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The Probabilistic Modeling of Common-Cause Failures and Failure Bunching in a Transmission System Reliability Model

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SUMMARY

Con Edison's electric power transmission system is designed to withstand at least a single contingency without having to drop load and much is designed to withstand additional contingencies. As such, the possible occurrence of common-cause failures and "failure bunching" are of particular concern as they might eliminate multiple transmission pathways and redundancies that are expected to prevent load drop. In this paper, we describe how common-cause failures and "failure bunching" are addressed in Con Edison's transmission system probabilistic reliability model—a detailed reliability model of its transmission system that makes use of a chronological Monte Carlo simulation of the system that, when combined with a massive contingency analysis allows us to determine whether and when thermal overloads and substation voltage problems occur.

Incorporating these models of common-cause failures and failure bunching into the probabilistic reliability model of its transmission system, the Fussell-Vesely importance of each component and failure mode to the predicted load drop frequency is ranked after calculating the percentage contribution of load drop events involving the specific failure or cause of failure bunching of interest to the total predicted load drop frequency. Early application of the transmission system reliability program identified mis-operation of relay protection schemes with communication channels or other equipment shared as being the dominant predicted cause of load drop. This vulnerability has been eliminated by replacement of or upgrades to relay protection schemes. Among the causes of failure bunching, multiple lightning strikes on overhead lines and outdoor substations appear to contribute ~ 11 % of predicted load drop events. In conclusion. **t**he modeling of common-cause failures and failures susceptible to bunching is described and the importance of addressing these types of failures in a conservatively design transmission system is demonstrated.

KEYWORDS

Transmission, reliability, probabilistic modeling, Monte Carlo, simulation, common-cause failures, failure bunching, weather.

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Introduction

Con Edison’s electric power transmission system is designed to withstand at least a single contingency without having to drop load and much is designed to withstand additional contingencies. As such, the possible occurrence of common-cause failures and “failure bunching” [1, 2] are of particular concern as they might eliminate multiple transmission pathways and redundancies that are expected to prevent load drop.

In this paper, we describe how common-cause failures and “failure bunching” are addressed in Con Edison’s transmission system probabilistic reliability model

The System

The Consolidated Edison Company of New York, Inc. (Con Edison) provides electric service to approximately 3.3 million customers in New York City and adjoining areas. Its transmission facilities are located in New York City and surrounding counties in New York State. They comprise 438 miles of overhead circuits operating at 138, 230, 345 and 500 kilovolts, 727 miles of underground circuits operating at 69, 138 and 345 kilovolts, 38 transmission substations and 63 area substations.

Con Edison provides electric service to numerous customers in New York City and adjoining areas. A noted feature of Con Edison's transmission system is its robustness: an imperative given that it serves a very high load density area and the institutions that comprise the nation's financial capital. Con Edison’s electric power transmission system is designed to withstand at least one and usually more contingencies at peak load. Thus, even at times of peak demand, multiple contingencies must occur before load is dropped. Furthermore, system operators can make use of spare transformers, transformer tap changers, phase angle regulators, reactors, capacitors and spare generating capacity as well as voltage reduction and demand response programs to mitigate these contingencies. In these circumstances, it can be seen that load drop is likely only when multiple or cascading contingencies occur in a short period of time or when equipment—specifically transformers—is out of service for prolonged periods of time.

In this system, the vulnerabilities to common-cause failures and conditions that might precipitate multiple failures that prevail simultaneously include:

1. Use of towers or supporting structures or a right of way shared by multiple feeders
2. Shared components in relay protection schemes
3. Shared auxiliaries (e.g., underground feeder cooling oil pumping plants)
4. Secondary failures
5. Adverse weather.

We will look at the modeling of these in turn. Before doing so, we should note that only random failures for which utility failure data are available are considered here. We do not touch upon such common-cause outages as earthquakes, physical attacks, cyber-attacks and “space weather”, all of which are discussed elsewhere [4].

The Model

To help ensure high reliability is maintained in a cost-effective fashion Con Edison has developed and makes use of a detailed reliability model of its transmission system [3]. It makes use of a chronological Monte Carlo simulation of the system that, when combined with a massive contingency analysis allows us to determine whether and when thermal overloads and substation voltage problems occur. A failure or inability to mitigate these might require that load be dropped.

Use of Towers or Supporting Structures or a Right of Way Shared by Multiple Feeders

Overhead feeders are vulnerable to common-cause failures if they share towers or a right-of-way as a result of damage to a tower, the sagging of lines or trees falling across feeders. Such failures are allowed for in the model, applying a "Beta factor" approach using Con Edison failure data. The same approach has been taken to model an instance where multiple feeders are slung below an elevated roadway. Here, both catastrophic damage to the roadway and a fuel spill and fire on a traffic deck, and the loss of all feeders, and the failure of individual feeder segments on the bridge are considered.

Shared Components in Relay Protection Schemes

Relay protection schemes that share communication channels, cabinets or other equipment might mis-operate "out of the blue" or in response to a fault causing the unwanted opening of breakers in one or more feeders and consequent feeder isolation. These failures are addressed in the transmission system model, relay protection schemes that share equipment having been identified. The failure rates and outage durations for the mis-operation of shared relay protection schemes are derived from Con Ediosn data, Bayesian updates being used to provide rates for each scheme and type of scheme.

Shared Auxiliaries

Underground transmission lines cooled by circulating oil transferred to and from pump plants will be removed from service immediately should circulation stop. In modeling the loss of cooling, we consider:

- The loss of the entire pumping plant and the removal from service of all feeders cooled by the plant. This loss might be caused by a fire that engulfs the plant or a complete loss of electric power to the plant.
- The loss of one or more feeders as a result of the rupture of a coolant line within the plant or pump failure.

These events are modeled, the frequencies of occurrence being derived from historical failure data.

Secondary Failures

A secondary failure of concern occurring in a transmission system is the catastrophic failure of a transformer subsequent to a through fault. This secondary failure might be instantaneous or delayed, the event resulting in degradation of the transformer. Secondary failures are modeled explicitly, their likelihoods being derived from failure data.

Other secondary failures modeled include the unwanted opening of breakers or faults on other feeders on the occurrence of a fault in a substation or the feeders leading to it. The conditional likelihood of these secondary events occurring is derived from Con Edison's failure data. We would note here that in modeling secondary failures, we make no assumptions as to causality—the model reflects the pattern of failures experienced.

Finally, having observed that faults and "out on emergency" events are more likely to occur in a substation whilst or immediately after maintenance is performed there, the failure rates for these events are increased whilst maintenance is underway or recently completed.

Adverse Weather Excluding Lightning

Adverse weather can affect transmission feeders and equipment over a wide area, increasing the probability of multiple failures and "failure bunching" and thus of load drop even in a conservatively designed system. As has been noted [5], to ignore these "weather effects can be quite misleading and optimistic".

In discussing the effect of adverse weather on transmission system reliability, we will distinguish between the modeling of lightning and other adverse weather. For the latter, we gathered hourly climate data[1] for a 10-year period at weather stations near to where overhead transmission lines and outdoor structures are located and equipment failure data for the same period. Examining the counts of specific failures occurring while the weather condition of concern prevailed or did not prevail, we can ascertain whether the weather condition has a statistically significant effect on the failure rate. If it did, failure rate multipliers are calculated to apply in the simulation whilst the adverse weather condition prevails. The components considered in these analyses are breakers, buses, circuit switchers, disconnect switches, transmission lines, reactors, phase angle regulators and transformers; the weather conditions examined were frozen precipitation, wind speed (in excess of 20 mph), rain and heat waves, both rain and heat waves[2] being in the absence of lightning.

The failure types considered were faults and device opening, literally for breakers, circuit switchers and disconnect switches. For other equipment device opening refers to the opening of the protective devices around them.

From the analysis of these data, we conclude that adverse weather has statistically significant effects as shown in Table 1.

Table 1

Statistically Significant Effects of Adverse Weather on Equipment Reliability

Equipment	Failure Mode	Adverse Weather	Failure Rate Multiplier
Breaker	Open	Frozen precipitation	2.11
Bus	Fault	Rain	3.40
Capacitor	Open	Heat wave	2.26
Circuit switcher	Open	Rain	3.79
Disconnect switch	Fault	Rain	4.00
Reactor	Open	Frozen precipitation	6.52

Hurricanes, with flooding and high winds, and tornadoes are also addressed in the reliability model.

Weather effects are introduced into the sequential Monte Carlo simulation through the use of hourly weather data—when, as the simulation proceeds through the period of interest adverse weather is assumed to prevail, failure rates increase as appropriate. It will be noted here that we follow specific weather conditions rather than characterize the weather in a discrete number of states (e.g., as normal, adverse and extreme weather [5, 6]).

Lightning

Lightning can result in overhead line faults, substation bus faults, the unwanted opening of substation breakers and the mis-operation of line relay protection schemes. Lightning is of particular importance as it might result in multiple outages within a short period of time, posing a challenge to even a transmission system as robust as Con Edison's.

As the modeling of lightning strikes and their consequences is by no means simple, we will describe the analysis upon which our model is based in some detail. The data used in this study comprise overhead line and substation failure data, relay protection scheme mis-operation data and lightning strike data for a 10-year period 2007-2016. The failure data used concern the occurrence of faults in overhead lines,

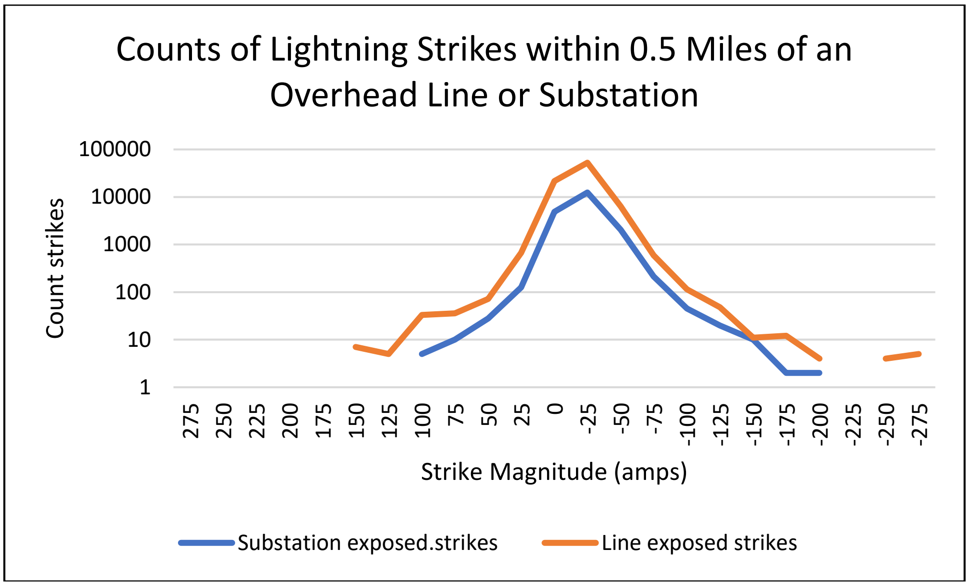
[1] NOAA, Climate Data Online, https://www.ncdc.noaa.gov/cdo-web/.
[2] The effect of heat waves might also be ascribed to load as well as temperature.

breaker opening in substations and relay protection scheme mis-operations. The lightning data are for lightning strikes that occur within 0.5 miles of a line[3] or substation.

In the analysis of lightning strike data, our concern is with the exposure of Con Edison overhead lines and substations to lightning strikes that occur within 0.5 miles of the line or substation. As an individual lightning strike might occur within 0.5 miles of multiple lines or substations, the counts of exposure events will be greater than the counts of strikes. In the remainder of this report, counts of strikes are in fact counts of strikes in proximity to individual overhead lines or substations. As might be expected, the patterns of strike frequency and amplitude are, however, quite similar.

Examining lightning strikes that occur within 0.5 miles of an overhead line, we note wide variations in the counts of strikes in proximity to the different lines. This variation will result from both the length of the line and its geographical location—the lightning strike density varies across the region. The amplitude of strikes also varies considerably (Figure 1). 73 % of strikes are negative with electrons traveling downwards to the ground. Of all these strikes, negative strikes had a higher average amplitude than positive strikes where electrons travel upwards from the ground (14.66 kiloamperes for negative strikes, 8.66 kiloamperes for positive strikes).

Figure 1



Breaking down the counts of strikes for each line, we find a statistically significant difference in the pattern of amplitudes.

A fault on an overhead line was assumed to be caused by lightning if a lightning strike was recorded as having occurred within 1 minute of the fault event. In the period 2007-2016, there were 11 such events. It will be noted that 3 of the 11 faults occurred as a result of a positive strike—the exact proportion we would expect if we were to assume that strikes had no effect on the likelihood of a fault. As might be expected then, the limited data provide no statistically significant evidence that positive strikes are more damaging. Consequently, the remainder of the analysis was performed examining only the absolute value of the strike magnitude.

[3] To the line data provided by Con Edison for strikes within 0.5 miles of a line, we have added all strikes within 0.5 miles of a substation in which an overhead line of concern terminates.

Examining the likelihood of a line fault caused by lightning, we see that regression analysis on the data confirms that there is a statistically significant correlation between the number of faults experienced by a line and the count of lightning strikes within 0.5 miles of that line[4]. A good fit to the damage and strike data with statistically significant coefficients is given by linear, polynomial and logistic regression. The historical probabilities that a lightning strike of a specific amplitude within 0.5 miles of the line will result in a fault are presented in Figure 2 together with the probabilities predicted using the various models. Because of its shape, Con Edison has elected to use the logistic regression model in modeling line strikes that cause a line fault. Using this model, the probability that a given strike causes a fault in an overhead line as:

Probability given strike within 0.5 miles causes fault = exp(eta)/(1+exp(eta))

where eta = -9.38736 + 0.0296054*Absolute(Amplitude)

This equation is used in the model with a Bayesian multiplier being applied to update the likelihood that a given lines experiences a fault. This multiplier addresses vulnerabilities of specific lines to line faults.

Next examining the outage durations following line faults caused by lightning, we note that of the 11 line faults, 6 were temporary with immediate restoration and 4 resulted in an outage of less than 15 minutes. In only one case did restoration take more than one day. This pattern of outage durations is employed in the model.

Examining lightning strikes that occur within 0.5 miles of a substation, we see that these average amplitudes are higher than those seen for strikes within 0.5 miles of a line. Looking at the counts of strikes for each substation and the average amplitude of these strikes, see that lightning strikes are more likely to occur in the vicinity of substations in Manhattan and Staten Island and least likely in the Bronx and southern Westchester. That said, we would note that substations located indoors are unlikely to be vulnerable to lightning.

Now a fault in a substation or other event was assumed to be caused by lightning if a lightning strike was recorded as having occurred within 1 minute of the event. In the period 2007-2016, there were 5 such events in in Westchester, the Bronx and Staten Island (and none elsewhere).

Given the paucity of data for events of one particular type and events associated with strikes of absolute amplitude in excess of 30 kiloamperes, we will assume that the probability that a strike results in an OA in a substation in Westchester, the Bronx and Staten Island (to a bus fault or breaker opening) follows the same distribution as line faults with the predicted likelihood that a strike causes a substation OA multiplied by a factor of 3.81 to give the actual count of substation OAs caused by lightning. No Bayesian updates were applied to individual substations.

Finally, examining the durations of outages caused by lightning, we note that the fault and breaker open events are of short duration. This pattern of outage durations is employed in the model.

Relay Protection Scheme (RPS) mis-operations result from RPS mis-operation following a line fault or or are "out-of-the-blue" mis-operations in which the RPS operates, opening breakers and causing a line-outage, in the absence of any precipitating fault.

The RPS mis-operations associated with lightning strikes were identified by matching the time, to the minute, of a strike within 0.5 miles of a nearby substation to the time of RPS mis-operation. It will be noted that some mis-operations held in RPS data to have occurred following a fault to not match any fault event in failure data, possibly because the fault was temporary and never recorded in any falure database or report.

[4] The probability that the count of strikes near a line has no effect is 3 %.

Examining mis-operations after faults, we see these are no more likley to occur after a lightning-induced fault as any other fault. From this we can conclude that insofar as lightning is concerned we need only consider "out-of-the-blue" mis-operations. Examining these, once again we will concern ourselves only with RPS mis-operations in Westchester, the Bronx and Staten Island. Given the paucity of data for events associated with strikes of absolute amplitude much in excess of 30 kiloamperes, we will assume that the probability that a strike results in an "out-of-the-blue" mis-operation follows the same distribution as line faults with the predicted likelihood that a strike causes a "out-of-the-blue" mis-operation multiplied by a factor of 3.81 to give the actual count of substation outages caused by lightning. No Bayesian updates are applied to individual substations.

Given a lightning strike of a specific magnitude within 0.5 miles of an overhead line or substation, we can predict the likelihood of a fault of a specific line, a fault or breaker opening event or an "out-of-the-blue" RPS mis-operation within a substation using the equations and Bayesian multipliers developed above. For substation bus faults, breaker opening and "out-of-the-blue" RPS mis-operations, the specific bus or breaker affected will be selected at random from among all buses or breakers within that substation. To model the occurrence of lightning strikes within the simulation, at the beginning of a period we ascertain whether and when a lightning strike occurs in that period in vicinity to a line or substation to see if that strike results at random in a fault or breaker opening. If so, the consequences of the event ensue and repairs are initiated using the outage restoration times proposed.

Effect of Common-Cause Failures and Failure Bunching

Con Edison's sequential Monte Carlo probabilistic reliability model of its transmission system ranks the Fussell-Vesely importance of each component and failure mode to the predicted load drop frequency—it calculates the percentage contribution of load drop events involving the specific failure or cause of failure bunching of interest to the total predicted load drop frequency.

Early application of the transmission system reliability program identified mis-operation of relay protection schemes with communication channels or other equipment shared as being the dominant predicted cause of load drop. This vulnerability has been eliminated by replacement of or upgrades to relay protection schemes. Among the causes of failure bunching, multiple lightning strikes on overhead lines and outdoor substations appear to contribute ~ 11 % of predicted load drop events.

Conclusions

The modeling of common-cause failures and failures susceptible to bunching is described. The importance of addressing these types of failures in a conservatively design transmission system is demonstrated.

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