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Towards Incorporating Protection and Uncertainty into Cascading Failure Simulation and Analysis

Ian Dobson
Iowa State Univ.
dobson@iastate.edu

Alexander Flueck
Illinois Inst. Technology
flueck@iit.edu

Sandro Aquiles-Perez
Electrocon International
sandro@electrocon.com

Shrirang Abhyankar
Argonne National Lab
abhyshr@anl.gov

Junjian Qi
Univ. Central Florida
Junjian.Qi@ucf.edu

***Abstract*—We advance the state-of-the-art in cascading failure simulation through an integrated modeling of system dynamics and protection coupled with data processing that analyzes the simulation results. An enhanced version of the TS3ph-CAPE simulator is used to produce the cascading data. The cascading data is processed to produce metrics describing the cascading size and risk, and to identify critical components contributing most to the cascading risk.**

I. INTRODUCTION

The protection system operation and misoperation plays a central role in blackouts because it is the main way that power system components are disconnected and load is shed. Widespread cascading blackouts always involve many protection actions that interact with each other and with the power system transient dynamics that are excited by the progression of events [1]–[3]. The protection system and transient interactions that cause blackouts are often unusual, rare, or poorly understood interactions, because the most common and easily analyzed problems have already been eliminated by engineers.

If we deterministically simulate the typical performance of the power system, we will usually not encounter cascading events. That is, the power grid is designed and operated to have high reliability, so that its typical behavior has little cascading. But cascading does sometimes occur when combinations of rare and unusual events happen, and we do need to somehow account for this. The way forward is to simulate the power grid in a probabilistic way that allows for rare events or interactions to occur and then process the results to evaluate the risk of the cascading and to identify critical components [4]. Indeed this paper pursues this goal with advanced simulation and new data processing in order to initially demonstrate this innovative and useful approach to power system reliability.

To elaborate, we can contrast two approaches to studying and mitigating cascading:

(1) Analysis of typical performance. One chooses a moderately stressed power system condition, and simulates the likely and typical performance for a class of faults. The protection system is assumed to work as designed. If any fault leads to significant cascading then that cascade is mitigated.

(2) In a comprehensive analysis sampling all performance, one samples from a range of stressed power system conditions, and simulates the performance for a class of faults. The protection system failures and more unusual interactions are considered. Many possibilities, including a sampling of rare events and interactions, are simulated. The risk of cascading is quantified. If the risk of cascading is too high, critical components contributing to that risk are identified and mitigated. Note that if one performs a comprehensive sampling of all the possibilities, a risk based approach is essential because it is not economic to mitigate combinations of events with low risk.

This paper initiates work towards approach (2) by developing detailed protection system modeling and analysis that samples from the initiating faults and considers the possibilities of stuck breakers. Some aspects of the paper are elaborated in much more detail in the forthcoming report [5].

Given the central importance of the protection system actions and the ubiquity of dynamic transients as the protection acts, one would think that the study of unusual protection system interactions would be routine. This is far from the case. The state of the art for detailed protection system design is to simulate typical cases on a more individual basis and to screen deterministically for some limited possibilities, particularly the case of a single contingency of one component failing or one misoperation that underlies the N-1 criterion. And when analyzing cascading failure at the system level, the state of the art usually ignores dynamics and models the protection system in a very crude way. For example, the TRELSS industry cascading failure model has groups of protection devices acting together and ignores transient dynamics [6]. Another example is the protection hidden failure modeling in which lines whose ends are "exposed" by a line outage trip with a loading dependent probability [7]. Recent work is progressing to deterministically model the typical behavior of protection models and dynamics with an applicability to cascading in large systems [8]. The objectives of our work complement [8] by simulating in a probabilistic context a smaller network with more detailed protection models. Indeed, our simulation platform, known as TS3ph-CAPE, models the transmission network as a complete three-phase, possibly unbalanced, system and models the protection system down to the individual manufacturer specific relays. Additional details are provided in the next section.

II. SIMULATION WITH DETAILED PROTECTION MODELS

In this work, an integrated dynamics and protection simulator, TS3ph-CAPE, shown in Fig. 1, is used for producing the cascading data. TS3ph-CAPE uses a full three-phase representation of the power system to enable analysis of unbalanced operating conditions, such as unbalanced loads and disturbances, and includes a variety of generator, control, and load models. To simulate the role of protection in cascading failures, the simulator interfaces with Electrocon's widely-use commercial package CAPE. TS3ph and CAPE communicate

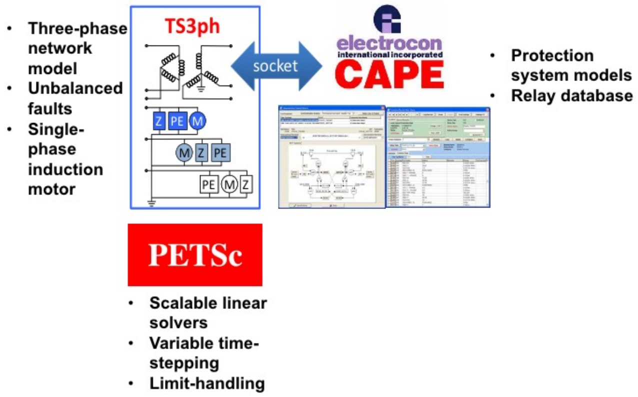

Fig. 1. TS3ph-CAPE platform architecture

through a socket at the end of each time domain integration step. Once the differential and algebraic equations describing the generation and transmission systems have been solved, TS3ph passes three-phase voltages and three-phase currents to CAPE. Then, CAPE evaluates the relay elements and notifies TS3ph of any future breaker operations.

TS3ph models the entire transmission system as a three-phase network, including three-phase transformer configurations, such as delta-wye-grounded. Three-phase models were chosen to make it easier to include unbalanced operating conditions, such as untransposed transmission lines, single-pole switching and independently controlled transmission devices, such as a static var compensator (SVC).

For the generation system, detailed round-rotor and salient pole machines can be included, along with saturation. Common exciters, governors, stabilizers and compensators can be included also. These generator controllers typically contain nonlinear elements, such as windup and non-windup limiters, as well as deadband elements.

For the system loads, a basic static model is available for real and reactive power load as a function of voltage magnitude. Additionally, a three-phase induction motor model is available with five dynamic states.

For the protection system, CAPE has hundreds of manufacturer specific relay models available. For this project, the following common relay elements were incorporated into the various substations:

- distance (line protection)
- over-current (backup protection)
- current differential (bus and transformer protection)
- under-/over-frequency (generator protection)

In addition to modeling the relay elements, the TS3ph-CAPE simulator has the ability to model breaker failure. At the end of each time-domain integration step, TS3ph sends voltages, currents and breaker status values to CAPE and receives breaker operations from CAPE. For each breaker operation, TS3ph "rolls the dice" and determines if the breaker operation should be executed. This decision involves the comparison of a randomly generated number against a user-defined threshold. If the breaker operation is determined to have "failed", then TS3ph ignores the switching instruction received from CAPE. Although the TS3ph-CAPE simulator has the ability to do so, proper breaker failure protection, that would normally contain cascading provoked by a stuck breaker on a faulted system, was not modeled for this project.

TS3ph models disturbances as switching events. Unbalanced faults, such as single-line-to-ground, line-to-line and double-line-to-ground faults can be included at any time during the simulation. Three-phase faults also can be included. Both bus faults and "end-of-line" faults can be simulated.

For large-scale simulations, TS3ph has the ability to run the computations in parallel across multiple processing cores. TS3ph is built on the parallel-enabled PETSc library developed by Argonne National Laboratory. PETSc provides state-of-the-art data structures, linear solvers, nonlinear solvers, time-domain integration algorithms and interfaces to third-party applications, such as partitioning packages for parallel computation.

III. SIMULATED CASCADES

The cascading data produced by the enhanced version of the TS3ph-CAPE simulator is summarized:

(1) Many sampled cascades. Here a cascade of events includes an initiating event such as a line fault that is possibly followed by a series of dependent events. We need to include in the cascades not only the long cascades of most interest that lead to load shed, but also the single initiating events and the shorter cascades, since these are successes that need to be included in any fair assessment of risk.

(2) There is variation and uncertainty in the system initial state, the initiating faults, and the progress of the cascade [9]. To be realistic, multiple cascades must be sampled in an unbiased way across the full ranges of uncertainties in order to properly estimate the probabilities and risks of cascading. This paper samples from the following uncertainties: (a) initial loading level, (b) initiating fault, and (c) whether a breaker fails to open when it is supposed to.

(3) The simulated cascading output data required for analysis is a list of discrete events with the exact time that they occurred and the component description. The discrete events include initiating fault, line and transformer trips, breaker misoperations, and load shed.

The test system has 130 buses. Two of the cascades are shown in Fig. 2.

IV. PROCESSING CASCADING DATA TO OBTAIN PROPAGATION AND RISK METRICS

The first task is to divide the events of each cascade into generations. Each generation of events either ends the cascade or produces a further generation of events. Generally primary protection acts as locally as possible to isolate a fault and secondary protection of neighboring components only acts if there is a misoperation or a severe transient. Accordingly, the outages in a cascade are divided into successive generations

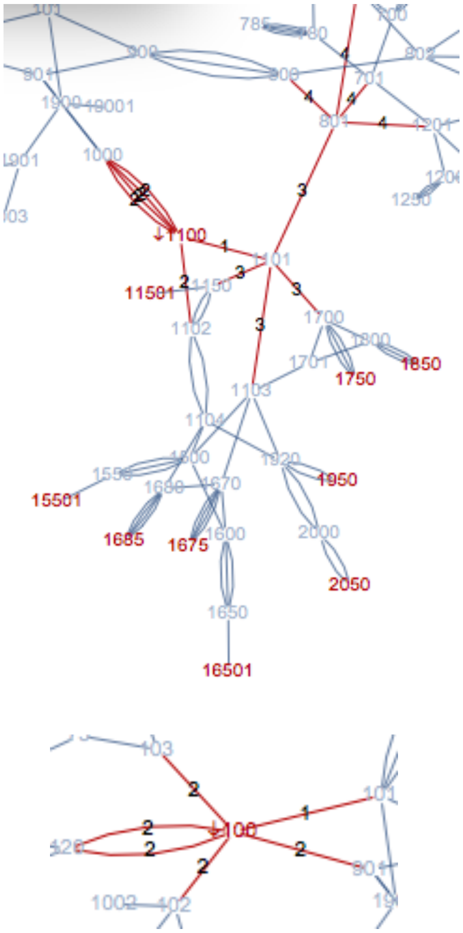

Fig. 2. Two examples of simulated cascades on the 130-bus test system. Numbers on lines are the generation number. The initial line fault occurs on the line labeled generation 1. These simulation results evaluate the consequence of a stuck breaker at the red bus that is specially indicated by a down arrow. Red lines are outaged in the cascade and red buses with no down arrow are buses at which load is shed. (The lower cascade sheds no load.)

according to their distance in the network[1] from the initial fault. The generations of lines for two example cascades are shown in Fig. 2. Moreover, if a breaker fails, then all subsequent events form a new generation.

Most events only involve primary protection outaging components next to the fault and all these outages are considered to be generation one. In this paper we consider only line faults in generation one, but the methods can be generalized. Occasionally the outages spread beyond the primary protection to higher generations further from the fault. The cascading events include load shed as well outages of lines and transformers and protection misoperations. Any load shed is assigned to the previously occurring highest generation.

This processing of the cascading events into generations based primarily on distance in the network and breaker misoperations is crude and simple. However, this simple processing appears to work well for our initial cascading data. In particular, the generations defined this way mostly agree with the time order of the events. Reference [10] processes cascading events into generations based on event timing. More sophisticated processing into generations based on both space and time are expected for the more general cascades simulated in future work.

1) Metrics for cascade size, propagation, cost and risk: The size of the cascade can be measured in terms of the MW load shed, the estimated blackout cost, the number of lines/transformers tripped or the number of isolated buses [11]. It is useful to express these metrics as the average cascade size; that is, the cascade size averaged over the sampled line faults. The average cascade size is the expected value of the cascade size assuming that each of the line faults is equally likely. (While we do not consider this, the extension to a weighted sum that considers line faults with different probabilities is straightforward.) Thus the average cascade size over a sample of line faults is naturally a probability-based metric. In particular, the average cost (the expected value of cascade cost) is the cascade risk.

The usual consequence of a line fault is that the breakers open at both ends of the line, and that radially connected load supplied through that line (if any) is shed. However, there is a small probability p_{stuck} that one of the breakers at the ends of the line will stick and fail to open. We use the representative value $p_{\text{stuck}} = 0.01$ based on the range of values in [12]. The simulation evaluates the impact of the stuck breaker. A breaker sticking has the same effect as a bus fault at that end of the line. Given the straightforward consequences of the correctly operating breakers (one line outaged, no transformers outaged, only radial load shed), for this paper it is efficient to only simulate the bus faults, and account for the correctly opening breakers in the processing [5].

We divide the cascade into the primary protection initial events in generation 1 and the subsequent events in generations 2 and higher. We can measure the size of the initial part of the cascade, the size of the subsequent part of the cascade and the total cascade size. Of particular interest is the size of the subsequent part of the cascade, since this quantifies the events beyond the necessary primary protection actions that are generally considered as "cascading".

Blackout costs are difficult to estimate, even if only the direct blackout costs are considered and the very significant reputational, regulatory and other indirect costs are neglected. However, because the investment in mitigation should be driven by cost and risk, it is necessary to make some approximate assumption about blackout costs. Here we follow [13] in approximating direct blackout costs in dollars as [2] $C = 500(\text{real power shed})^{1.5}$ \$. The expected value R of the cost metric C properly accounts for fault and breaker misoperation probability as well as the cost or impact of the blackout and therefore R is a measure of cascading risk:

$$R = \sum_{\text{cascades}} (\text{cascade probability})\,(\text{cascade cost } C). \qquad (1)$$

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[1] Network distance between 2 elements is defined as the minimum number of buses one has to pass through in the network to pass from one element to the other element. For example, lines with a common bus are distance 1 apart.

[2] The constant multiplier 500 is very approximate and is obtained by combining the estimate EENS $= 0.5(\text{real power shed})^{1.5}$ MWh from [13] with a blackout cost guesstimate of \$1000 for 1 MWh.

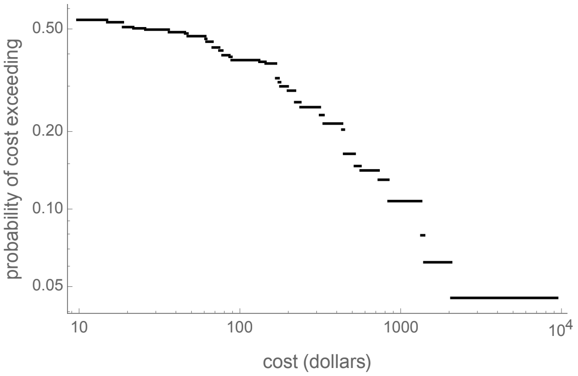

Fig. 3. Survival function probability distribution of cascade cost. Almost half the cascades have cost zero. Note log-log scale.

More precisely, R is the system cascading risk assuming a line fault.

There are two metrics that directly describe the cascade propagation. ρ is the average probability that a generation of events produces a further generation, and N_{gen} is the average number of generations. These two metrics are closely related according to $N_{\text{gen}} = \frac{1}{1-\rho}$ or $\rho = 1 - \frac{1}{N_{\text{gen}}}$.

Table I shows metrics for the 130-bus test system. These metrics are system-wide probability weighted averages of the metrics assuming a line fault. The last column of Table I shows the metrics quantifying the increased cascading size and risk when the load is increased by 50%. Changes in metrics can be useful in assessing system upgrades.

Fig. 3 shows a large range of cascade costs from zero to almost 10,000 and a probability distribution of cost with a heavy tail. The heavy tail implies that higher impact low frequency cascades occur both rarely and routinely, and this makes these cascades a substantial concern. (In contrast, extreme events are vanishingly unlikely in most conventional probability distributions with exponentially decreasing tails.) Heavy tails in the distribution of cascade size or impact are a characteristic feature of the cascading phenomenon [10], [13], [14].

2) Critical components and mitigation: We present two initial approaches to risk mitigation.

The first approach focuses on mitigating breaker failures and line faults at the beginning of the cascade. Equation (1) for total risk has terms $p_{\text{cascade}} C_{\text{cascade}}$ that are the risk contribution of the cascading following a stuck breaker after a line fault. We can rank these contributions of these buses to the risk, and focus on maintaining the relays and breakers at these buses or hardening the lines incident on these buses against line faults.

Looking more closely at the total risk of 12.37 in Table I, it is useful to examine the bus faults that contribute the most to the total risk. Table II shows the top 5 bus faults that contribute most to the risk. Table II shows that the top 3 bus faults at buses 1101, 1100, 1000 are responsible for (4.17 + 2.09 + 2.09)/12.32=68% of the risk. Therefore mitigating the risk by suppressing the beginnings of the cascade should focus on maintaining the relays and breakers at buses 1101, 1100, 1000, or hardening the lines incident on buses 1101, 1100, 1000 against faults. Here we are mitigating the subsequent cascading risk in generations 2 and higher, since the part of the risk directly due to the initial line fault corresponds to correct protection action and is always incurred.

TABLE I. CASCADING METRICS

cascading metric	base case load	1.5×base case load
real power shed (MW)	0.0543	0.07586
risk R ($)	12.37	43.38
number of lines out	1.051	1.065
number of transformers out	0.0344	0.04611
number of generations N_{gen}	1.041	1.046
chance of further propagation ρ	0.0397	0.0439

The second approach focuses on mitigating the cascading risk throughout the cascade as it propagates. The idea is to associate each component (line or transformer) with the "risk after", which is the total risk of the subsequent cascading *after* that component outages in any cascade. "After" means that the time of the outages in the subsequent cascading is strictly greater than the time of the component outage. The "cost after" for each cascade is then multiplied by the probability of the subsequent part of the cascading and then summed over the cascades involving that component to obtain the "risk after". The rationale for the "risk after" is that if the component had not outaged in the cascades then the subsequent load shed would often be mitigated. "Risk after" accounts for the component participation in any of the cascades, weighted to account for more heavily cascades that are more likely and that have higher cost (more load shed) after that component fails. A component that outages in cascades with no subsequent load loss in each of these cascades will have "risk after" of zero.

The components with the top 5 values of "risk after" are shown in Table III. Mitigation of these components outaging, either by hardening the component so that it tends not to outage, or by mitigating the effects of the component outaging on other components can be expected to suppress the interactions by which the cascade propagates further to cause load shed and incur blackout cost.

TABLE II. 5 BUS FAULTS THAT CONTRIBUTE MOST TO CASCADE RISK

faulted bus	probability	cost	risk contribution
1101	0.000444	9390.	4.17
1100	0.000222	9390.	2.09
1000	0.000222	9390.	2.09
1301	0.000556	1340.	0.746
1701	0.000333	2060.	0.688

TABLE III. "RISK AFTER" FOR THE 5 MOST CRITICAL COMPONENTS

Component	Risk after
LINE 1100-1101 (1)	0.010625
LINE 801-1101 (1)	0.00910711
LINE 1100-1102 (1)	0.00758926
LINE 1101-1700 (1)	0.00655778
TRANSFORMER 1101-1150 (1)	0.0060714

V. CONCLUSION

Modeling, simulation, and analysis of cascading failure is a challenging task, yet it is becoming increasingly important as more cascading failures have been observed over the last two decades. This paper advances the state-of-the-art in cascading failure studies by demonstrating an initial proof of principle for:

(1) Use of integrated dynamics and protection models that more accurately model a cascading failure. TS3ph, a three-phase dynamics simulator, is interfaced with Electrocon's protection simulation tool CAPE to accurately represent the response of the protection actions as the dynamics evolve after an initial disturbance. This integrated dynamics and protection simulation philosophy brings together protection and transmission (or distribution) planning/operation engineers who typically work in silos.

(2) Providing new ways of processing volumes of cascading simulation data, including rare but high-impact events, to compute metrics to quantify cascading impact and risk. Metrics for cascade size (in terms of MW load shed, number of lines or transformers outaged), cascading propagation, and cascade risk and cost are formulated and presented.

(3) Developing two new ways to identify critical components, the elements that participate most in cascading failures, for mitigating the risk of cascading. The first approach focuses on breaker failures and line faults at the beginning of the cascade, while the second one associates a "risk after" value for each component that describes the total risk of subsequent cascading after that component outages.

(4) Instead of examining a handful of most likely outages or cascades, as typically done in the industry, our methodology samples more comprehensively from a series of events that span low-probability low-impact events to the low-probability high-impact events that can pose a substantial risk. Accounting for these rare but risky cascading events produces much data, so to be useful, the advances in modeling and simulation are coupled with advances in data processing and analytics that compute meaningful metrics from the voluminous cascading outage simulation data.

A 130-bus system was prepared to demonstrate the modeling, simulation, and analysis advancements done in this project. A series of simulations were conducted involving bus fault events that produced tripping of equipment and load loss. The analysis of this cascading simulation data provides insight into the cascading size, propagation, and risk, and a crude estimate of the dollar impact. It is important to follow analysis through to the dollar impact, even if the estimates are rough, since this provides quantitative guidance for justifiable investments in mitigation. The cascading risk increased three-fold when the loading on the system increased by 50%. The analysis also provides information on critical elements that participate most in the cascade initiation or propagation. The analysis enables the joint consideration of both more frequent, smaller cascading outages and rarer, higher impact outages. Both should be mitigated for high reliability and the analysis allows this to be done on the basis of their contribution to overall risk.

We have developed an initial version of practical risk-based cascading simulation, with detailed dynamics and protection, and analysis that accounts for high impact low probability events in power system. Compared with the existing cascading failure simulation and analysis tools that consider protection systems and dynamics, including the Dynamic Contingency Analysis Tool (DCAT) developed by PNNL [8], this project uses detailed dynamics modeling (three-phase network and single-phase induction motor with stalling capability) and protection system models in CAPE for high-fidelity protection modeling. There are prospects for faster simulation for larger networks (assuming data availability). We also have initiated a new analysis methodology that uses a probabilistic/risk based approach to perform systematic sampling and risk quantification from the simulation output.

An important step in the future is to expand the range, depth, and speed of the combined modeling, simulation, and data processing to encompass more different types of events and interactions. Pursuing this in an integrated way will enable a comprehensive risk-based identification and mitigation of the protection related mechanisms of cascading failure.

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