Modeling and Analysis of Cascading Failures in Large-Scale Power Grids

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***Abstract*—This work presents results on the dynamic modeling and analysis of cascading failures in large-scale electric grids. In this study, cascading outages are simulated using a 2000-bus synthetic grid with detailed modeling of generator dynamics, protection systems and other system elements. A selection of N - 2 contingencies are applied to cause an initial system disturbance. The sequence of events following the initial disturbance are recorded and discussed. Analytical studies are performed on two most severe scenarios. Current literature describing the evolution of cascades using power system simulations with dynamic models are limited in quantity. This study aims to contribute to the current literature and to show that simulations utilizing full dynamic modeling of power system elements have the ability to demonstrate cascading failures.**

***Index Terms*—Cascading failures, Power system dynamic simulation, Synthetic networks, Power system protection.**

I. Introduction

In the context of power systems, cascading failures occur when an initial disturbance, or a set of disturbances, triggers the successive outage of multiple system elements [1]. Initial disturbances may include component failure due to aging, natural disasters, poor component design or operating settings, and transmission line or generator outages [2, 3]. When a component fails, transients can cause power to be redistributed across other components in the system. The effects of a component failure may be either contained locally, or it may propagate to components further away, potentially causing wide-spread damage to the power system, or a blackout [2]. The current literature describing the propagation of cascades is quite limited in number. The aim of this study is to bridge this gap by demonstrating the evolution of cascading events using full dynamic models of power system elements.

Although infrequent, large blackouts are expensive, and its impact can propagate into other sectors [4]. The number of recent cascading blackouts around the world and their potential for widespread devastation has prompted the power industry and academia to investigate the mechanisms of cascading failures as well as develop tools to analyze and model such phenomena. Current efforts to understand and mitigate cascading failures can be demonstrated by these studies [2–9].

Most approaches used to understand and assess failure analysis require the use of simulation tools. Developing and validating these tools remains to be a substantial challenge due to the diverse and interdependent set of mechanisms involved with cascading failure propagation. Numerous developmental efforts have been made in the space of modeling and simulation techniques. Most of which have been thoroughly reviewed and strategically judged in these studies [2–7, 9].

Many cascading tools can largely be classified into four general categories: historical data, high-level statistical models, probabilistic simulations, and deterministic simulations [3]. High-level statistical models are used for high-level bulk analysis in which only key features of the cascading system are included. In these types of models, parameters are estimated from short observations or simulations. Unlike using historical data, the models eliminate the need to wait long periods of time for the next large blackout for model parameters to be obtained [3]. An example of these types of models includes the CASCADE model as presented by Dobson, et al. [2, 10].

All simulation techniques assume only a subset of possible mechanisms that are involved in the cascade. Probabilistic simulation involves uniform sampling from a representative subset of possible cascades to quantity aggregate risk and event probabilities [3]. On the other hand, deterministic simulations sample only a particular subset of cascading scenarios for risk mitigation analysis [3]. A summary of known commercially available and research-grade simulation tools can be found in [5]. The tools are classified based on application (planning, operational planning, or real-time environments), sampling algorithms (analytical or Monte Carlo), power flow solution (DC, AC, steady-state or static) and system size limitations.

Notably, recent advancements in integrating machine dynamics into cascading failure models have been proposed and studied in [7, 9]. In the model proposed by Song et al. (COSMIC), the full non-linear dynamic behaviors of a power network and its protection systems are represented as a set of hybrid discrete/continuous differential algebraic equations. Randomized N-2 contingency simulations using COSMIC (1) demonstrate ability to produce good correlation in blackout

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size distribution relative to historical trends, (2) demonstrate that different types of load models produce different cascade sizes [7]. Moreover, the authors of [9] show that the inclusion of machine dynamics reveal additional failures that would otherwise be masked when using static power flow models to simulate a cascading system.

The reaction of a power system to an emergency largely depends on the dynamic behavior of its protection scheme. As reported by NERC (North American Electric Reliability Council), protective relays were involved in the majority of previous major system disturbances [11]. Given the importance of protective relays to a power system's response to a perturbation, it is critical that they are appropriately represented in system test cases during simulations of cascading failures. Five types of relays commonly represented in power system models includes over-current, distance, temperature, under-voltage, and under-frequency load shedding relays. Several key topics that have been brought up and addressed by leaders in the power system community includes, identifying critical relays to represent in a system model or test case [12], representing relay reaction to system transient state changes [7, 13], and the need to appropriately represent line tripping threshold of relays in sequential steady-state analysis [3].

Electric grid test cases are representations of a power system operating at one or multiple states. Most cascading failure analysis involving tool validation or simulations rely on the use of test cases. A summary of some existing test cases categorized by system size, generation and load capacity can be viewed in this study [6]. In addition to test cases reviewed in [6], Texas A&M University (TAMU) has built a growing number of fictitious but realistic 'synthetic' electric grid test cases which capture the complex dynamic behavior of real electric grids and their system elements. Synthetic grid models were developed using publicly available data from actual system cases and do not reveal any confidential information. These test cases are publicly available online [14]. Details on the algorithms used to generate the synthetic test cases, generator cost models, dynamic generator and load modeling are elucidated in these studies [15–19]. In this present study, we will use ACTIVSg2000, a 2000-bus synthetic grid, to model and assess cascading failures. The test case can be downloaded from [14].

The purpose of this paper is to model and analyze cascading failures using large-scale synthetic electric grids [15]. Methods proposed in [18, 20] are used to model and tune system dynamics in the test case according to generator fuel type (i.e., coal, natural gas, nuclear, wind, solar, etc.). Protection systems are modeled based on NERC standards. The dynamic models and relay models integrated test case is capable of simulating system dynamics, and its potential applications include simulating cascading failures and interactive simulations [21, 22]. A selection of N - 2 contingencies is chosen to cause an initial disturbance to the system and the resultant sequences of events are captured and assessed.

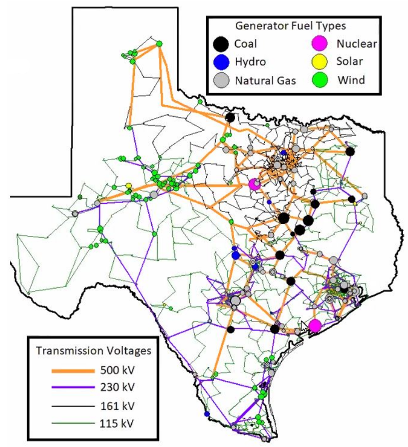


Fig. 1: Synthetic 2000-bus test case oneline diagram. Transmission voltages and generators are sized based on relative MW capacity and color-coded according to fuel type, respectively. This grid is fictitious and is not representative of the actual Texas grid.

TABLE I
SYNTHETIC 2000-BUS TEST CASE STATISTICS

Table	Number
Number of buses	2,000
Number of substations	1,250
Number of areas	8
Number of zones	1
Number of transmission lines	2,345
Number of transformers	861
Number of loads	1,350
Number of generators	544
Total design load(MW)	67,109

The rest of the paper is organized as follows: A detailed description of the synthetic test grid as well as the dynamic models of the generating units and protection relays are presented in Section II. Section III discusses simulations results of cascading events following the N-2 contingencies. Finally, concluding remarks are presented in Section IV.

II. Test Grid

A. Case Information

A 2000-bus synthetic grid is shown in Fig. 1, which is a natural fit for engaging student interest in large power systems at Texas A&M University since it covers the geographic footprint of the Electric Reliability Council of Texas (ERCOT) [15, 23]. Table I and Fig. 1 illustrate 2,345 high-voltage transmission lines at 4 voltage levels, connecting 8 areas and 1,250 substations. Each line is sized according to its transmission voltages. There are 544 generators having about 98 GW of generation capacity and serving about 67 GW of load. The generators are colored-coded according to their fuel types. Fuel types that are represented in the test case include coal, natural gas, nuclear, hydro, solar and wind. A breakdown of the number of units present and installed capacity for each fuel type is shown in Table II.

TABLE II
DETAILS OF GENERATIONS IN THE 2000-BUS CASE

Fuel Type	Number of Units	MW Capacity
Coal	39	6,422
Natural Gas	368	46,945
Nuclear	4	5,137
Solar	22	400
Hydro	25	1,049
Wind	87	8,962
Total	545	68,916

B. Modeling of Machine Dynamics and Protective Relays

Various dynamic models are assigned to generators of the 2000-bus test case according to their fuel types. Reference [18] proposed a way to create dynamic data for synthetic generators based on various fuel types such as natural gas, coal, nuclear and hydro. In work [20], the dynamic cases are further developed through integration of renewable generators.

This present study utilizes the methodology proposed in [18] and [20] to model system dynamics of the 2000-bus test case. Dynamic models and parameter templates are identified and extracted from actual cases and then assigned to generators in the 2000-bus case. Parameters are further tuned to obtain optimal dynamic responses. The generators in the 2000-bus case are mainly natural gas generators with total capacity of 46 GW. Multiple machine (GENROU, GENSAL), governor (GGOV1, HYGOV, IEEEG1), exciter (ESAC1A, ESAC6A, ESDC1A, ESDC2A, ESST4B, EXAC1, EXAC2, EXPIC1, IEEET1, SCRX) and protective relay (TIOCRS, ZLINI) models are utilized in the case. A description of all dynamic models is presented in Table III.

C. Protection Relays in Cascading Failures

The general procedure to model and analyze cascading failures is to first illustrate the response of protective relays to different contingency events. The well-tuned protection system protects the power system from faults by disconnecting the faulted parts from the rest of the electric grid. All simulations are run on the PowerWorld Simulator. A python package, called Easy SimAuto, is used to collect simulation results [24]. The following is an example case of a distance relay with three operating zones. Distance relays are assigned to both ends of the transmission line; each is capable of sending a trip signal to the other end upon sensing faults. The initial event is a balanced three-phase fault on branch 7004-7106 circuit 1. Three scenarios are simulated at different fault locations. In Scenario I, the fault is applied to 10% of the branch from bus 7004 to bus 7106. In Scenario II, the fault is applied to the middle of the branch. In Scenario III, the distance relay on this branch is disabled for comparison. Details of each scenario is expressed in Table IV.

TABLE III
DYNAMIC MODELS USED IN THE TEST CASE

Model	Description	Number
GENROU	Solid rotor generator	411
GENSAL	Salient pole generator	25
GGOV1	GE General Governor-Turbine model	368
HYGOV	Hydro Turbine-Governor model	25
IEEEG1	IEEE Type1 speed-governor model	43
ESAC1A	IEEE TypeAC1A excitation system model	4
ESAC6A	IEEE TypeAC6A excitation system model	7
ESDC1A	IEEE TypeDC1A excitation system model	12
ESDC2A	IEEE TypeDC2A excitation system model	1
ESST4B	IEEE Type ST4B exciter model	279
EXAC1	IEEE Type AC1 excitation system model	6
EXAC2	IEEE Type AC2 excitation system model	38
EXPIC1	Proportional/Integral excitation system model	61
IEEET1	IEEE Type 1 excitation system model	23
SCRX	Bus fed or Solid fed static excitation model	5
TIOCRS	Time Inverse Over-Current Relay Standard	2345
ZLIN1	Distance Relay with 3 zones	4,690
DLSH	Rate of Frequency Load shedding model	1350
LVSH	Undervoltage Load shedding model	1,350
LHFRT	Low/High Frequency ride by Gen protection	543
LHVRT	Low/High Voltage ride by Gen protection	543

TABLE IV
DETAILS OF THE THREE SCENARIOS

Description	Scenario I	Scenario II	Scenario III
Branch	7004-7106	7004-7106	7004-7106
Violation Location	10%	50%	50%
Distance Relay Status	Active	Active	Not Active

Table V summarizes the sequence of events for each scenario after an initial fault. In Scenario I, a fault is applied to Zone 1 and Zone 2 of the relays on the From End and To End, respectively. For optimal fault clearing, Zone 1 and Zone 2 tripping is coordinated by setting a 0.3 s coordination delay for Zone 2. Both ends are opened by protective relays in order to isolate the faulted element. In Scenario II, the fault is applied to Zone 1 of the relays on both the From End and the To End. As a result, the two line relays trip their corresponding circuit breakers simultaneously. In Scenario III, impacts of line faults persists longer since the distance relay on this branch is disabled. This results in multiple relay actions (i.e., 34 load relay LVSH actions and 3 line relay TIOCRS actions) on nearby lines.

The goal of this paper is to showcase the modeling and analysis of cascading failures using a synthetic electric grid that captures system dynamics. N - 2 events are modeled and simulated to examine the system stability under severe contingencies. The following chapter presents the illustrative simulation results to demonstrate the ability of the synthetic test case to replicate cascading events.

III. SIMULATION RESULTS AND DISCUSSION

This section presents results and analysis for N - 2 contingency events using the 2000-bus test grid mentioned above. It is important to note that in actual system operation, outages of transmission lines with higher line flow will have larger impacts on system stability. Under each contingency, two transmission lines out of a list of one hundred transmission lines with the highest power flow were opened at 5 seconds. Thus, the total amount of contingencies simulated will be

TABLE V
SEQUENCE OF EVENTS IN SCENARIO I - III

Sequence of Events in Scenario I		
Contingency Name	Time (s)	Description
Line fault event	1	Apply Solid Fault (3PB)
Line fault event	1.05	Line Relay ZLIN1 Zone 1 action: Open From End
Line fault event	1.35	Line Relay ZLIN1 Zone 2 action: Open To End (Both ends now Open)

Sequence of Events in Scenario II		
Contingency Name	Time (s)	Description
Line fault event	1	Apply Solid Fault (3PB)
Line fault event	1.05	Line Relay ZLIN1 Zone 1 action: Open From End
Line fault event	1.05	Line Relay ZLIN1 Zone 1 action: Open To End (Both ends now Open)

Sequence of Events in Scenario III		
Contingency Name	Time (s)	Description
Line fault event	1	Apply Solid Fault (3PB)
Line fault event	4.51	Load Relay LVSH action: Change Percent Load scalar changed to 0.95. (# of relay actions: 34)
Line fault event	5.04	Line Relay TIOCRS in Device at From Bus action: Open (# of relay actions: 2)
Line fault event	5.71	Line Relay TIOCRS in Device at From Bus action: Open (# of relay actions: 1)

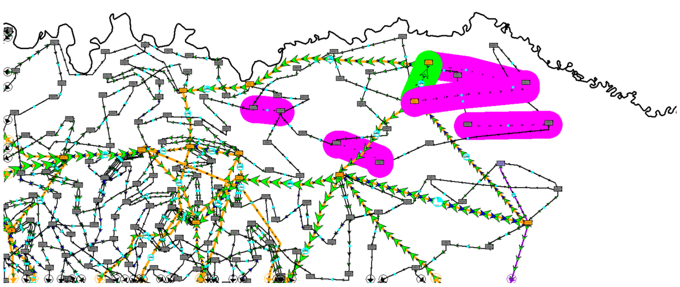


Fig. 2: Zoomed-in display of events after an illustrative N - 2 contingency in the test case. One of the initial opened lines is marked in green. The other opened line is not shown in this zoomed-in view due to its far distance away from lines that were later tripped. Sequential line outages are marked in magenta.

$\binom{100}{2}$ = 4,950. The objective is to perform comprehensive simulations of high-impact low-frequency events in order to determine the system's stability and provide insight into cascading failures. Each dynamic simulation is set to end at 50 seconds since the cascading process is quite fast and most failures occur in the first 20 seconds [25]. The total simulation time is relatively short without sacrificing much accuracy. A time step of 0.250 cycles (4.167 ms) is used in simulation to capture the dynamic response of the system.

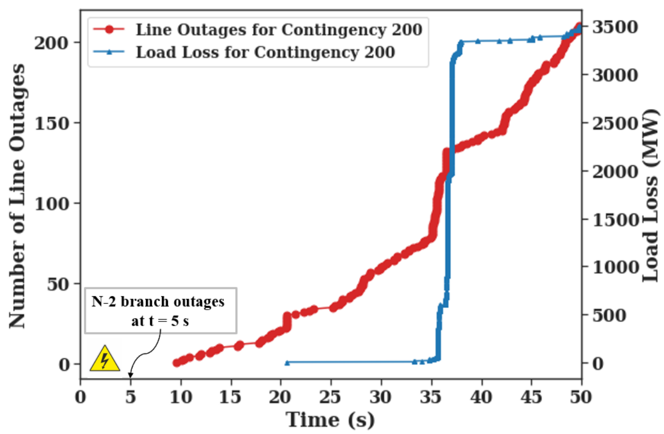
An example result is shown in Fig. 2. Two initial events occurring at 5 s, result in the outage of several other lines. In the figure, one initial event is highlighted in green, while the other is not depicted due to its considerable distance from the center of event. Initial line outages have cascading effects on other lines as well. Lines marked in magenta are tripped successively due to relay actions.

In total, 4,950 N-2 contingency scenarios were simulated, of which 3,906 converged and completed simulation. In this study, only cases which have completed simulation were analyzed. Out of the 3,906 scenarios that converged, only 19 cases were N-2 reliable and did not result in any cascading events while 3,887 cases led to a series of events consisting of line outages and load shedding. The number of transmission line outages and the amount of load shed were used to quantify the size and impact of cascading failures for each contingency.

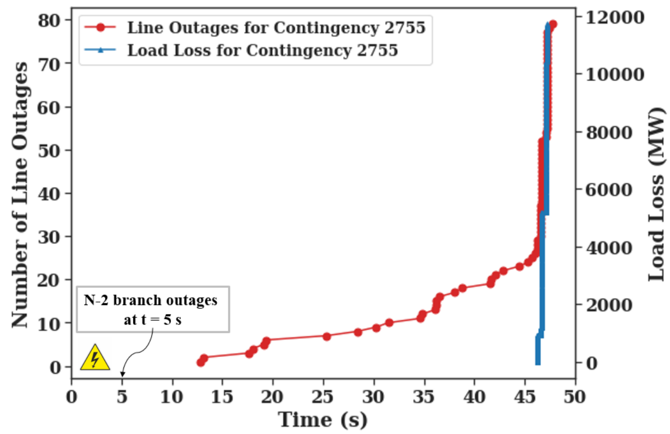
Two of the most severe scenarios are presented as case studies to illustrate the effects of cascading failures. Case study 1 (Contingency_200) resulted in the highest number of line outages while case study 2 (Contingency_2755) resulted in the highest amount of load shed. For both cases, the branches that were taken out of service were 500 kV transmission lines. In case study 1, the two branches (branches 6161-6056 and 7346-7125) that were taken out carried an initial power flow of 1,616 MW and 1,710 MW, respectively. In case study 2, the two branches (branches 5055-5196 and 7199-7331) that were taken out had an initial load of 811 MW and 981 MW, respectively.

Cumulative line outages and load losses over the course of a simulation time of 50 s are illustrated in Fig. 3a and Fig. 3b for case study 1 and case study 2, respectively. The N-2 contingency is simulated by opening two transmission lines at t = 5 s. It was observed that the concentration of line outages with respect to time is heavily correlated with the trajectory of load loss. In case study 1, transmission line outages began to occur 4.6 s after the initial N-2 branch outages. Line outages between 35 s and 38 s were much more concentrated than ones that occurred during the first 35 s. Consequently, there was a dramatic increase in load loss between 35 s and 38 s. By the end of simulation, case study 1 experienced a total of 210 line outages and 3,496 MW of load loss. A similar trend was observed for case study 2. In case study 2, line outages began to occur at around 7.8 s after the initial N-2 branch outages. Line outages during the first 46 s were sparse enough to leave the system load unaltered, but the system was successively weakened. However, at approximately 46 s until 48 s, the line outages occur rapidly in succession, leading to a rapid increase in the amount of load loss. By the end of simulation, case study 2 experienced a total of 79 line outages and 11,726 MW of load loss.

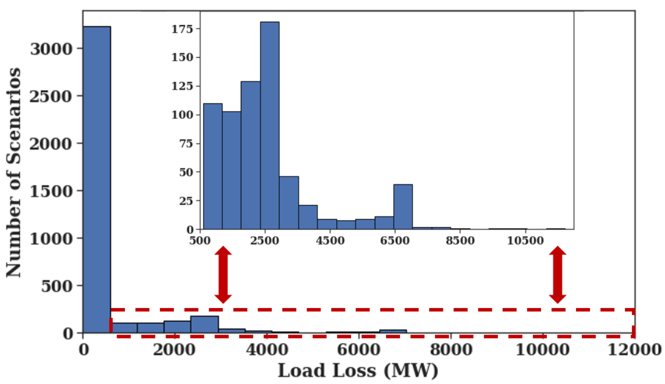
The distribution of load loss and line outage events across all N-2 converged contingency scenarios are shown in Fig. 3c and Fig. 3d, respectively. Most contingencies resulted in relatively minor load losses with a median loss of 4.6 MW. The average load loss was 481 MW, which is skewed towards the high values by more severe but rare load losses such as the losses observed from case study 2. About 83% of converged cases resulted in a load shed of less than 600 MW. The distribution of line outage events demonstrates a similar bias towards less severe outcomes with a median line outage count of 33 and a mean count of 45.



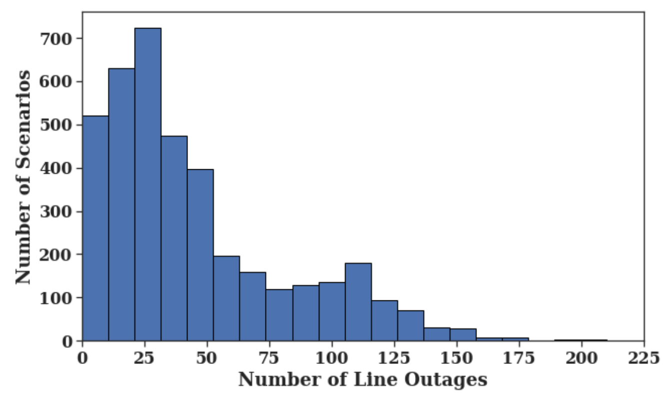
(a) Number of Line outage events and load loss for case study 1.



(b) Number of Line outage events and load loss for case study 2.



(c) Distribution of cumulative load loss.



(d) Distribution of cumulative line outage events.

Fig. 3: (a) and (b) depict the timeline of cumulative transmission line outage events and their associated cumulative load-shedding events following the initial two branch outages in case study 1 (Contingency_200) and case study 2 (Contingency_2755), respectively. (c) and (d) respectively illustrate the distribution of load loss and line outages across all 3,906 N-2 contingencies which converged.

IV. Conclusions

This paper presents the analysis of cascading failure impacts on the power grid. The AGTIVSg2000 2000-bus synthetic grid was selected as a test bed to capture the full dynamic response of renewable generators, machines, governors, exciters and protection relays to initial N-2 branch outages. The subset of N-2 contingency scenarios were selected from the top 100 transmission lines out of 2,345 lines that were carrying the highest initial MVA load. A total of 4,950 contingency scenarios were simulated over 50 s, and the system responses to those contingencies were analyzed. Of all N-2 scenarios that were simulated, 3,906 cases (80% of cases) completed the simulation time of 50 s and 19 cases (0.5%) did not result in any cascading events.

The system response from each contingency were varied. A majority of the contingencies resulted in relatively minor load shed (600 MW or less), but rare occurrences of severe load shedding events were present as well. The time-series analysis of line outage and load shedding events for the two most severe cases show that relative speed of line outage is heavily correlated with the amount of load loss in the system.

Acknowledgments

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