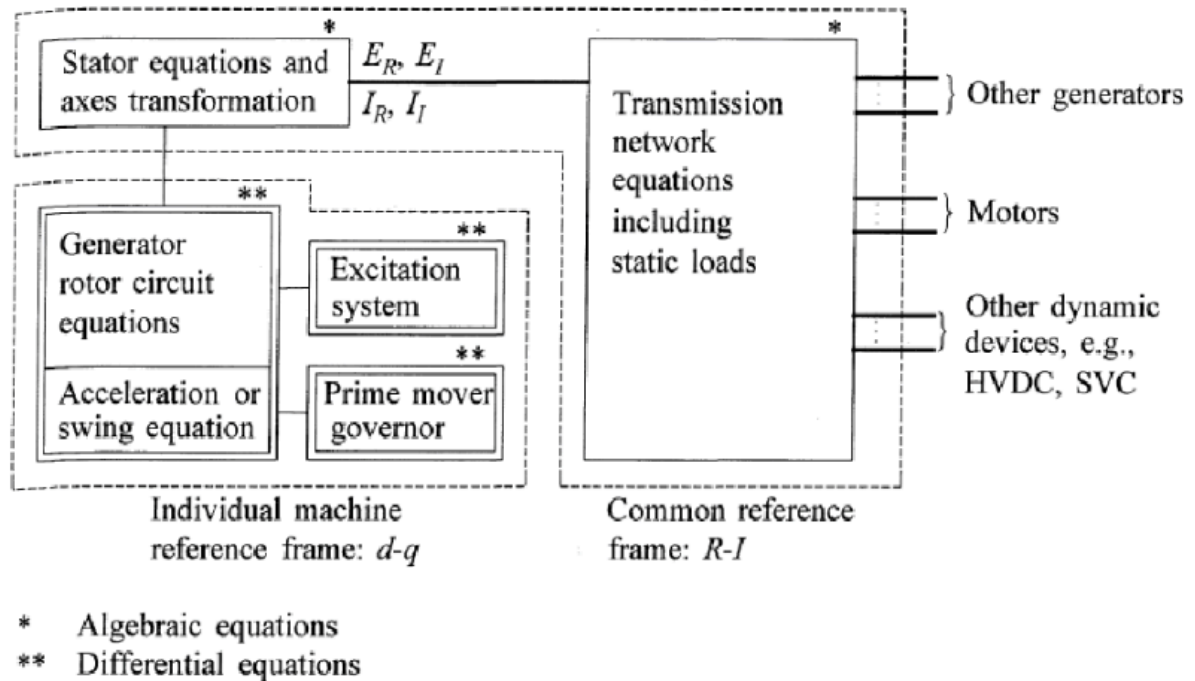


Figure 4 Layout of models used in power system transient stability studies shown in [1].

1.2 Significance of Power System Transient Stability Analysis

Transient stability analysis is an important part of understanding a system and protecting the grid from events such as blackouts. The significance of performing studies on power system transient stability has always been recognized by some parts of the power grid, such as the Western Electricity Coordinating Council (WECC). Additionally, as wind generation technology continuously matures in the last few decades, there are more and more wind farms being built and the installed capacity of wind power in the system keeps growing. While updating the current energy profile with more renewable energy sources is a positive step towards the future, the integration of electricity from the wind into the overall power grid presents particular challenges that require transient stability analysis because of the impact of such integration on the system stability. The cause of these challenges is the stochastic fluctuation characteristics of wind power generation. Therefore transient stability studies on power systems are gaining more attention throughout North America, as well as other parts of the world.

Transient stability analysis is performed on software packages through simulations. The results from these simulations then help system operators determine how to implement protective measures on the grid in the event of a significant disturbance on the system. Having a good understanding of how to respond to different levels and kinds of disturbances is crucial to protecting the grid and preventing incidents such as blackouts from occurring. This is the reason why having a certain level of confidence in the simulated results is very important.

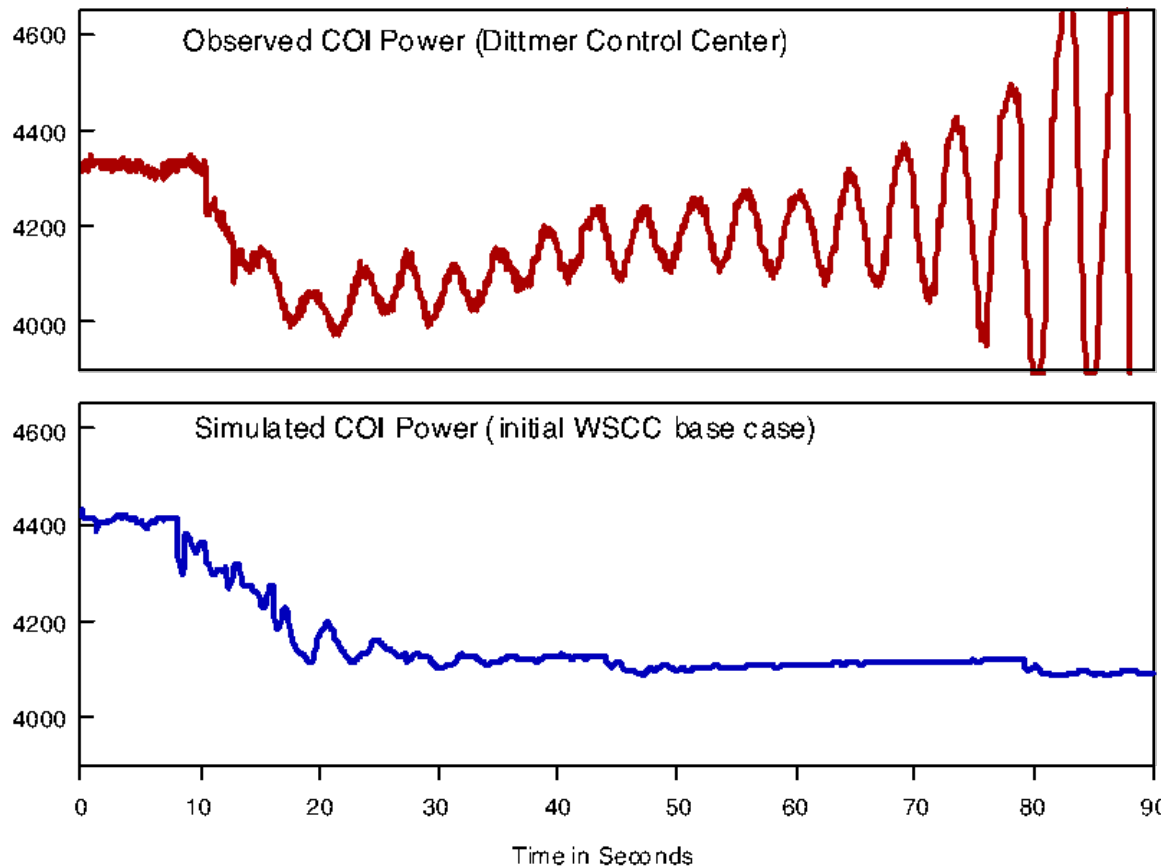


Figure 5 Transient stability observed results versus simulated results from the 1996 California Oregon Intertie (COI) Power as shown in [4].

Figure 5 provides a good example of the kind of event that motivates this research project. The event, known as the 1996 Western North America blackout, occurred on August 10th, 1996, and affected millions of customers stretching from Canada to the western part of the U.S. to Mexico. The power outage ranged from several minutes to several hours for different customers. The root cause of the

blackout was a combination of different factors, including inadequate tree-trimming practices, improper system operation and outdated equipment [5]. Here we will discuss the improper system operation that ultimately led to this incident. The plots illustrate the power flow on a line against time in seconds. The top graph is the recorded values observed and shows what really happened on the grid – the disturbance is significant enough that it caused the system to lose synchronism and therefore a blackout occurred. However, the bottom graph is the simulated behavior of the system in response to this disturbance. As we can clearly see, computer simulation showed that the system will be able to recover on its own and return to steady state operating conditions. This caused the operators to assume that the system would be fine and they did not need to take any action. In this case, incorrect power system transient stability modeling led to the blackout and caused inconvenience and disruption for customers.

We have since then come a long way towards improved and more accurate simulations that more closely match the real-time results. However, there is still much room for improvement. For example, Figure 6 shows the actual versus simulated bus frequency in Hertz at one bus during the 2011 Southwest Blackout. As can be seen on the graph, the accuracy of the simulation results has improved compared to over a decade ago. The simulated initial response quite closely matches the actual recorded values on the system. However, the difference grows larger as time goes on, and a few seconds later, the difference is significant enough that it no longer accurately represents the actual system behavior.

The significance of conducting power system transient stability study has been discussed in this section. But more importantly, the accuracy of the results often has an even larger effect on our ability to predict and prevent events like blackouts from occurring. This research project is part of the effort to validate current modeling of power system components against real-time data. By comparing the results, we can then develop methods to detect areas of improvement of the current modeling to make the data match more closely.

Figure 14: Actual and Simulated Frequency at Miguel 500 kV Bus

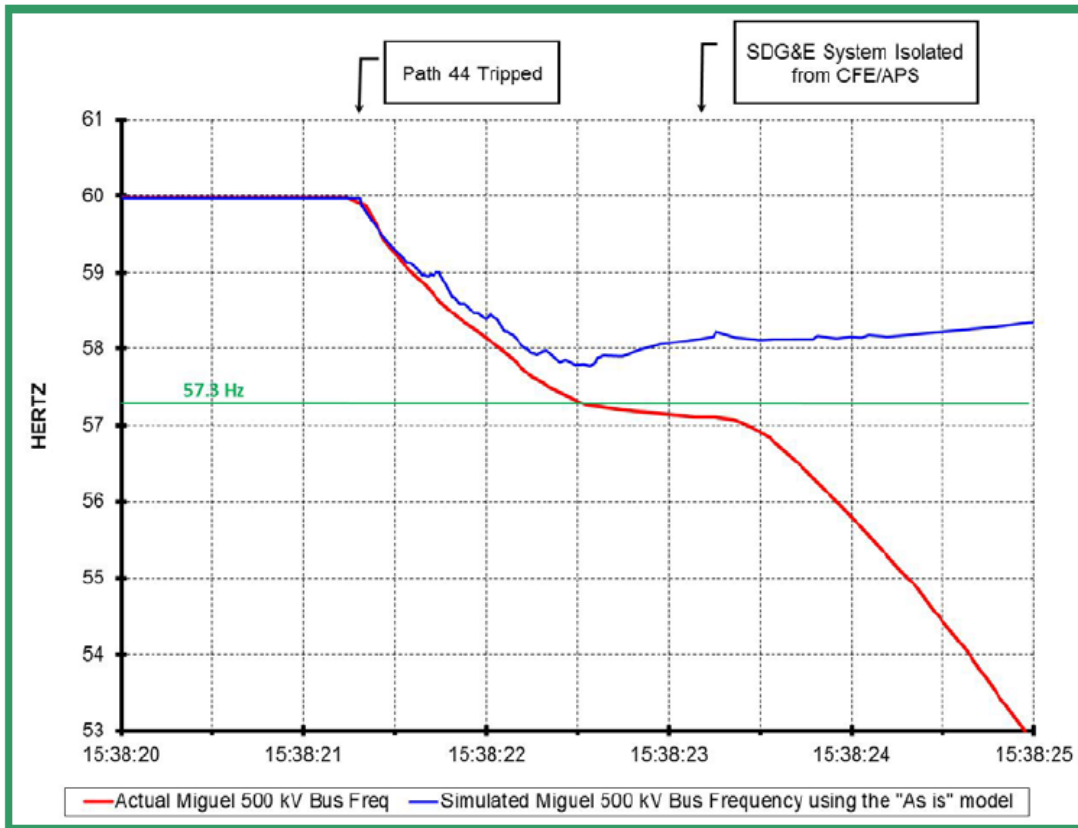


Figure 6 Transient stability observed results versus simulated results from the September 8, 2011, Arizona-Southern California blackout as shown in [6].

1.3 Project Objective

As discussed in Section 1.2, it is of vital importance to conduct power system transient stability studies.

However, ultimately the simulation results would be useless without a somewhat accurate model of the system. Achieving a model that perfectly mimics the existing system is always going to be an ongoing effort that perhaps can never be achieved because the real system is constantly evolving with new technologies and configurations. What we can strive for, however, is to improve the current modeling so that its behavior is as close as possible to the actual system behavior.

When the system is running in steady state without any disturbance, it does not reveal any information to researchers because all the parameters are constant. It is when a contingency occurs that we can

capture the data and study how the system responds to get valuable information to help improve the model. Ideally, the contingency is large enough to cause some disturbance on the key parameters of the system, such as bus frequencies and voltage levels, and at the same time small enough to not cause any major incidents such as a blackout. Once the data is obtained, the same fault is simulated in a software package to compare and improve the modeling.

The objective of the project is to achieve a more optimized transmission grid by facilitating better planning studies and operational enhancement.

2. Literature Review

In order to achieve the project objective, two different but related milestones both need to be completed. The first one is to develop tools to verify the dynamic simulation packages utilized to conduct system simulation studies against each other. The second part is to develop tools to validate power system dynamic models against real-time data and make modifications where necessary based on the results. This project focuses on the latter, but nevertheless both parts are equally important to achieve the overall goal.

The two parts are very much interrelated – they differ in some ways and are similar in others. One difference is that verification between software packages involves comparison of simulation results using different packages. All the results that are being compared are simulated instead of real-time. In the validation part of the project, the comparison happens between simulated and real-time results. However, the two parts are similar in that they both involve studying the transient stability models, comparing the system response generated from these models, and figuring out a systematic way to interpret the discrepancies and make modifications based on them.

The project cannot be successful unless both parts are completed. Only completing the verification part against different software packages will result in better, more trust-worthy dynamic analysis software and confidence in the result. It is a great start, but potentially all of the software packages could be wrong. This calls for the second part – validation against real data. The second part also cannot be conducted without the first part. If the software-to-software verification has not been done, when comparing simulation results to real-time results, researchers could potentially have to compare multiple simulation results to the same real-time result. This creates unnecessary work and confusion.

Shetye et al. [7] discuss in great detail some methodologies to systematically determine the discrepancies across different transient stability software packages.

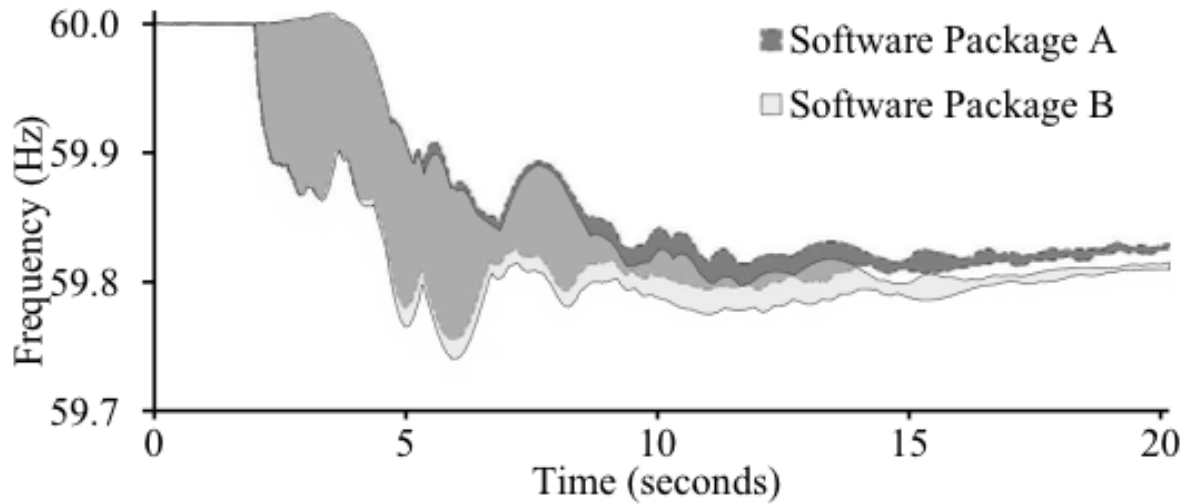


Figure 7 Ranges of bus frequencies of 18,000 buses obtained from simulating the same power system planning model in Software Package A and Software Package B for a large generator drop contingency from [7].

Figure 7 is an example of the motivation behind paper [7]. The example used a planning model of the North American interconnection, which consists of about 18,000 buses and over 2,000 generators. A contingency was inserted and the system is simulated in two different software packages. Figure 7 shows the frequencies of all the buses in response to the contingency, using dark grey for one software package's results and light grey for the other. The medium grey area shown in the plot is the overlap between the two software packages. It is obvious that the frequency results from one package are consistently higher than the other, despite the majority of the results being overlapping. What this presents is that while the different software packages mostly deliver similar results, discrepancies do exist. The paper then goes into detailed discussion on an automated approach for signal comparison, discrepancy identification, isolation of the models causing these discrepancies, and the methods available to detect the sources of errors in these models.

Shetye et al. [7] provides an excellent foundation for this work, as well as introducing methods of data analysis and signal comparison techniques that can be utilized in the validation phase of the project.

3. Description of Research Results

This section discusses in more detail the research results, focusing both on how to prepare the cases for simulation runs as well as ideas about the methodologies for comparing the simulated versus real-time results.

3.1 Mapping Methodology

There are two types of transient stability cases used in studying power systems, namely planning cases and real-time cases. Planning cases are comprehensive cases used for power system planning. They contain dynamic models for all the generators and loads. Real-time cases, or state-estimator cases, can be seen as “snapshots” of power systems in real time. State-estimator cases contain actual generation and consumption data at the time the “snapshot” was taken. As discussed in previous chapters, a system operating in steady state does not offer much insight into the system because all values are constant. Therefore the time of interest for state-estimator cases is around the time of contingencies.

The issue we face, however, is that no dynamic models are available in state-estimator cases for any generators or loads. As previously discussed, in order to perform any transient stability analysis on a system in a commercial software package, there needs to be at least one dynamic model. Obviously, the more models the system has for its generators and loads, the more accurate the results will be.

Therefore researchers and system study engineers are faced with the challenge of mapping the dynamic models from the planning case over to the state-estimator case.

Mapping of the dynamic models is no small task. It is a challenging but important part of performing transient stability analysis. The importance lies in the fact that without the dynamic models, transient stability analysis simply cannot be conducted. In addition, incorrect or incomplete models will result in invalid data. The challenge, though, comes from several areas.

First of all, the size of the systems makes manual mapping impossible. In a real world state estimator case and planning case, there are about 18,000 buses and over 2,000 generators. Each generator has dynamic models for its machine, exciter, governor, stabilizer and sometimes more. Each part of the generator that has models also contains dozens of parameters that almost always need to be changed to accurately represent the behavior of the generators. Taking that into account, there are hundreds of thousands of parameters that need to be mapped, which makes it impractical to manually carry out the process.

The second challenge comes from the fact that the two types of cases have different topologies. In planning cases, generators are associated with buses and sometimes there are multiple generators at one bus. This means multiple generators can have the same bus number. The only way to distinguish between them is through a generator ID. In state-estimator cases, generators are associated with nodes and each one is unique. Therefore each generator has its unique bus number. This difference in the topology makes mapping the dynamic models challenging because the models cannot be mapped by renumbering the buses. If they were mapped by renumbering the buses, the ones with multiple generators attached in the planning case would only have one generator model mapped over to the state-estimator case, without even the guarantee that the model is mapped to the correct generator in the state-estimator case.

Figure 8 shows this difference in network topology between the two types of cases. The top network is the topology for planning cases. It shows one bus attached to two generators. So both these generators would have the same bus number associated with them. In addition, they would also have a generator ID to distinguish between the two. The bottom network is the topology for state-estimator cases. As shown, each generator has a unique bus number attached.

The third challenge is that node numbers change in every state-estimator case. Therefore even if an algorithm were developed to map the dynamic models to a state-estimator case using bus-renumbering scheme, the algorithm would not work on any other state-estimator cases. Since the idea behind performing transient stability studies is to be able to perform them on multiple systems quickly to detect as many issues as possible, it would be of no value if analyzing each case takes months or even years to complete.

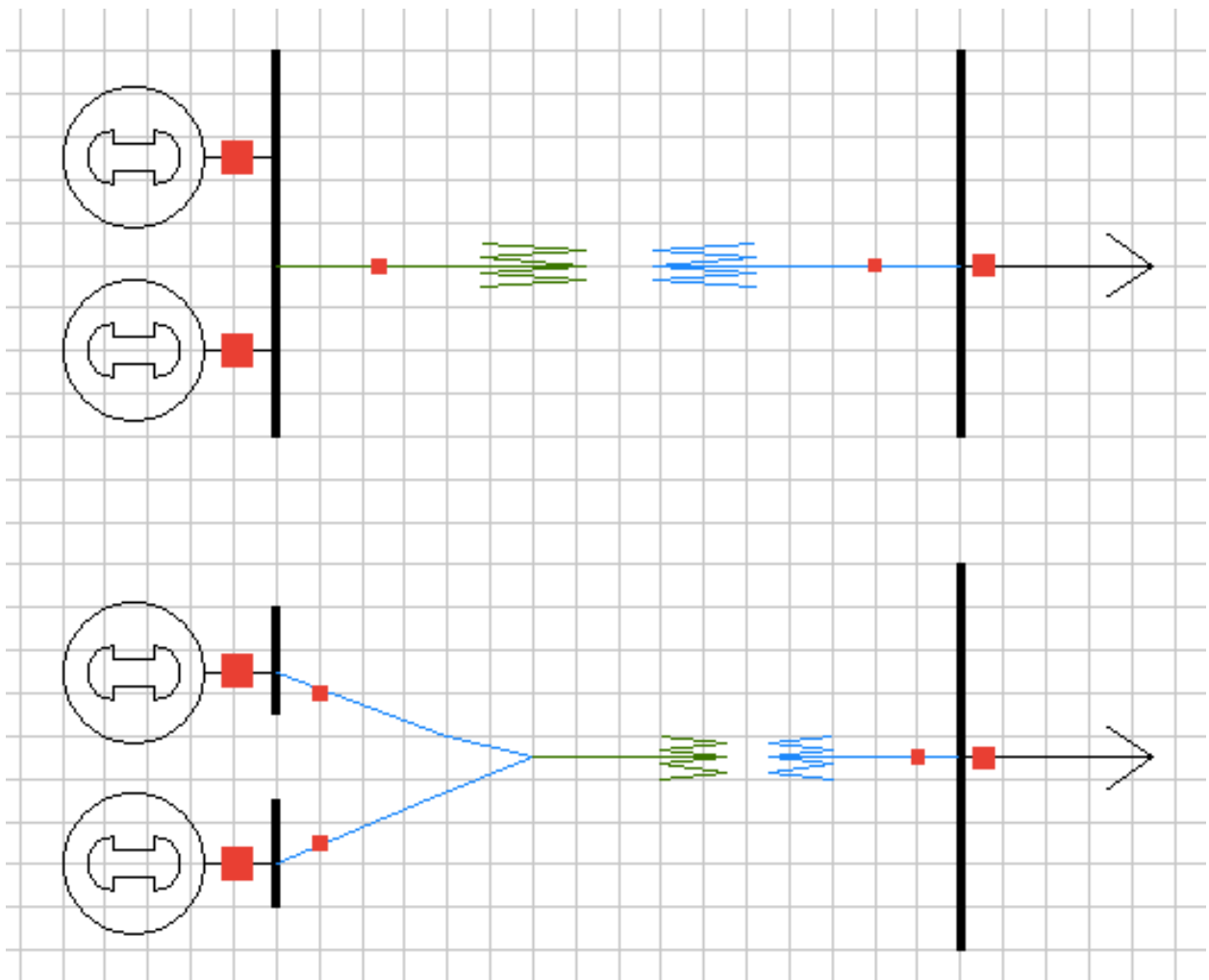


Figure 8 Difference in network topology between the two types of cases.

Despite the challenges present, it is a crucial step in the effort to achieve a more optimized transmission grid. Two approaches were taken in the attempt to map the dynamic data from the planning cases to the state-estimator cases as automatically as possible.

Both approaches rely on a file that lists all the generators in the planning case and what each one of them corresponds to in the state-estimator case. Developing this file can be a lengthy process due to the number of generators there are. The two types of cases also have different naming conventions, which makes it more difficult to develop the mapping file because a generator name could be abbreviated to different codes in the two types of cases. Some assistance from system administrators or operators might be required to ensure as many generators are mapped as possible. This file also needs to be constantly revisited and updated as new information becomes available to keep the contents accurate and up-to-date.

Once the mapping file is obtained, two approaches were taken to utilize the mapping file and map the dynamic models. The first approach is bus renumbering. In this approach, code is developed to read the mapping file and extract relevant and useful information. This information includes the bus number associated with the generators in the planning case and state-estimator case, and brief information about the generators' power output, voltage level, etc., to analyze and validate the generator numbers are matched correctly. Once information is extracted, a swap list is created. The swap list consists of the old and new bus numbers each bus in the planning case should be assigned, so that when the list is loaded into the planning case the buses will have the new numbers. Once the buses are renumbered, the dynamic data is loaded from the planning case to the state-estimator case.

Figure 9 shows the screenshot of one step in the renumbering process in a power system simulation software package.

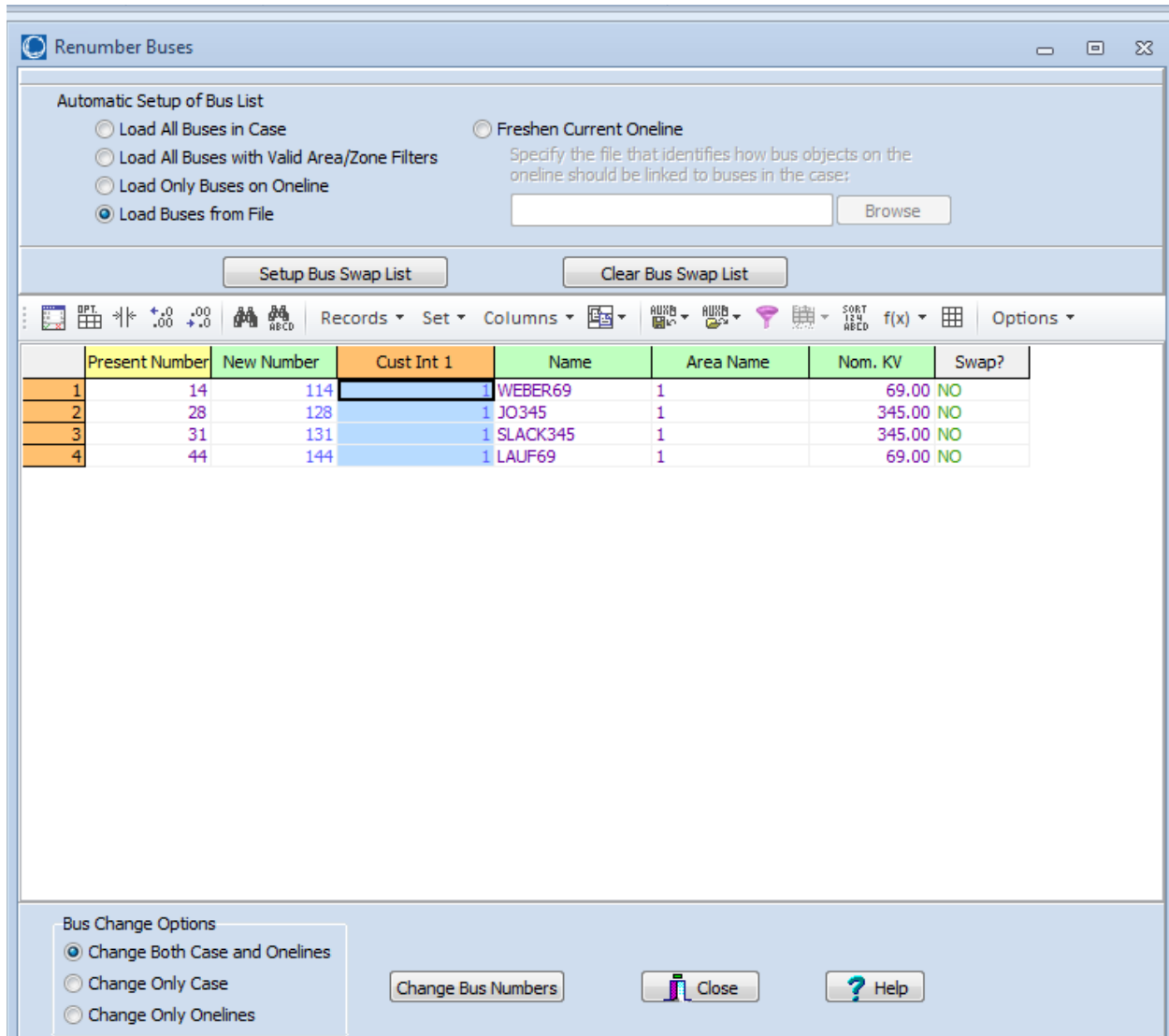


Figure 9 The process of renumbering buses to load dynamic data into state-estimator cases.

The result of this approach is that for the specific case it was tested on, about 48% of the generation in mega-watts was matched automatically. This is not a satisfying result, considering the fact that the more dynamic models there are, the more accurate the simulation data will be. With only 48% of generation having dynamic models, the simulation results will likely be inaccurate. Besides the low percentage of successful mapping, there are other issues that make this method undesirable. As addressed before, the planning case and state-estimator case have different network topology. In the planning case, there are many buses with multiple generators attached. Each of these generators then has a unique number

distinguishing it from the other generators attached to the same bus. By simply renumbering the buses, duplicate generators create issues because only one generator's dynamic model is transferred to the state-estimator case. There is also no guarantee the correct dynamic model is mapped to the corresponding generator in the state-estimator case. Another issue with this method is that, also as discussed before, the node number changes every time there is a new state-estimator case. Therefore even though in this attempt the code is able to map 48% of the generation, the code might not work on the next state-estimator case at all. This greatly increases the amount of work required to map additional cases.

The second approach worked much better than the first. This method utilizes a unique feature in one of the power systems simulation software packages called Labels. This feature allows each generator to be identified with a unique label that consists of the generator's name, voltage level and power generation. Inserting a label to each generator in the planning case helps us identify the dynamic models associated with these generators by label, instead of bus number. This helps resolve the issue around multiple generators at one bus. The labels are obtained from the mapping file discussed earlier in this section. The dynamic data is then transferred using labels into the real-time case. Detailed steps regarding this procedure can be found in Appendix A.

Using this method, 2155 out of 3371 generators dynamic models have been mapped from the planning case to the state-estimator case, corresponding to about 90% of the total generated mega-watts. Applying the Labels method to the same state-estimator case as previously used in the first method derives this result.

There are several advantages of using the Labels method. The process is very fast because no coding is required. It is easily modifiable should any changes need to be made. The method is also easily

applicable to every state-estimator case without making any adjustments as long as the mapping file is available. The accuracy is also improved compared to the previous method.

This concludes the work on the mapping of dynamic models. Currently research efforts are only focused on generator models. However, load models can be implemented using the same approach when it is desired to study the dynamic response of loads. Mapping of the models is not the only step before a case can be used to run simulations. The next section discusses further troubleshooting that needs to be conducted in order to obtain accurate results in transient stability simulations.

3.2 Case Preparation

This section discusses the issues associated with a state-estimator case after dynamic models for generators have just been automatically mapped over from a planning case.

When no contingency is applied in transient stability simulations, the power system should operate in steady state in theory. When a system operates in steady state, all its parameters should stay constant. After dynamic models have been mapped over from the planning case into the state-estimator case, due to the errors that may have resulted from the mapping process, as well as the fact that not 100% of the generation has been mapped with a dynamic model, the system almost never operates in steady state initially. As discussed in previous sections, the more dynamic models a system has, the better the simulation results will be. In order to prepare the state-estimator case for a transient stability simulation in response to a disturbance, it is crucial to fix the errors and ensure it operates in steady state without any contingencies applied. Without this step, there is no way of knowing if the discrepancies between the simulated and real-time results are due to mapping errors or model inaccuracy. The research effort to improve generator dynamic modeling would be in vain because researchers could be chasing the wrong target the entire time.

Figure 10 shows the transient stability response of the speeds of all 3,400 generators in the planning case with no contingency applied. The vertical axis is generator speed in Hertz and the horizontal axis corresponds to time in seconds. The simulation is run for a total of 20 seconds to ensure the system continues running in steady state for a sufficient amount of time. Ideally all the generators should run at 60 Hz. Although the plot seems to show slight variations in the speeds, a closer look at the axis scales would reveal that all variations stayed within 60 ± 0.01 Hz, which is within 0.002% tolerance for accuracy. This can be interpreted as an acceptable range of variation, which means the case runs flat.

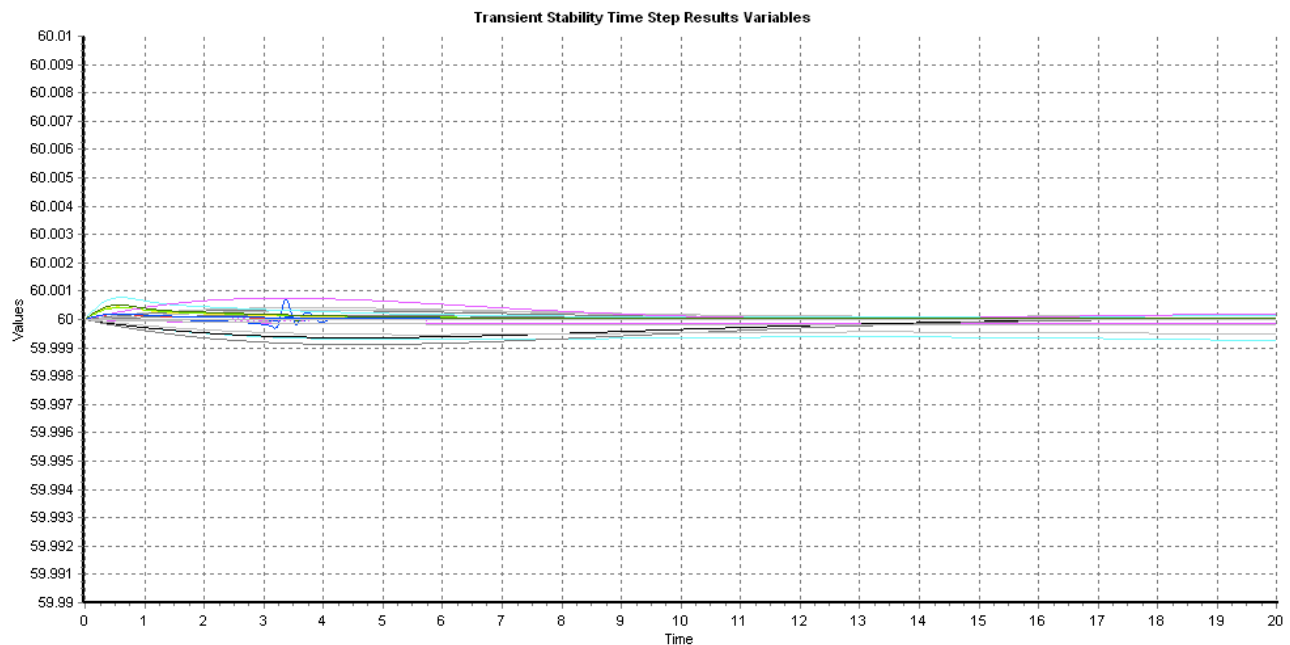


Figure 10 Planning case transient stability results for 20 seconds of generator speeds plotted against time with no contingency applied.

The preparation procedure will be demonstrated using an example – a specific state-estimator case.

After initially mapping over the dynamic models, sort the generators by MW output. Go through the generators with the largest power output and identify important ones that do not have dynamic models.

This is an important step because the larger generators will have a bigger impact on the system. Trying

to get the largest ones mapped as much as possible will ensure the final simulation results are as accurate as possible.

Sometimes before the case can even be simulated for transient stability, certain validation errors need to be cleared out and addressed; otherwise the simulation will automatically abort. Figure 11 shows some examples of such validation errors. In this case, all of the validation errors arise from certain generators having multiple models mapped over. For instance, one generator had 2 machine dynamic models mapped over; therefore the system automatically chose one model to be active. When the one chosen as active is incorrect and incompatible with the dynamic models for its exciter, stabilizer or governor, validation issues are caused. Simply going through the error log and checking the listed generator will fix this problem.

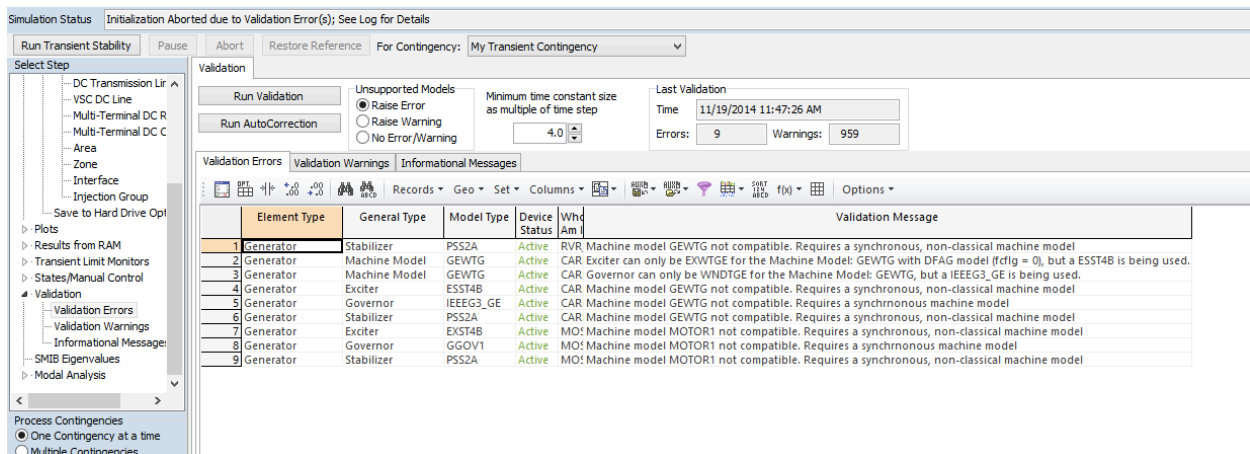


Figure 11 Example validation errors when conducting transient stability study.

After fixing the validation errors, the next step is trying to conduct a transient stability simulation run without any contingencies inserted. Figure 12 shows the generator speeds in the same state-estimator case after the initial automatic mapping simulated when no contingency is applied. This case clearly needs some work because the vertical axis goes up to as high as 155 Hz when it should stay at 60 Hz, like

in Figure 10. A slight variation is acceptable, but a variation of 158% obviously indicates issues that need to be fixed.

As mentioned above, a good place to start is finding large generators without dynamic models and trying to map them first. Having identified several groups of large generators that do not have dynamic models mapped, we can go back to the mapping file and locate them to troubleshoot what could have gone wrong. In this case, because of errors in the naming of the labels, we are able to map 20 additional generators adding up to hundreds of MW output.

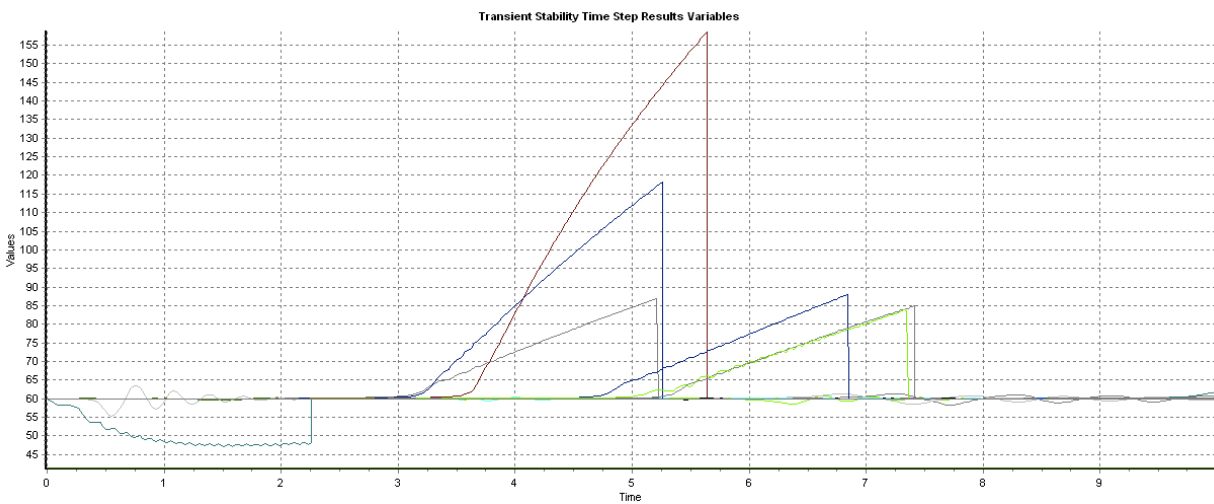


Figure 12 State-estimator case transient stability results of generator speeds plotted against time with no contingency applied after initial automatic mapping.

Figure 13 shows the generator speeds in the same state-estimator case after the additional mapping of the largest generators and simulated when no contingency is applied. Compared to Figure 12, the variation is actually worse, going up to speeds as high as 185 Hz.

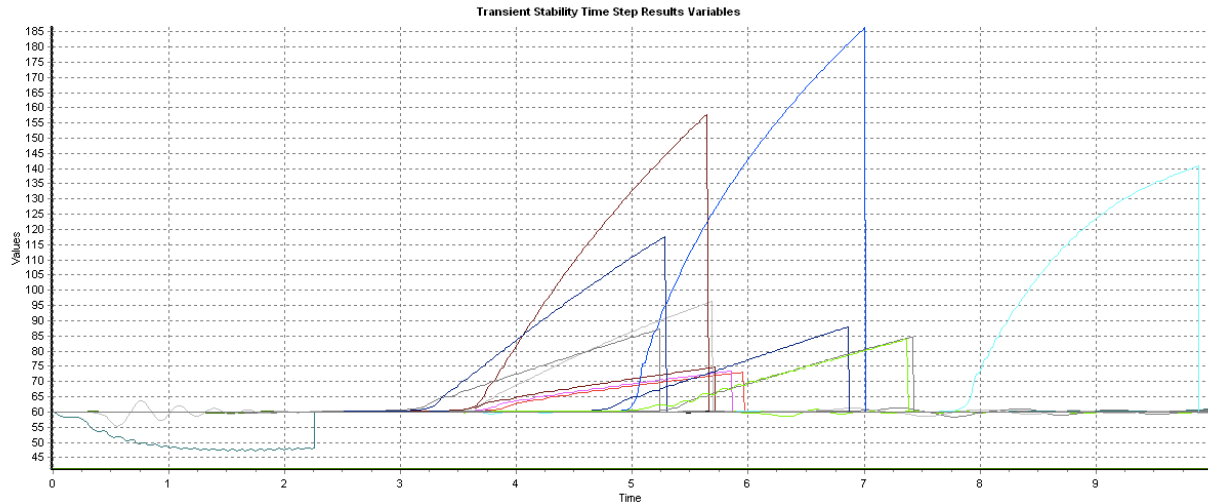


Figure 13 State-estimator case transient stability results of generator speeds plotted against time with no contingency applied after manually mapping additional largest units.

There are several ways to fix the issues regarding a non-flat start by troubleshooting which models were causing disturbances. The fastest way to identify the unstable generators is to examine the minimum and maximum generator speeds recorded after each simulation run. Usually the generators with unstable or incorrect models are very small compared to the total generation, meaning their power output corresponds to less than 1% of the power generated in the system at a given time. When this is the case, their dynamic models can simply be disabled to avoid causing further issues when interacting with the rest of the system. In some cases, the generator causing stability problems is very large, with generation exceeding 100MW. When this happens, it helps to locate the generator in the planning case by referring to the mapping file. First check the labels of each to verify that the correct labels are attached to the generator in both cases. After verifying the corresponding generator in the planning case with dynamic model data, compare all parameters to check for any discrepancies. Take corrective measures where necessary.

Using the maximum/minimum tracking method, we have identified several buses with the peak speeds in Figure 13. Disabling and troubleshooting them have produced an improved stability result, as shown

in Figure 14. The plot still looks quite dramatic, but it is worth noting that the vertical axis is in fact only from 58.4 to 61.3 Hz, which is significantly improved compared with Figure 12 and Figure 13.

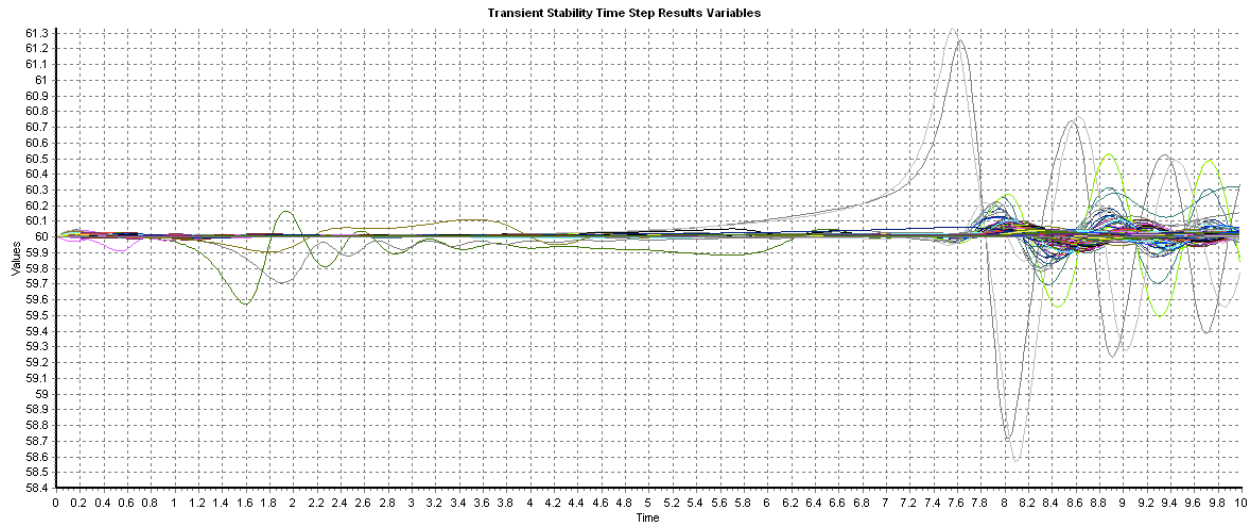


Figure 14 State-estimator case transient stability results of generator speeds plotted against time with no contingency applied after manually mapping additional largest units and applying the minimum/maximum tracking method.

Iterate through this process to arrive at improved results every time, as shown in Figure 15. Compared with Figure 14, the variation has decreased and the vertical scale is now between 59.55 and 60.2 Hz.

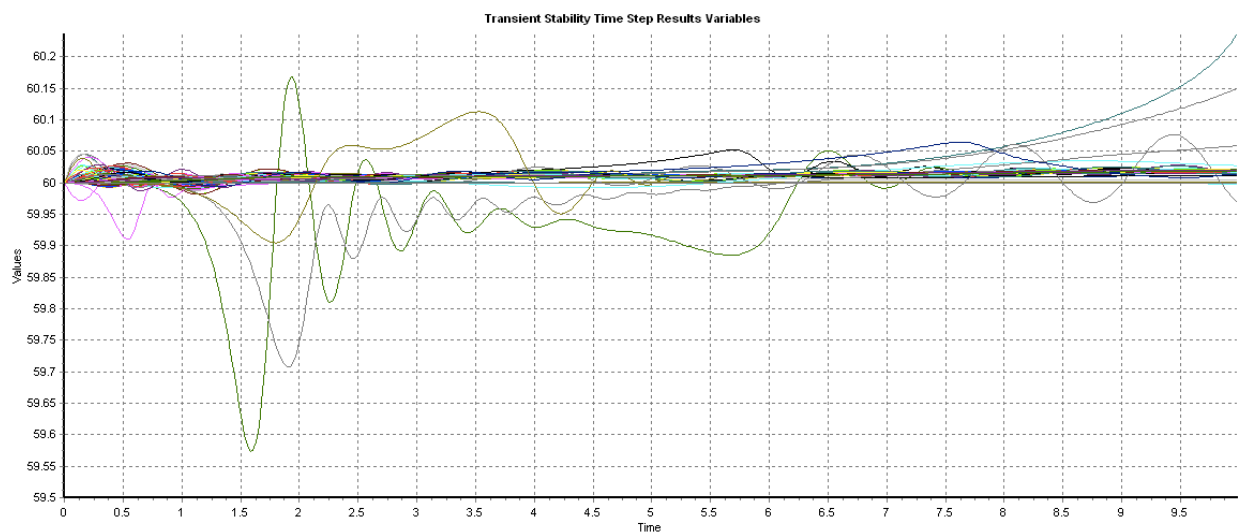


Figure 15 Improved results after applying minimum/maximum tracking method.

Another area that might cause problems with a flat start is negative generation. Sorting the generators by MW generation and analyzing them can help tackle this issue. Some machines are being modeled as synchronous condensers. It also helps to go through the power flow mismatches log to identify if any buses in particular are causing most of the problems when solving the power flow equations of the system.

After applying these methods, the case should be ready for simulation and real-time data comparison.

As long as the variation is within 0.01% it should be considered to be in the tolerated range.

Figure 16 shows the final results of the case ready for real-time comparison studies. As we can see, the variation is around 0.005% of nominal value, 60 Hz. Now we can apply the same contingency as what happened in real-time, and compare the simulated and recorded data for further analysis.

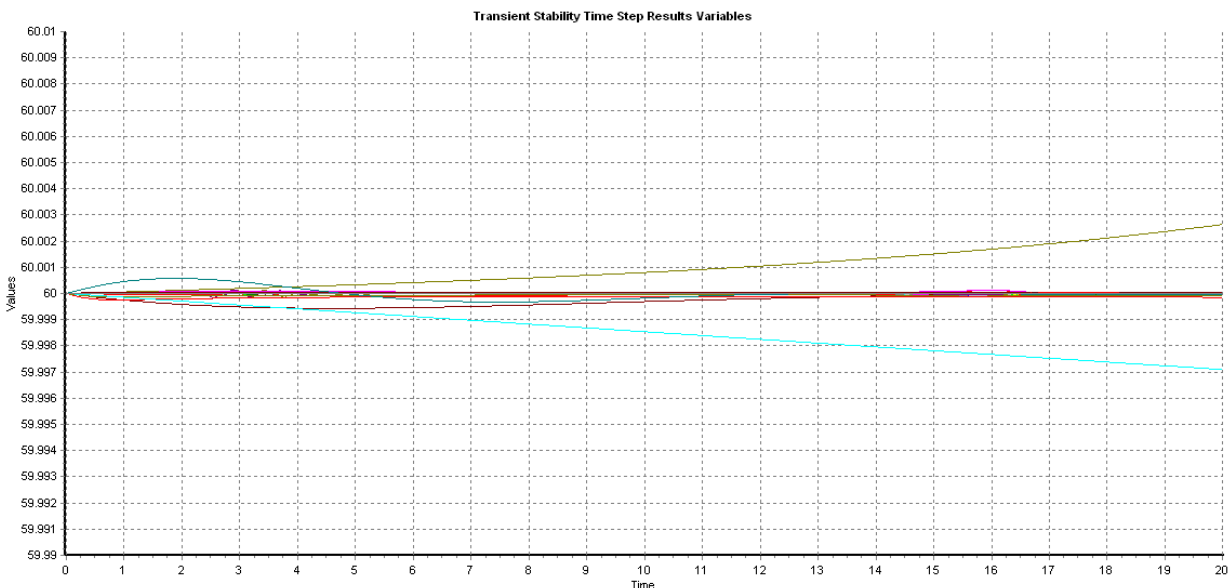


Figure 16 Final results of the simulated generator speeds in state-estimator case without contingencies applied.

3.3 Event Simulation and Real-Time Data Comparison

The final and most important step is to simulate the contingencies and compare simulated results with real-time results to analyze the discrepancies. Figure 17 and Figure 18 are good examples of similar work done previously. These plots illustrate the actual data and simulated data comparison after a disturbance on a major generator station. The red curve is the actual data and the blue one is plotted with simulated data. The difference between Figure 17 and Figure 18 is that for the simulated data, Figure 17 uses an older dynamic model for the generators while Figure 18 uses an improved model. Because of such improved accuracy, the older models should be replaced with the newer ones.

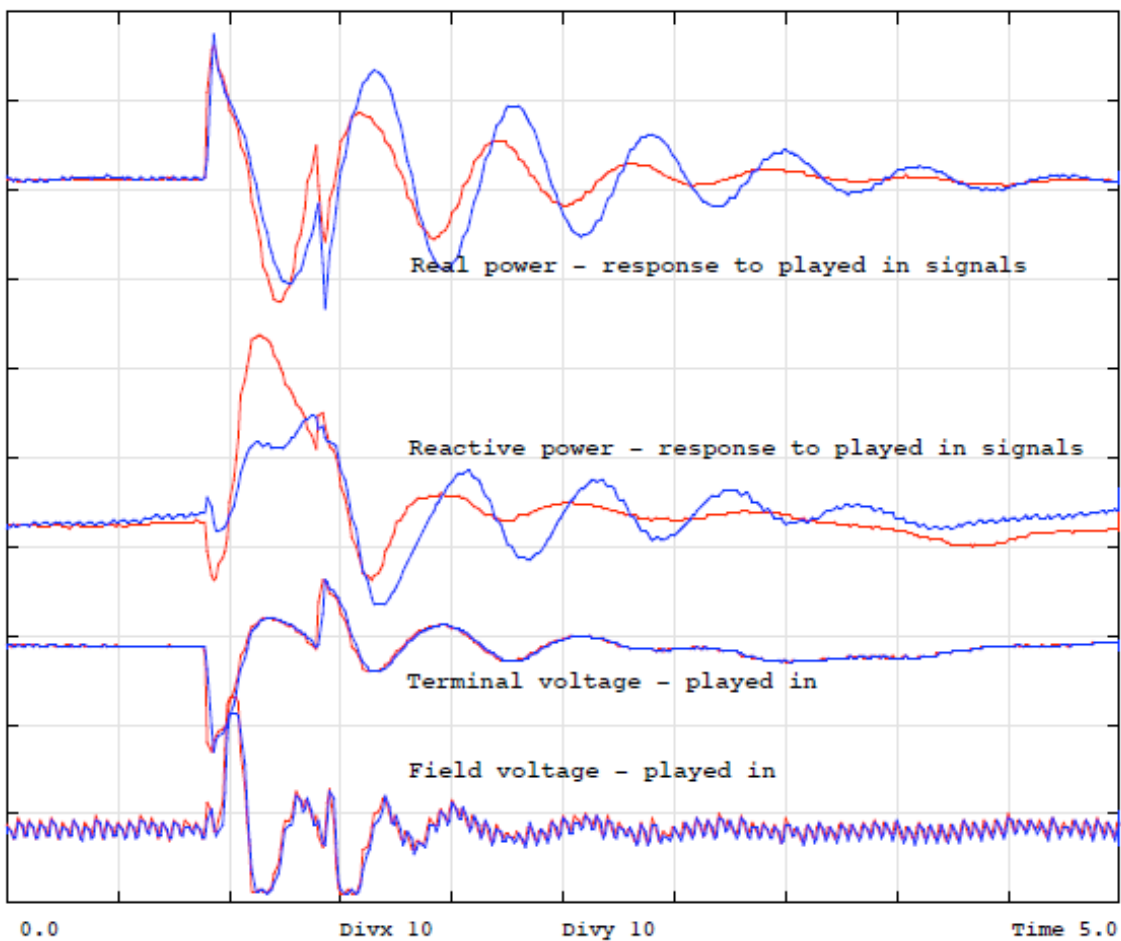


Figure 17 Simulated and real-time data comparison for a disturbance [8].

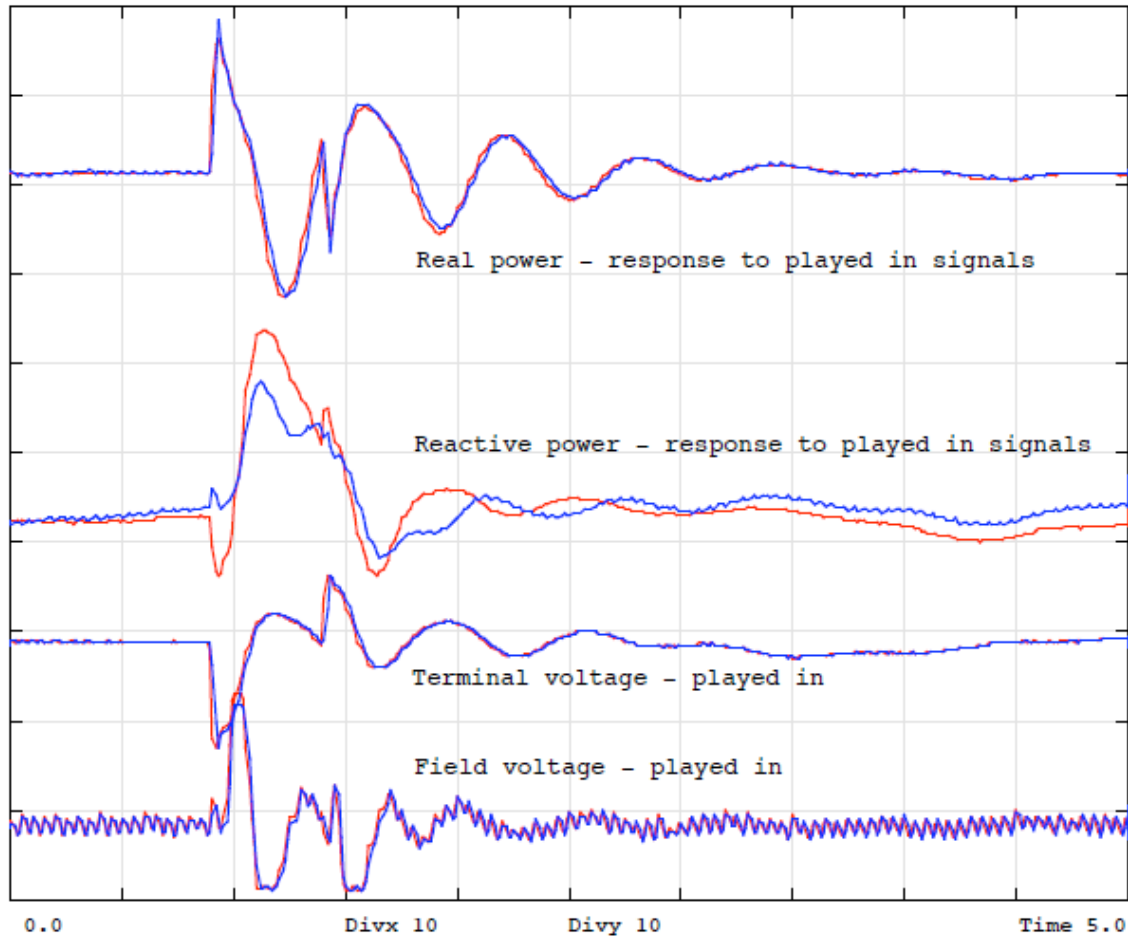


Figure 18 Simulated and real-time data comparison for a disturbance with improved dynamic model [8].

The newer models introduced provide a better match between simulated and actual system results in transient stability studies for salient pole machines. The goal is to analyze more state-estimator cases following a contingency to identify potential issues associated with other models as well. Figure 19 shows the real-time recorded generator speeds for 10 seconds of about 50 machines following a contingency. Figure 20 is the same plots but zoomed in to only show the enlarged response in the first second. As we can see there are a lot of interesting dynamics going on at different buses. This is in the same time frame as the previously used state-estimator case. Therefore we can insert the faults and simulate the same events to compare the simulated results to real data.

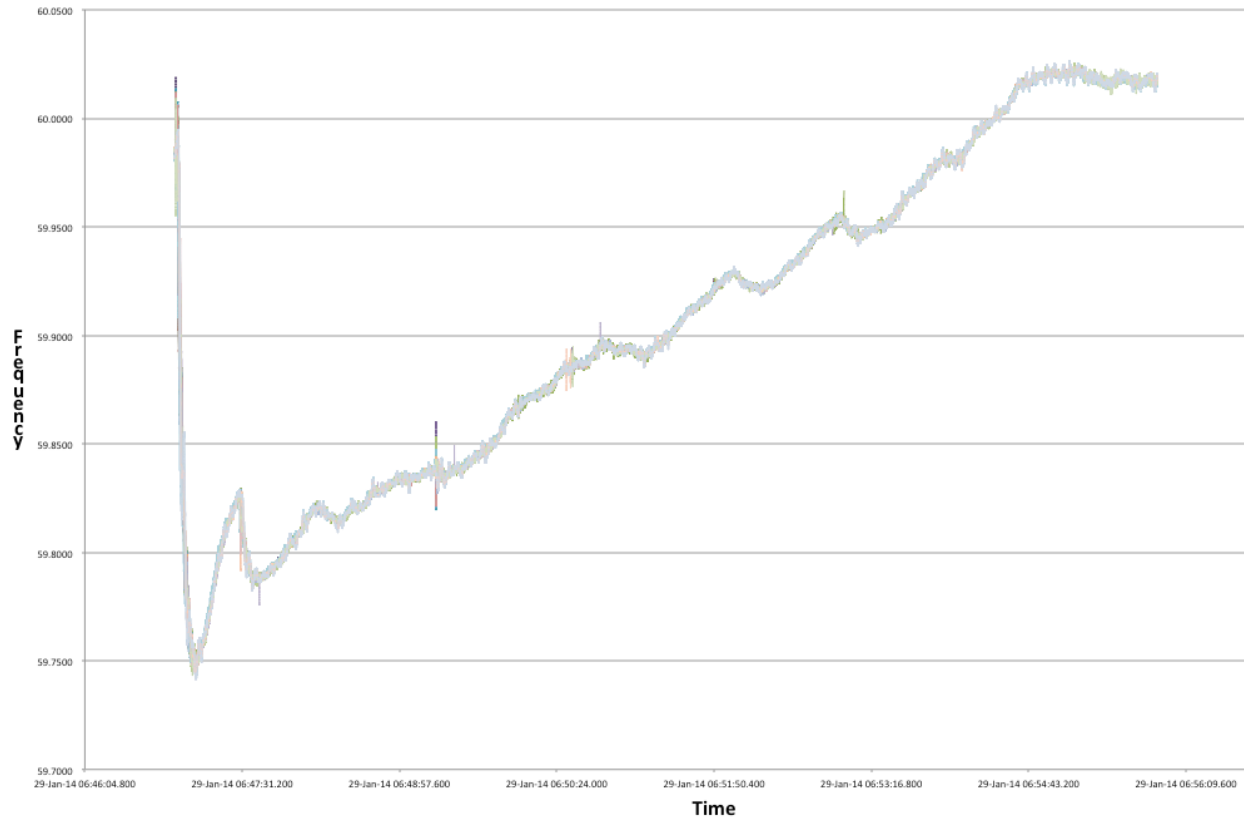


Figure 19 Real-time recorded generator speeds in response to several contingencies at a major generator station.

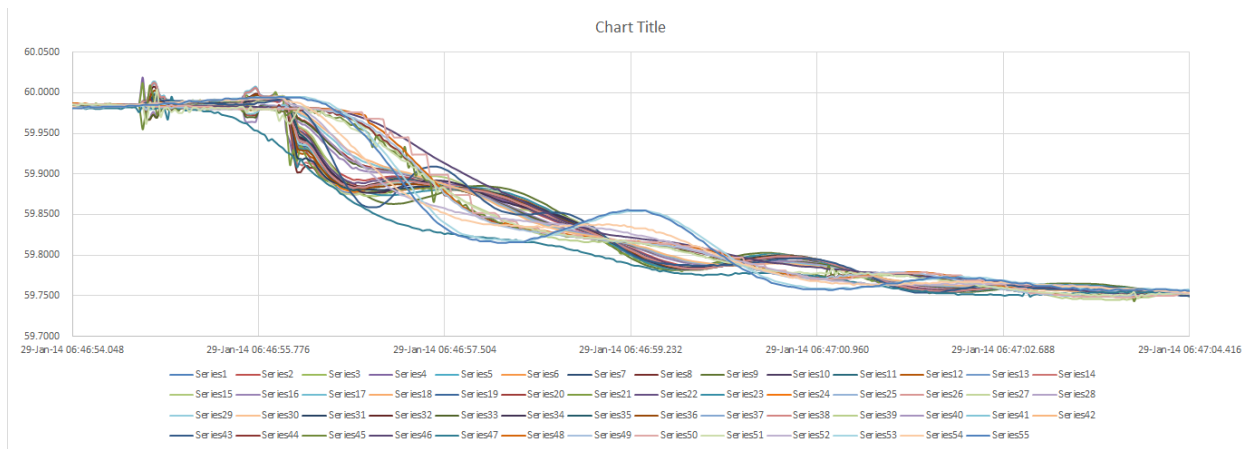


Figure 20 Zoomed-in view of Figure 19 of only the first second.

In order to be able to simulate the events, we need to know exactly what the events are, the time at which they occurred, the duration of the events, and the locations. Going through the event log provided by the system operator helps identify these parameters and create a table like Table 1.

Table 1 Transient Stability Event List

Event	Time	Location
C Phase fault on transmission line	06:46:51, 11/11/2014	Between Bus 1 and Bus 2
Generator tripped 900 MW	06:46:52, 11/11/2014	Generator A at Bus 3
Resistive brakes inserted	06:48:54, 11/11/2014	Substation A
Generator tripped 400 MW	06:48:54, 11/11/2014	Generator B at Bus 4

Inserting these contingencies into the transient stability simulation allows the software packages to recreate the events as they occurred. It is a good idea to wait a second or two before starting to insert contingencies to allow time for verification that the system is in steady state.

4. Concluding Remarks

The ultimate objective of this project is a more optimized transmission grid. The work laid out in this thesis is a good starting point for continuing toward this objective. Future work will include simulating the events in transient stability software and comparing the results with real-time data. Analyzing the data and identifying sources of discrepancies will require extensive work. A systematic methodology to automatically compare the data and interpret the discrepancies would reduce the workload significantly, and therefore should be pursued. For cases whose results match the real-time data closely, it would be a good indication that the models are largely accurate. For those whose results deviate quite a bit, proposing and testing some theories to account for these deviations is a good place to start. Next steps would be to consider changing the parameters in the model to make it a better fit. Other options include creating completely new models, like that illustrated in Chapter 3.

There is always room for improvement as technologies evolve and new generators are added to the system. There is definitely work ahead that needs to be done in order to achieve a more reliable and optimized power grid.

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Appendix A Procedure for Mapping Generator Transient Stability Models Using Labels in PowerWorld Simulator

This document describes the procedure used to automatically map generator transient stability models in the planning case to the generators in the real-time case, particularly, the case from January 29, 2014. The real time case does not have any models for its 3371 generators to begin with.

To start, first open the planning case. Under the “Add Ons” tab, open “Stability Case Info” → “Generator Model Use”, which shows a list of all the generators and their corresponding transient stability models.

Next, right click on any of the generators and choose “Display/Column Options”. Under “Column Options” tab, in the “Available Fields” selection, choose “Labels” folder → “Labels All”, and click “Add”. A screenshot of this step is shown in Figure 21. This adds a column “Labels All” to the Generator Model Use page as the first column.

Go back to the “Generator Model Use” page, right click on any generator and choose “Save As” → “CSV (Comma delimited)” and choose “No” for the two windows that pop up afterwards.

Open the CSV file. The only columns of interest are the first four, i.e. “AllLabels”, “BusNum”, “BusName” and “GenID”. So go ahead and delete all the other columns. Delete as well the contents of the first four columns – we will replace them with the information from the mapping file.

Open the mapping file. Copy the “GEN Long ID/EMS Label”, “Planning Bus No.”, “Planning Bus Name” and “Planning GenID”, and paste them onto the CSV file respectively.

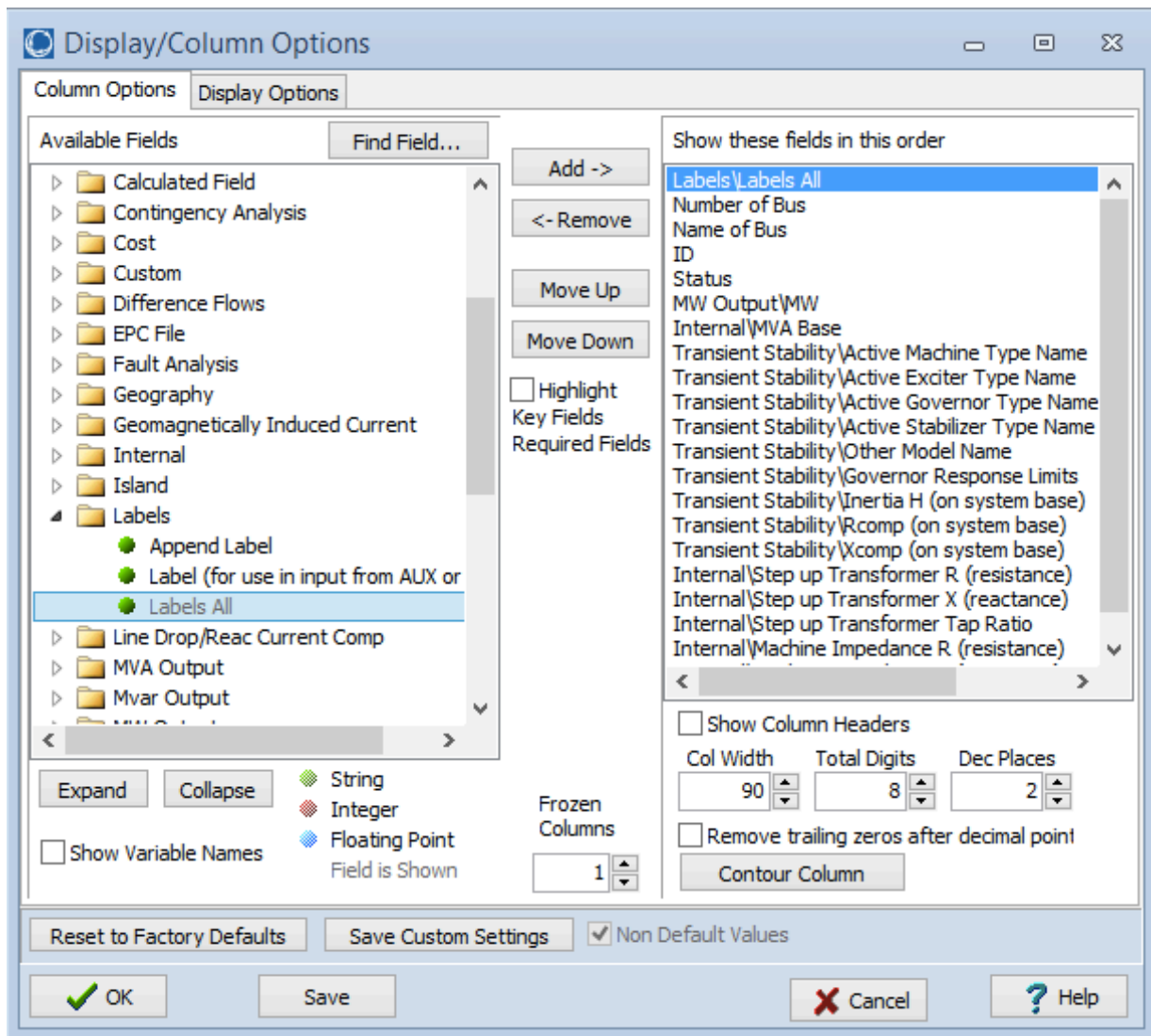


Figure 21 Screenshot of dialog window to add “Labels All” as a column.

Copy all the information in the CSV file and paste onto Generator Model Use page. The generators should now all have labels in the “Labels All” column.

Go to “Stability Case Info” again → “Save Transient Stability Data” → “Save Data with Options”. In the window that pops up after assigning it a name, under “Save Data Using”, select “Label (Use Primary if no label)” option. Click OK. This step is shown in Figure 22.

Open the real time case. Open “File” → “Load Auxiliary” to load the file we just created. Now the generator models have been mapped over.

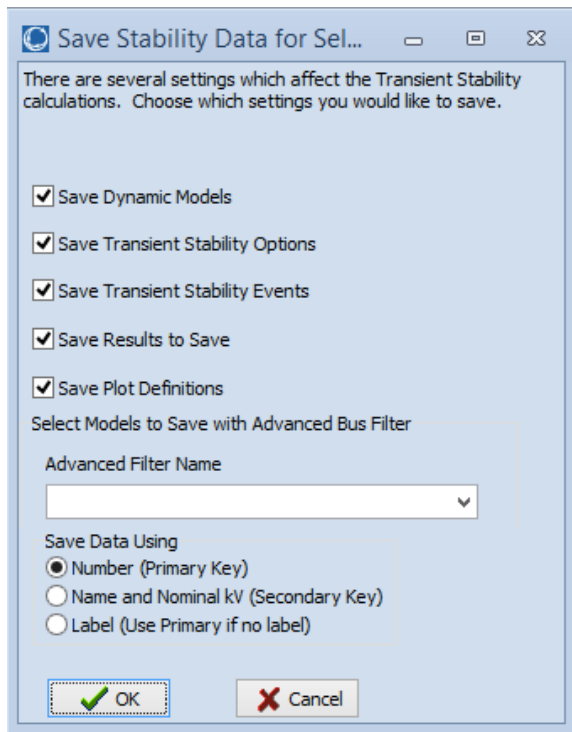


Figure 22 Screenshot of the dialog window to save transient stability data.