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Fall 10-22-2012

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Yezhou Wang and Ross Baldick, "Cascading Outage Analysis Using Sequential Outage Checkers" in "Modeling, Simulation, And Optimization for the 21st Century Electric Power Grid", M. Petri, Argonne National Laboratory; P. Myrda, Electric Power Research Institute Eds, ECI Symposium Series, (2013). http://dc.engconfintl.org/power_grid/11

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Cascading Outage Analysis using Sequential Outage Checkers

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10/22/2012

Outline

- Project introduction and background
- Cascading Outage Analyzer (COA)
- Simulation and Results
- Integration with Optimization Framework
- Future work

Project Introduction

- Project Title: Defending Interdependent Infrastructure Systems, supported by Defense Threat Reduction Agency (DTRA).
- The project is under the cooperation between UT-Austin and Naval Postgraduate school.
- The research at UT focuses on developing an analysis tool which analyzes cascading outages caused by terrorist attacks in large-scale electricity grids.
- The Cascading Outage Analyzer (COA) will also be built into an optimization model to perform the worst-case interdiction analysis [1,2] with both short-term and long-term impacts.

Project Introduction

- Power Systems are designed and operated according to $n-1$ security criterion, where the system can survive through any single component failure.
- However, if multiple contingencies occur, cascading outage events could be triggered and the consequence could be catastrophic. Examples are 2003 Northeastern Blackout [3] and 2012 India Blackout [4].
- Numerous techniques have been proposed to analyze and mitigate the cascading outage events.[5,6]
- We propose a Cascading Outage Analyzer (COA) using Sequential Outage Checkers.

Cascading Outage Analyzer (COA) Framework

- The COA is designed with a sequence of checkers to analyze the system reaction after certain initial disturbance (trip of elements (transmission line, transformer, generator, load), short-circuit of transmission lines, etc).
- Framework:
 - The COA utilizes the Power World readable input system data, together with some user settings as the system inputs.
 - The analysis engine is developed with Excel, VBA and PowerWorld scripts.
 - A graphical user interface and report scheme are also designed using VBA and Excel.

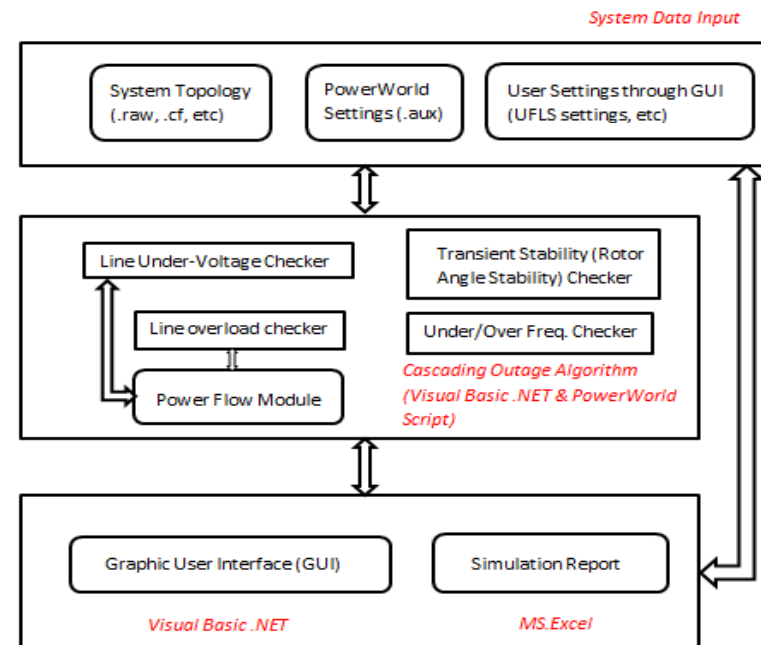


Figure 1: COA Framework

COA Workflow

- The analysis starts from identifying the initial disturbances. Then the COA performs the cascading outage simulation by sequentially checking the system working conditions and act according to different practical control settings.
- The outage checkers perform the check after each of the control actions until no system parameter is violated.
- Then the COA writes a report in Excel to show the whole cascading process.

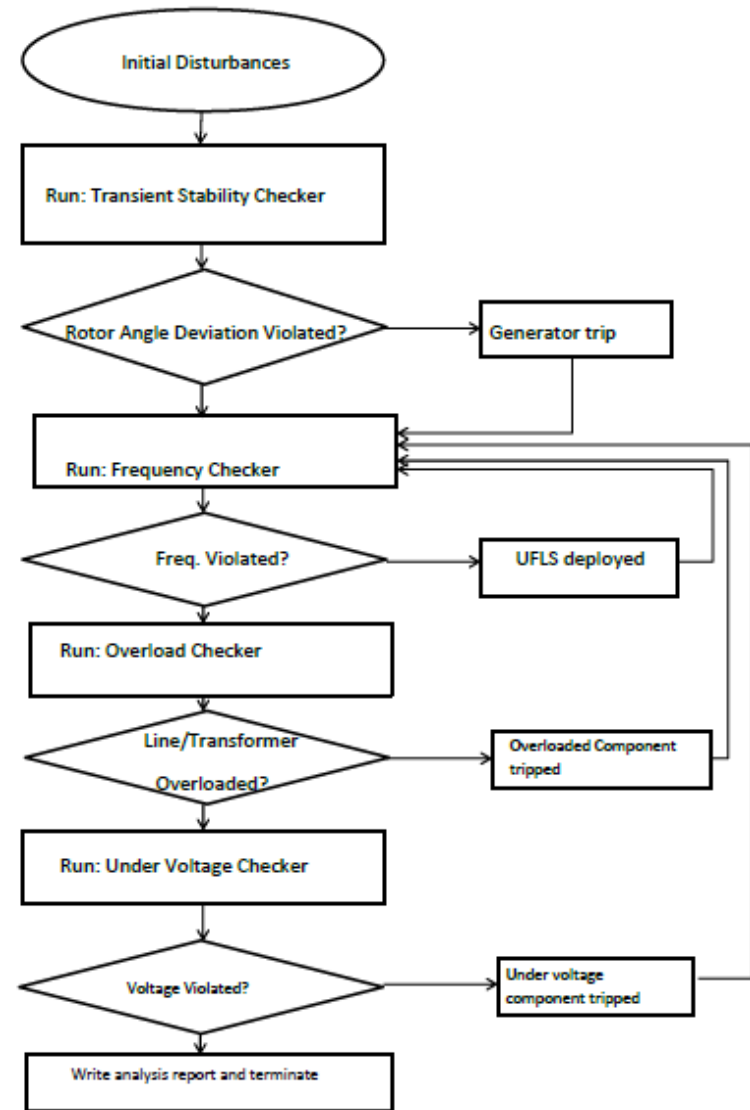


Figure 2: COA Workflow

Transient Stability Checker

- According to IEEE proposed classification of power system stability [7], transient stability (TS) is commonly referred to, the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line.

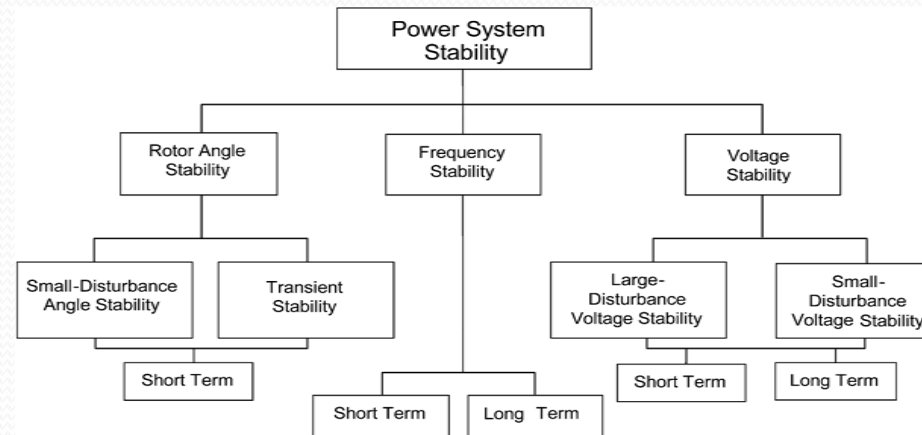


Figure 3: Definitions of power system stability [7]

- Numerous methods are used to analyze and simulate the transient stability problem. However, time-domain simulation is regarded as the most accurate tool for TS analysis.
- Transient stability checker uses the PowerWorld transient stability solver to simulate the system reactions after certain short-circuit fault. If the rotor angle deviation is bigger than a certain threshold (say, 180 degrees), the generator will automatically be tripped.

Transient Stability Checker cont...

- A simulation is performed using IEEE RTS-96 one area test case to show the implementation of transient stability checker [8].
- The scenario is a three phase fault applied on the transmission line from Bus 13 to Bus 11, circuit 1 at 1.0 second, and the relays cleared the fault at 1.3 second. As can be seen from the generator angle plot below, the generator angle deviations increase dramatically, and generator unit #1 at bus 13 is tripped out due to angle deviation larger than 100 degrees at roughly 1.3 seconds.

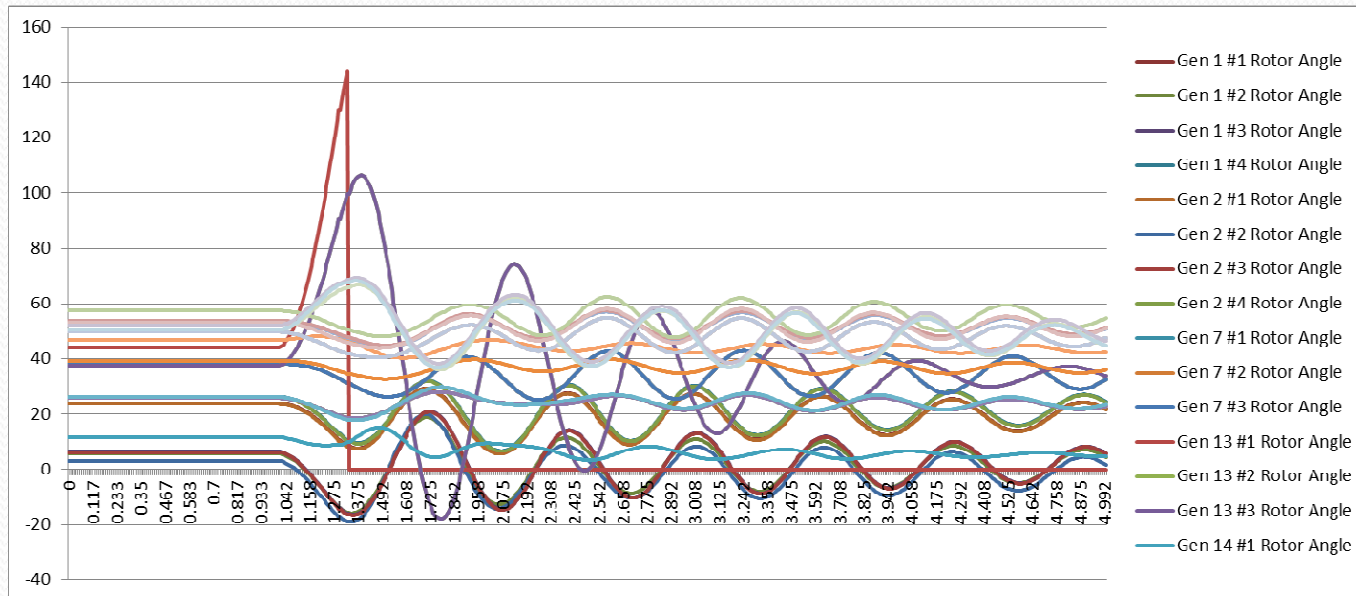


Figure 4: Generator angle plot for TS checker

Frequency Checker

- According to [7] Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load.
- Frequency checker uses System Frequency Response (SFR) model introduced in “A Low-Order System Frequency Response Model” by Anderson and Mirheydar (1990) [9].
- The frequency model comes from a typical generator frequency control model.

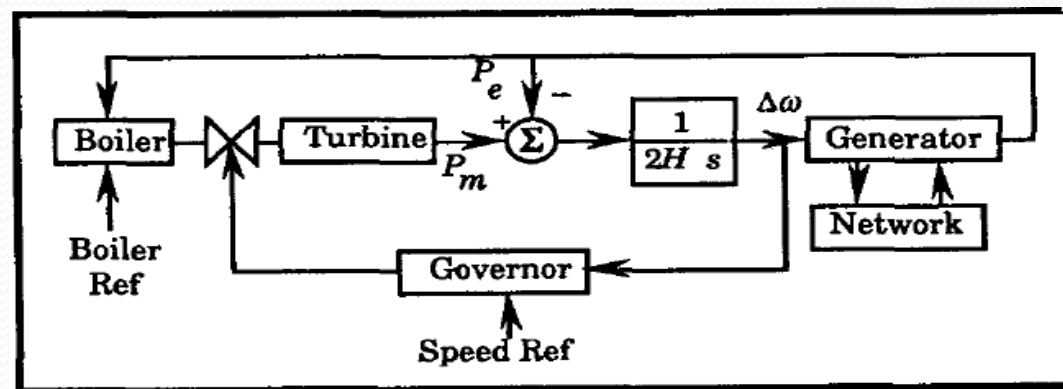


Figure 5: Typical generator frequency control model

Frequency Checker Cont...

- In the SFR model, we ignore the thermal system dynamics of the boiler and the generator response. This leaves a reduced system consisting of the governor servo motors, steam turbine, and inertia. The governor model is shown in Fig. 6.
- After we assume that the two time Constants, the reheater T_R and inertia F_H dominate the response in the first few seconds, we have the reduced plant model, shown in Fig. 7
- If the calculated frequency after a disturbance is below the pre-set threshold for particular time (the ERCOT UFLS standards are assumed here), the UFLS trips out pre-determined load to restore frequency.

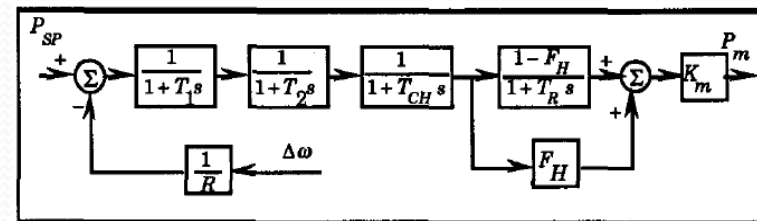


Figure 6: Typical Reheat Turbine Governor Model

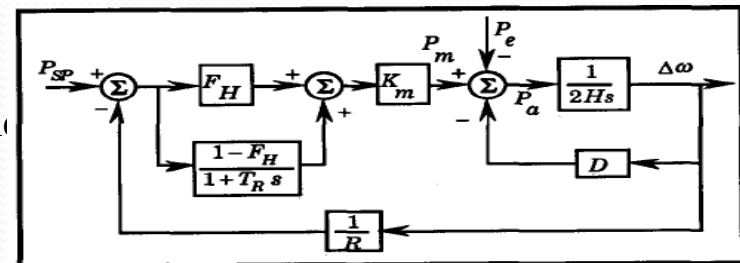


Figure 7: Reduced order SFR model

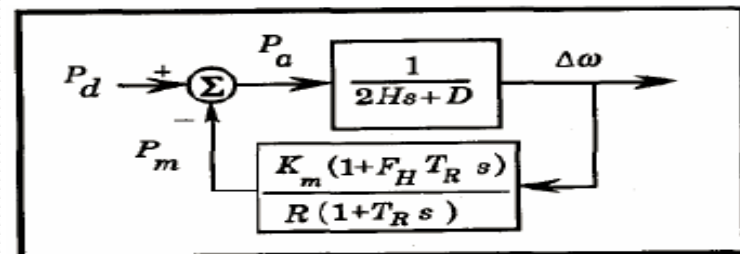


Figure 8: Simplified order SFR model

Frequency Checker Cont...

- Model Validation:
 - We simulated the IEEE RTS-96 system with numerical integration (using PowerWorld simulator[10], results shown in the right) and compared the system frequency response with the reduced model.
 - Despite the fluctuations of the frequency, the two curves share almost the same result.

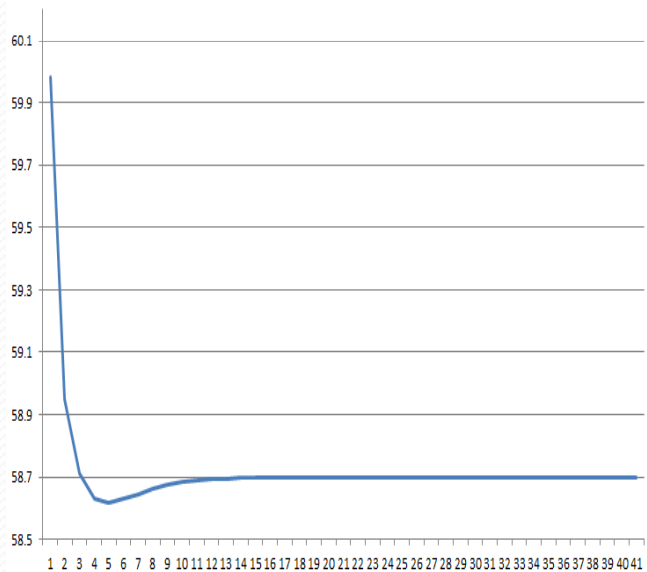


Figure 9: The reduced model result

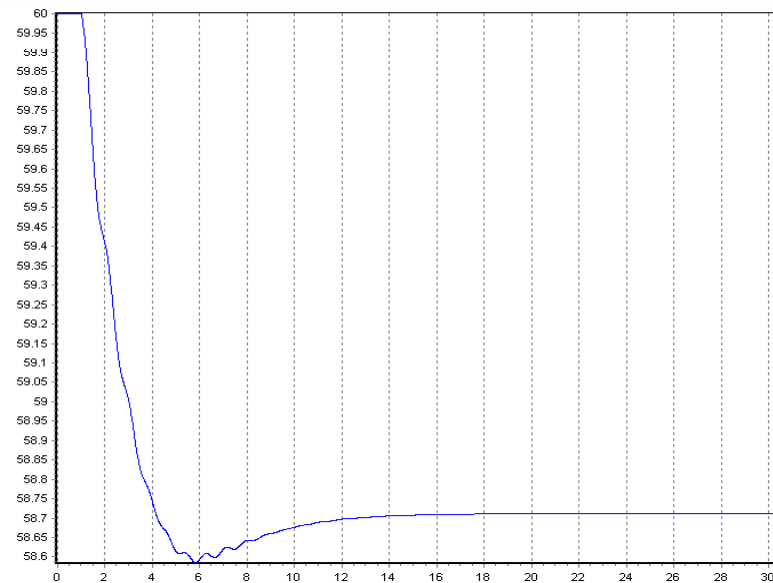


Figure 10: The PowerWorld result

Overload checker, Under voltage Checker

- After the system checks the rotor angle stability and frequency fluctuation, the COA utilizes the PowerWorld AC Power Flow Module to check the MVA loading conditions and the voltage conditions.
- If the component loading is above the threshold, the component will be automatically tripped out.
- If the under voltage happens at the load or generator bus, UVLS schemes will take place by tripping out pre-determined loads.

Simulation and results

- Implementation:
 - A Graphical User Interface is designed to customize the setting of the simulator, including thresholds for voltages, MVA, and under-frequency load shedding (UFLS)
- Simulation:
 - Multiple simulations are performed and validated on IEEE 118 Bus Test Case
 - The test case has 54 Gen, 177 Lines, 3.7GW Load
 - Initial Disturbance:
 - Tripping Line 35-37-1
 - Tripping Transformer 38-37-1
 - Tripping Line 45-49-1
 - Tripping Line 85-88-1

Simulation and Results cont...

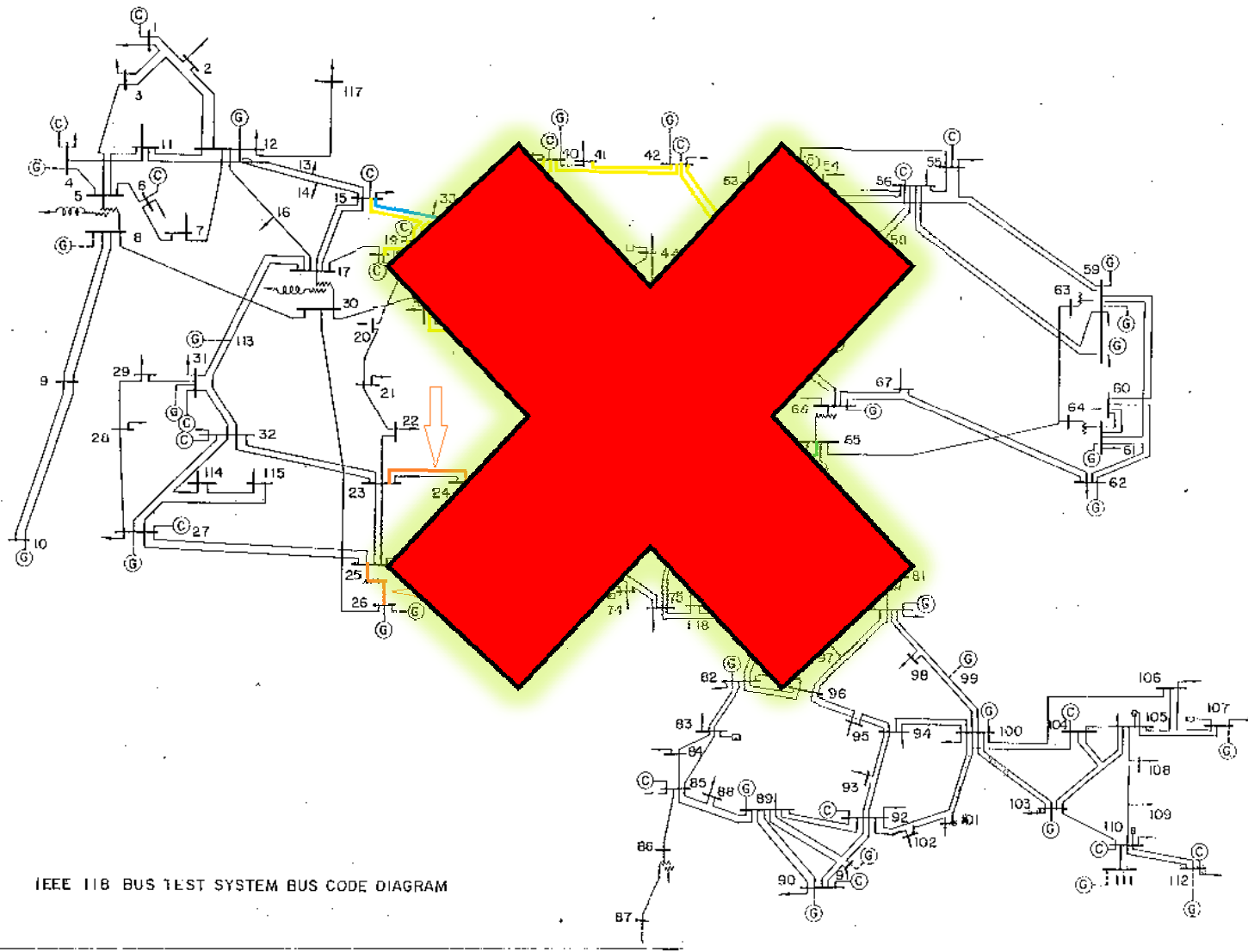


Figure 11: simulation results of IEEE 118 Bus Test System

Integration with Optimization Framework

- The cascading outage analysis is designed to assess the short-term system reactions to some initial disturbances.
- Another analysis tool called Vulnerability of Electric Grids Analyzer (VEGA) is used to utilize the optimization framework and OPF scheme to determine the worst-case medium to long term impacts with possible terrorist attacks.
- Some work has been done to combine these two tools to make integrated systematic analysis of the system vulnerability.

$$\begin{aligned} (\text{Mm}^3) \quad & \max_{\delta \in \Delta} \min_p c'p + d'f(\delta) \\ & \text{s.t. } g(p, \delta) \leq b \\ & \quad p \geq 0 \\ & \quad f(\delta) \text{ from COA model} \end{aligned}$$

Figure 12: Proposed integrated optimization framework

Future Work

- Further modify the checkers and system model to represent more accurate system simulation.
- More tests on large-scale systems (the current implementation could run up to ERCOT scale cases).
- Further incorporate the optimization model and develop efficient algorithm to solve the problem.
- Develop models and techniques to assess the SCADA failures, SPS schemes, etc.
- Compare and contrast the impacts of different natural disasters with terrorist attacks.

References

- [1] “Reducing the Vulnerability of Electric Power Grids to Terrorist Attacks, Final Project Report”, The University of Texas at Austin, Jan. 2009
- [2] Javier Salmeron, Kevin Wood, and Ross Baldick, “*Worst-Case Interdiction Analysis of Large-Scale Electric Power Grids*”, IEEE Transactions on Power Systems, 24(1):96-104, February 2009.
- [3] “Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations”, U.S.-Canada Power System Outage Task Force, April, 2004
- [4] “*Report of the enquiry committee on Grid Disturbance in Northern Region on 30th July 2012 and in Northern, Eastern and Northern-Eastern Region on 31st July 2012*”, Enquiry Committee on India Blackouts 2012, August, 2012
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- [7] IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, “*Definition and Classification of Power System Stability*”, IEEE Transactions on Power Systems, Vol. 19, No. 2, MAY 2004
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- [9] P. M. Anderson and M. Mirheydar “*A Low-Order System Frequency Response Model*”, IEEE Transactions on Power Systems, Vol. 5, No. 3, August 1990
- [10] “Simulator version 16, User’s guide”, PowerWorld Corporation, 2009

Appendix

- Frequency Model:

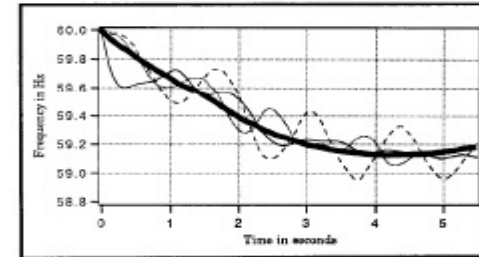


Figure 3.6 Simplified SFR Model with disturbance input¹

The basic SFR model averages the machine dynamic behavior in a large system into an equivalent single machine and it is a representation of only the average system dynamics, while ignoring the inter-machine oscillations shown in figure 3.6.

According to this model, we have the frequency change function in frequency domain

$$\Delta\omega = \left(\frac{R\omega_n^2}{DR + K_m} \right) \left(\frac{(1 + T_R s)P_{step}}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)} \right)$$

where,

- $\Delta\omega$ = Incremental speed, per unit
- T_R = Reheat time constant, seconds
- P_{step} = Disturbance magnitude in per unit (based on the system voltage base SSB)
- D = Damping Factor
- R = Governors droop
- K_m = Mechanical Power Gain Factor
- F_H = Fraction of total power generated by the HP turbine

After transforming this into time domain and simplifying some parameters, we have

$$\Delta\omega(t) = \frac{RP_{step}}{DR + K_m} [1 + \alpha e^{-\omega_r t} \sin(\omega_r t + \phi)]$$

where,

$$\begin{aligned} \omega_n^2 &= \frac{DR + K_m}{2HRT_R} \\ \zeta &= \left(\frac{2HR + (DR + K_m F_H)T_R}{2(DR + K_m)} \right) \omega_n \\ \alpha &= \sqrt{\frac{1 - 2T_R \zeta \omega_n + T_R^2 \omega_n^2}{1 - \zeta^2}} \\ \omega_r &= \omega_n \sqrt{1 - \zeta^2} \\ \phi &= \phi_1 - \phi_2 = \tan^{-1} \left(\frac{\omega_r T_R}{1 - \zeta \omega_n T_R} \right) - \tan^{-1} \left(\frac{\sqrt{1 - \zeta^2}}{-\zeta} \right) \end{aligned}$$