Con Edison Transmission System Reliability Model

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SUMMARY

The Consolidated Edison Company of New York, Inc. (Con Edison) has developed a detailed probabilistic reliability model of its transmission and sub-transmission systems. This model focuses on the occurrence of multiple contingencies within a short period of time and common-cause and weather-related failures. It is now used routinely to identify vulnerabilities that might result in load drop from distribution stations and to assess how proposed projects affect reliability. In this paper, we describe the model, its implementation in a Monte Carlo simulation and highlights of its application by Con Edison to enhance system reliability in a cost-effective manner.

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. Accordingly, the transmission system is designed to withstand at least a single contingency without having to drop load and much is designed to withstand additional contingencies. 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.

To help ensure high reliability. this model is used to identify the anticipated dominant causes and locations of load drop made necessary to remedy thermal overload or voltage problems or as a result of the isolation of substations; to identify the lines and substations that are most frequently challenged by events that, unless remedied, would require load to be dropped; to determine how effective proposed improvements will be in addressing reliability problems and to assess various alternative transmission system and substation designs

The model makes use of a Monte Carlo simulation of the transmission system to predict the likelihood and causes of load drop. It can be distinguished, however, from simulations reported upon previously by its magnitude, the massive contingency analysis performed to ascertain whether thermal overloads and substation voltage problems will arise, its emphasis on the characterization of the failure of relay protection systems and the cascading of failures that together, with common-cause events, might force load drop, the use of a sequential Monte Carlo simulation, the consideration of all causes of equipment unavailability including faults, the unwanted opening of protective devices and emergency and planned maintenance and the calculation of load drop duration

The model is now applied routinely by Con Edison.

KEYWORDS

Transmission, reliability, modeling, Monte Carlo, simulation

Introduction

To help ensure high reliability is maintained in a cost-effective fashion, Con Edison has developed and makes use of a reliability model of its transmission system. This paper describes the model and how the results obtained are being used.

The Model

The reliability model Con Edison has developed makes use of a Monte Carlo simulation of the transmission system to predict the likelihood and causes of load drop. Such a model is nothing new: Billinton and Li in their seminal text [1] describe the application of Monte Carlo simulation of the reliability evaluation of electric power systems; the application of simulation is described in various papers, in particular, those of Billinton, Li, Choudhury, Chowdhury, Koval and their colleagues [2-6]. More recently, Cadini et al [7] have made use of simulations in examining the effect of extreme weather on transmission systems. This present effort is distinguished, however, by:

- Its magnitude: in contrast to the few transmission lines or buses addressed in other studies, we model over 10,000 individual lines and components applying component-specific outage rates and durations to each.
- A massive contingency analysis performed to ascertain whether and where thermal overloads and stability problems will arise.
- Its emphasis on the characterization of the failure of relay protection systems and the cascading of failures that, with common-cause events [8] and adverse weather, will likely be the major cause of load drop.
- The use of a sequential Monte Carlo simulation in contrast to the non-sequential simulation performed by Xu and Singh [9] or the probability index applied by Kwon et al to the Korean power system [10]. By introducing historic weather and load data into the simulation, we address vulnerability to weather and consider the problems that arise at the prevailing system load.
- The consideration of all causes of equipment unavailability including faults, the unwanted opening of protective devices and emergency and planned maintenance.
- The calculation of load drop durations—these will vary widely according to their causes as, for example, outages occasioned by relay mis-operation are usually short, especially if the lockout relay is reset automatically.
- Its ability to predict the frequency of challenges that, if not mitigated, will lead to load drop.

The load drop frequencies predicted by this model can be combined with predictions of distribution system reliability to obtain composite load drop frequencies for individual customers.

Overview

The software used to predict the reliability performance of Con Edison's transmission system comprises a reliability model embedded within a Monte Carlo simulation. The software predicts when failures occur and identifies the components that are out of service at any time. Knowing this we can ascertain if a substation is isolated or whether contingencies have occurred that, unless remedied, would cause a thermal overload or substation voltage problem.

The program and simulation process will now be described.

Components Modeled

The following components and sub-systems are modeled:

Breakers	Lines (overhead lines and forced cooled, oil insulated and solid dielectric underground lines)
Buses	Phase angle regulators
Capacitors	Reactors
Circuit switchers	Transformers
Disconnect switches	Voltage regulators
Dielectric pumping plants	Special protection systems (SPSs)
Generators	Relay protection schemes

The topology of the transmission system is input as a list of pairs of components connected to each other. This topology defines how power is fed and determines the consequences and response to events.

Failures Modeled

The following failures or causes of equipment outage are modeled:

- Faults including those caused by fires or line rupture in the dielectric pumping plants used to cool some high voltage underground lines.
- The unwanted opening of breakers or other devices. Breaker opening may occur because of problems with the breaker (e.g., low gas or air pressure), the mis-operation of a relay protection scheme or the actuation of a special protection system.
- Relay protection scheme mis-operation subsequent to a fault or occurring “out-of-the-blue”. While the focus in modeling relay protection schemes is on schemes that protect transmission lines, the mis-operation of schemes protecting buses, transformers and other equipment is also modeled.
- Failures of devices to open on demand.
- Emergency and scheduled maintenance of equipment.
- Common-cause failures. Of particular concern are common-cause failures in relay protection schemes, overhead feeders sharing towers or a right-of-way, underground feeders in a shared manhole or of multiple feeders slung below a bridge. Other potential causes of multiple contingencies, such as adverse weather including hurricanes, tornadoes and coastal water surge, are addressed explicitly in the program. Seismic events, “Black Swan” events, terrorism and solar magnetic disturbances are excluded from consideration. Common-cause failures are modeled assuming that a fraction of component failures result in, or from, a common-cause failure.
- The failure or unavailability of generators.

In addition, fires and line ruptures in dielectric pressurizing plants and hurricanes and tornadoes can also be modeled.

Contingencies of Concern

The contingencies of concern are typically defined as sets of line or transformer outages occasioned by failures or maintenance work that result in the isolation of an area substation, or thermal overloads of lines, transformers or phase angle regulators or voltage stability problems for a specific system load and generator dispatch. Several specific load levels are considered: peak summer load, 80 % of peak summer load, etc.; the matching generator dispatches used are those normally assumed for planning purposes. A thermal overload is deemed to be of concern if the load exceeds the Long-Term

Emergency (LTE) ratings of the overloaded equipment, the magnitude of the overload determining how quickly it must be eliminated before power has to be dropped.

Potential Remedies

Remedies may be available to mitigate the consequences of thermal overloads and so avoid load drop (Table 1); it should be noted that the ability of remedies to address problems depends upon their magnitude of the overload and the time available in which to act before having to drop load. Having applied all remedies, load drop will ensue if the normal rating of the overloaded component is still exceeded. A number of points should be made about these remedies:

- While small gas turbines can provide power at short notice to remedy problems, other generation cannot unless it is already on line or is being brought on line.
- Remedies might fail. Thus, for example, a spare transformer might not be available as breakers failed to close.
- Their ability to eliminate a problem will be limited. In a contingency that occasions multiple thermal overload, remedies may apply to all or several of these problems. Where they are insufficient in themselves to address all problems, remedies are allocated to maximize their benefits.
- Voltage may be reduced and demand response programs exercised to avoid dropping load.

Table 1 **Remedies Available to Mitigate Thermal Overload and Substation Bus Voltage Problems**
Energize a spare line or transformer
Transfer load from a substation fed by an overloaded component
Add generation so as to unload the overloaded component
Move taps on phase angle regulators
Drop generation to match transmission and generating capacity
Place shunt reactors in service or remove them from service
Remove shunt reactors from service
Place shunt capacitors in service
Move transformer taps
Provide voltage support using a generator that feeds directly into the substation

The Simulation

The simulation process is one in which we follow a progression of events in time. Failures and outages occur, repairs are made, contingencies of concern appear and disappear and load might be dropped.

The time to be simulated is divided into a series of periods based on temperature data. Starting at the beginning of the first period, random numbers are drawn for all components to ascertain whether and when the components will fail or be removed from service within the period, making use of the basic failure rates for the prevailing temperature. Intervals of rain, freezing rain, high winds, extreme cold and lightning are identified and again random numbers are drawn to ascertain whether and when components vulnerable to inclement weather fails. The events that occur within the first time period, these events are then allowed to occur in turn and the consequences are determined. If contingencies of concern at the prevailing load arise, available remedies will be applied. Events occasioned by maintenance that is not required immediately are reversed should they result in an unwanted contingency.

We then proceed to the next event. This event may be another failure or outage or an event, such as the completion of repairs or a switching action, that occurs in response to earlier events. Once all the events in the first time period have been examined, the simulation proceeds to the next time period, a process that is repeated until the end of the last period is reached. The next iteration in the simulation is then started at the beginning of the first period.

To illustrate the simulation process, let us examine the modeling of a fault. When a fault occurs, it is allowed to propagate until it terminates at an open breaker or switch, a source, a load point or a closed device that should open. In the last case, should the device fail to open (i.e., should a random number between 0 and 1 fall below the probability that the device fails to open on demand), propagation continues until another open device or end point is reached. Disconnect switches, circuit switchers or removable links encountered in tracing this path are scheduled to be opened later to further isolate the failure.

The status of both the component that failed and any device that fails to open on demand is set to "failed" and repairs are initiated setting the time taken to complete the repairs at random employing empirical distributions that characterize the repair time. The completion of repairs is then added to the list of events anticipated. In modeling transformer replacement, the availability of spare transformers and their order and delivery times are addressed explicitly. Once the fault is isolated, a check is made to ascertain if breakers open as a result of relay protection system mis-operations. The possibility of other relay protection scheme mis-operations occurring in response to the fault is then examined as is the possibility of a common-cause failure or a second fault occurring shortly after a first.

The contingencies that arise following the fault are then identified. Should challenges that might result in load drop arise, the simulation identifies remedies that might be taken to mitigate or eliminate the problem. Should there be no adequate remedy, load will be dropped from isolated area substations or to eliminate the thermal overload. With that, counts for the calculation of reliability indices are augmented and the simulation proceeds to the next event.

Equipment Failure and Outage Rates and Other Data

The failure and outage rates and other data required for the model are derived from the analysis of Con Edison equipment outage data provided by maintenance management systems and operator incident reports. Failure rates and outage durations are developed for different classes and voltage of equipment. Fault rates for transformers and breakers are predicted from equipment condition; for other equipment, a Bayesian analysis is applied to integrate generic and component-specific failure data. Failure, weather and load data for the period beginning in 2007 are used in the simulation.

Shortcomings of the Transmission Reliability Model

When compared to an ideal in which the simulation of the system's reliability performance is combined with load flow and dynamic stability analyses triggered by component failures, the removal of equipment for maintenance, changes in load and the re-dispatch of generators in the system, our model has shortcomings:

- The model is conservative in that events that do not result in thermal overloads might not be seen to elicit a response from the system operators.
- We assume that a single dispatch of generation applies at each load level unless, and until, contingencies apply.
- We ignore transient stability problems though not necessarily their manifestations in terms of failures and relay mis-operations triggered by failures. The frequency of these events is not known.

Implementation

The software predicts a number of reliability indices, focusing in particular on the load drop and challenge frequencies. It also allows us to identify the dominant contributors to load drop; ascertain the benefits proposed reliability improvements might give; and evaluate how best to address the major contributors to the possibility of load drop within the context of competing demands for capital and other resources. Knowing the likely causes of load drop, we identify and cost measures that might address them. These measures typically include the redesign or upgrading of specific relay protection schemes, enhanced maintenance to improve the "health" of equipment, its replacement with more reliable equipment, changes to system topology and the installation of fire suppression systems in pumping plants.

Rather than explicitly define reliability goals for its transmission system, at this time Con Edison seeks to ensure that the contribution transmission system failures make to customer power interruptions is similar in magnitude to the contribution made by distribution system failures. That said, "Efficient frontier" and "ranking" curves have been created to identify a portfolio of reliability improvement projects for expeditious implementation.

Application

To date, applying the reliability model, Con Edison has:

- Demonstrated the importance of relay protection scheme mis-operation as a cause of load drop particularly as a result of multiple feeder trip outs caused by shared communication channels and software problems. These issues have and are being addressed by eliminating shared communication channels and other possible common-cause failures and by upgrading relay protection schemes (Figure 1). These improvements not only eliminate a major cause of load drop but are also among the most cost-effective of any improvements considered.
- Identified an inventory of spare transformers that is optimal from the perspective of load drop frequency. This will entail the purchase of some new spares and, more controversially, a decision not to replace certain spares when they are used.
- Conducted stress tests to show it is important to maintain the health of transformers and breakers —a marked increase in load drop frequency occurs should their condition be allowed to deteriorate and failure rates increase.
- Identified dielectric pumping plants where fires and line ruptures might result in the removal of multiple lines from service. These observations provided additional support for a decision to upgrade fire protection in dielectric pumping plants.
- Concluded that several proposed reliability improvement schemes would not result in any material or cost-effective reduction in the predicted load drop frequency. One such scheme involved the creation of a ring bus from two separate buses in a transmission system substation (Figure 2). While this improved switching flexibility in a load pocket and enhanced power transfer capability, the reduction in predicted load drop frequency from area substations in the area was judged insufficient to justify the capital expenditures. A second scheme, involved the installation of additional breakers failed to lessen the risk of area substations being lost (Figure 3).
- Flagged a number of system topology issues where the design exacerbated the effect of failures. In particular, the model flagged a design issue in which, because of space and structural issues, a single fault might result in the loss of two high voltage transformers. This issue was resolved with the installation of a new elevated design with a modular hybrid switchgear as part of improvements made subsequent to Super storm Sandy.

Figure 1

Effect of Relay Protection System Upgrades on Predicted Load Drop Frequency

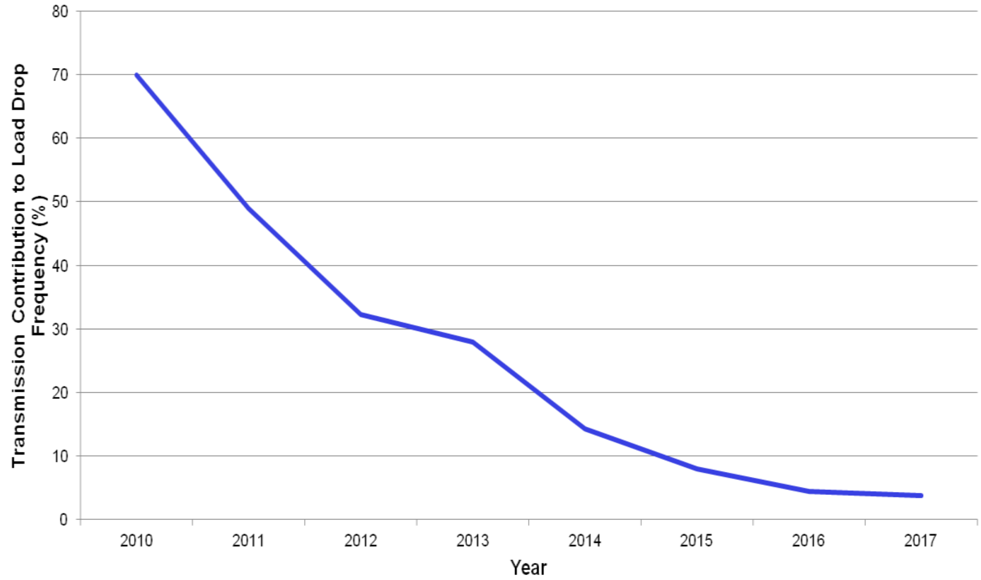


Figure 2

Proposed Ring Bus

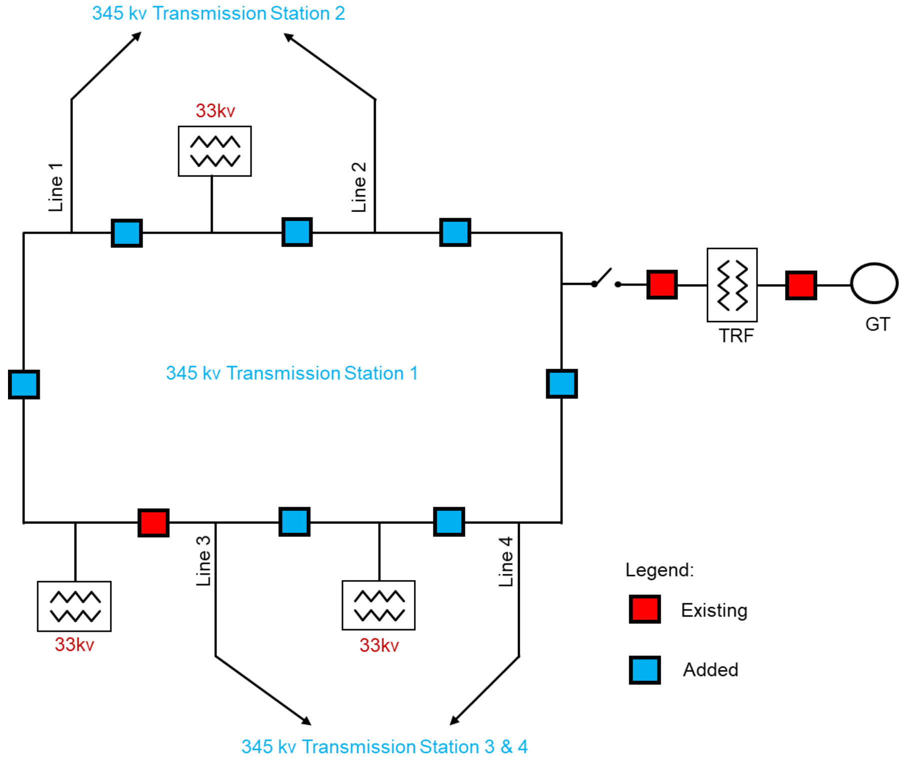
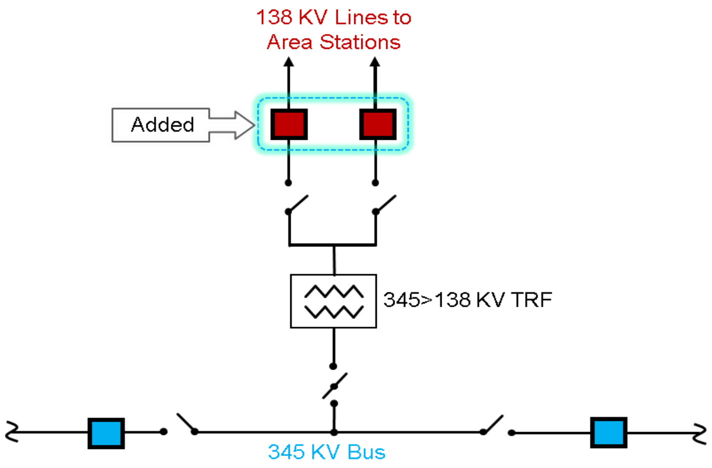


Figure 3

Proposed Breaker Addition



Conclusions

Con Edison now makes routine use of a detailed reliability model of its transmission system to justify and contribute to its 5-year capital plan and to influence asset management decision making.

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