Assessing Vulnerability to Cascading Outages

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***Abstract*— This paper addresses the testing and implementation of a fast process for sequential contingency simulation in order to identify potential cascading modes due to thermal overloads. It also presents computation of the vulnerability index of cascading, based on the estimated likelihood and consequences of cascading outages. The approach described in this paper offers a unique capability to automatically identify initiating events that may lead to cascading outages. It predicts the development of cascading events by automatically identifying and visualizing potential cascading tiers. The proposed approach was implemented using a 50,000-bus Eastern Interconnection power system network. The results of the study indicate that initiating events and possible cascading chains may be quickly identified, ranked and visualized in on-line and off-line environments. This approach may be used to improve the reliability of a transmission grid and reduce its vulnerability to cascading outages. It may be added to the existing contingency analysis tools to assess the impact of cascading events in both on-line and off-line environments.**

***Index Terms*— Transmission reliability, cascading outages, initiating events, cascading tiers, vulnerability index.**

I. INTRODUCTION

SECURITY and safety of a power system network are fundamental aspects of electric utility operation. The events of September 11 raised the significance of secure power system operation. As the security issues related to the power industry become more critical, the challenge of maintaining secure operation of bulk power systems is growing, [1]. The utilities should be able to quickly assess an outcome of a larger impact on the transmission network.

Major blackouts are usually the outcome of cascading outages, which NERC defines "as the uncontrolled loss of any system facilities or load, whether because of thermal overload, voltage collapse, or loss of synchronism, except those occurring as a result of fault isolation", [2]. Since uncontrolled, cascading outages may have such a wide-spread effect and take extensive time and difficulty to recover from, NERC, under its transmission planning standards [3], requires analysis of the following categories of contingencies:

- Resulting in a loss of a single element (Category B)
- Resulting in a loss of two or more (multiple) elements (Category C)
- Extreme events resulting in two or more (multiple) elements removed or cascading out of service (Category D)

Category D is the highest level of severity. NERC notes in [3] that these contingencies may involve substantial loss of customer demand and generation in a widespread area or areas. It also notes that portions or all of the interconnected systems may or may not achieve a new, stable operating point.

This means that the system may collapse resulting in a major blackout. Major blackouts occur rarely, but when they occur, they can have serious economic and social impact. A steady increase in the number of large blackouts has been observed over the past 40 years: the number of blackouts that result in a loss of over 1000 MW of demand doubles every 10 years, [4]. Many past blackouts, such as Northeast blackouts in 1965 and 2003, New York City blackout in 1977, two WECC blackouts in 1996, were caused by cascading failures [5, 6].

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Table 1 lists some of the major blackouts that occurred in North America over the past 40 years.

Table 1. Major Blackouts in North America

Date	Location	Customers Affected	Collapse Time	Nature of Collapse
Nov. 9, 1965	Northeast	30,000,000 people/ over 20,000 MW	13 min	Successive tripping of lines
July 13, 1977	New York City	9,000,000 people/ 6,000 MW	1 hour	Successive tripping of lines and generators
Dec. 22, 1982	West Coast	12,350 MW	Few minutes	Successive line tripping, protection coordination scheme failure
Dec. 14, 1994	Western US	9,336 MW		Transient instability, successive tripping of lines, voltage collapse
July 2, 1996	Western US	2,000,000 (10 % of the customers in the WECC); 11,850 MW	36 sec	Successive tripping of lines, generators and voltage collapse
Aug. 10, 1996	Western US	7,500,000 customers; 28,000 MW of demand shed by under-frequency load-shedding relays	> 1 min	Voltage collapse
June 25, 1998	MAPP, NW Ontario	152,000 customers; 950 MW	>44 min	Successive tripping of lines
August 14, 2003	Northeast	10,000,000 customers in Ontario, 40,000,000 customers in US/61,800 MW	> 1 hour	Successive tripping of lines (400), generators (531), and voltage collapse

Analyses of 2003 Northeast Blackout (the largest blackout in North American history) and of every major blackout since implementation of the Open Access Order FERC 888 and 889 have concluded that system operators likely could have mitigated the extent and damage of the blackout if they had had access to real-time software tools that could have identified the impending crisis and provided operators with the data needed to make timely, informed decisions, [7].

The need to provide system operators with real-time information is vital and growing more acute. In addition, this type of monitoring application may be used to assist planners in predicting possible cascading modes, [8], and optimize transmission system expansion which will reduce blackout risk and improve system reliability, [9].

The two most frequent scenarios of cascading outages are:

1. As a result of a contingency, branches are overloaded above a certain limit, and protection schemes initiate tripping of overloaded branches.
2. Following a contingency that causes deficit of reactive sources; there would be a considerable reduction of voltages, which may further cause motors to stop.

Protective relays were involved in 75% of major disturbances reported by NERC from 1984 to 1988, [6]. Given the importance of the protective schemes during system blackouts, the approach described in this paper addresses the first scenario and allows operators and planners to quantify a power system's ability to withstand cascading outages caused by thermal overloads:

- Identify contingencies that lead to cascading.
- Simulate cascading outages due to consecutive opening of overloaded branches.
- Identify the impact of cascading outages.
- Identify geographical locations of cascading events.

The paper addresses the testing and implementation of a fast process to predict and analyze cascading outages. This framework for analysis of cascading outages has the capability to quickly identify potential cascading outages in near real-time, operations and planning environments:

- Utilizes "smart" logic to identify initiating events that may lead to cascading.
- Predicts development of cascading events by automatically identifying potential cascading chains.

Preliminary results showed that the technique used in the study is a very fast approach to predicting and analyzing cascading outage.

Implementation, testing and validation of the presented framework are being performed under a supplemental EPRI Project "Cascading Outages".

The programs "Physical and Operational Margins" (POM) and "Potential Cascading Modes" (PCM) of POM Suite were used as the basis for all computations in this project [10, 11].

POM is an extremely fast AC loadflow and contingency analysis program that solves a 45,000-bus case in approximately 0.1 s., [12]. POM contingency analysis and transfer simulation results are always within three system limits, which may be simultaneously monitored by the user. Those three constraints are: (1) Voltage stability, (2) Thermal overload of lines and transformers, and (3) Voltage violation (voltage range and/or pre- to post-contingency voltage drop).

POM capabilities include:

- Automatically perform contingency analysis (N-1, N-1-1, N-2, N-3 and higher) for large power system models;
- Simulate multiple power transfers while monitoring voltage, thermal, flowgate, voltage stability constraints during massive AC contingency analysis;
- Determine voltage stability margins;

- Visualize power system behavior.

PCM capabilities include:

- Quickly identifying initiating events;
- Automatically identifying cascading chains;
- Ranking cascading outages
- Visualization of cascading outages

II. THE PROJECT BACKGROUND, OBJECTIVES AND SCOPE

A cluster approach to quick identification of potential cascading outages in a bulk power system network was introduced during an EPRI research project "Assessing Vulnerability to Cascading Outages" in 2007, [13].

Since the results of the research project were promising, eight U.S. utilities initiated the extension of that project to perform a proof-of-concept study and assess their network vulnerability to cascading outages.

Implementation, testing and validation of the presented framework are being performed under a supplemental EPRI Project "Cascading Outages" that was initiated in January, 2008. Project participants are:

- American Electric Power
- Con Edison of NY
- Entergy Services
- Exelon Corp.
- FirstEnergy Corp.
- ISO New England
- New York Power Authority
- Tri-State G&T

The main objective of this study is to generate new technical knowledge about possible cascading outages in a transmission grid by testing and implementing a "smart" logic for prediction of cascading outages and further quantifying the impact of cascading outages. This is being tested using one of the project participant's power system model.

Another objective is to identify the benefits that monitoring of the transmission system in terms of cascading outages can provide to transmission owners, particularly those facing the new reliability standards of FERC 890 and NERC/ERO.

This project is still under way with the completion date of December, 2008.

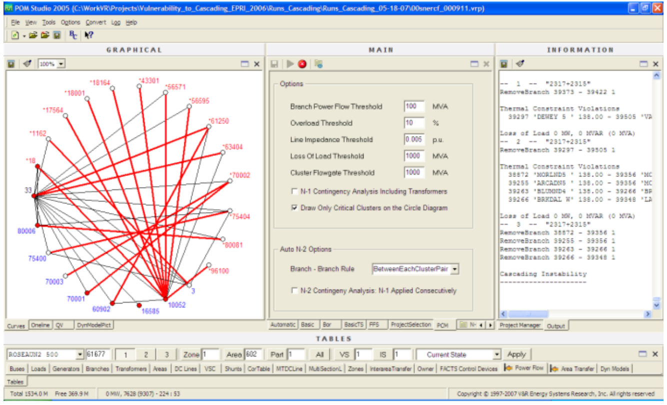
Analyses of the blackouts in North and South America, and in Europe show that over 50% of the blackouts involved many cascading elements and were "slow" in progression. This means that optimal measures that would prevent the spread of cascading events may be identified and implemented to alleviate or reduce the impact of cascading outages. The current project is planned to be extended in 2009 in order to identify and study preventive measures for cascading failures.

III. METHODOLOGY

A. *"Cluster" Approach to the Analysis of Cascading Outages*

It is practically impossible to apply all N-k contingency combinations in a bulk power system. A "cluster" approach is utilized in the study to quickly identify possible initiating events that may lead to cascading outages.

A power system network is represented as a number of groups (clusters) that are connected to the network with "critical" lines (cutsets). A cutset connecting clusters with large generator output or load is determined. If one of the "critical" lines (e.g., initiating events) within the cluster or connecting two clusters is outaged, it may cause large overloads on other line(s). If an overloaded line(s) is switched off as a system protection measure, this may lead to cascading. A cluster view of the system is shown in Fig. 1.



Options

Branch Power Flow Threshold 100 MVA

Overload Threshold 10 %

Line Impedance Threshold 0.005 p.u.

Loss Of Load Threshold 1000 MVA

Cluster Flowgate Threshold 1000 MVA

☐ N-1 Contingency Analysis Including Transformers

☑ Draw Only Critical Clusters on the Circle Diagram

Auto N-2 Options

Branch - Branch Rule: BetweenEachClusterPair

☐ N-2 Contingeny Analysis: N-1 Applied Consecutively

```
-- 1 -- "2317+2315"
RemoveBranch 39373 - 39422 1

Thermal Constraint Violations
  39297 'DEWEY 5 ' 138.00 - 39505 'VA

Loss of Load 0 MW, 0 MVAR (0 MVA)
-- 2 -- "2317+2315"
RemoveBranch 39297 - 39505 1

Thermal Constraint Violations
  38872 'MORLND5 ' 138.00 - 39356 'MC
  39255 'ARCADN5 ' 138.00 - 39356 'MC
  39263 'BLUMND4 ' 138.00 - 39266 'BR
  39266 'BRKDAL W' 138.00 - 39348 'LA

Loss of Load 0 MW, 0 MVAR (0 MVA)
-- 3 -- "2317+2315"
RemoveBranch 38872 - 39356 1
RemoveBranch 39255 - 39356 1
RemoveBranch 39263 - 39266 1
RemoveBranch 39266 - 39348 1

Cascading Instability
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Total 1534.0 M Free 369.9 M | 0 MW, 7628 (9307) - 224 : 53 | Copyright © 1997-2007 V&R Energy Systems Research, Inc. All rights reserved

Fig. 1. A Cluster View of the Power System Network

The approach is used to identify initiating events and automatically determine possible cascading chains. Initiating events and cascading chains are also displayed on the geographical map.

The network is divided into three types of clusters:

- Generator clusters
- Load clusters
- Connecting cluster

An initial bus in each generator cluster is a generator bus. If a bus being connected to a cluster already belongs to another generator cluster, these clusters are merged. Cutset of lines that connect the cluster with other clusters is identified; usually these are high-voltage lines. Then, the sum of flows on the lines comprising the cutset and the sum of ratings of these lines is computed. Those clusters that have large flows on the cutset are of interest within this analysis framework.

An example of a generator cluster is shown in Fig. 2.

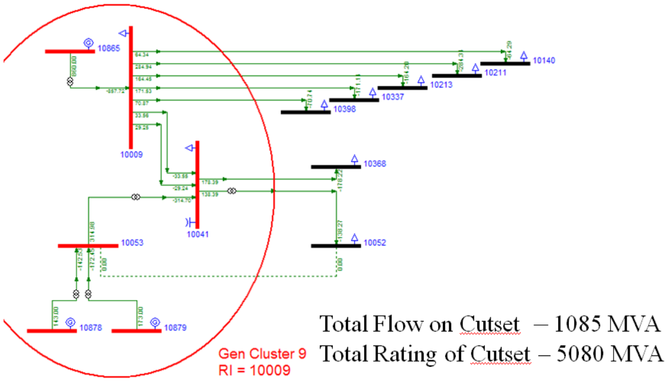


Fig. 2. A Generator Cluster

An initial bus in each load cluster is a load bus. If a bus being connected to a cluster already belongs to another load cluster, these clusters are merged. Cutset of lines that connects the cluster with other clusters is identified. Then, the sum of flows on the lines comprising the cutset and the sum of ratings of these lines is computed.

An example of a load cluster is shown in Fig. 3.

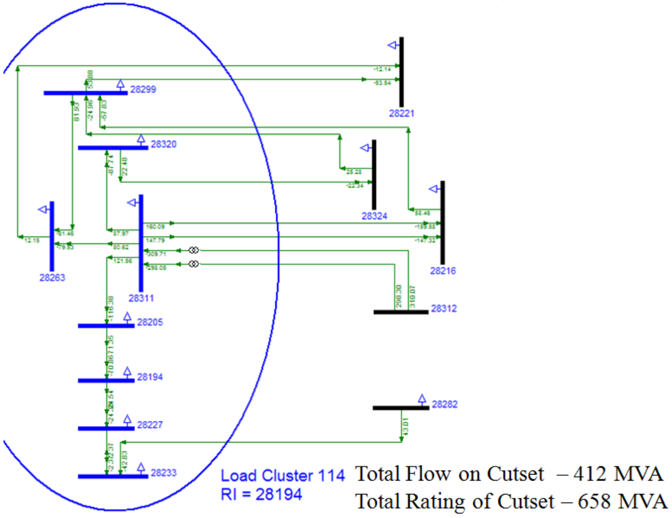


Fig. 3. A Load Cluster

There is also a connecting cluster that contains buses that do not belong to any generator or load clusters. For example, a bus with a disconnected generator belongs to this cluster (see Fig. 4).

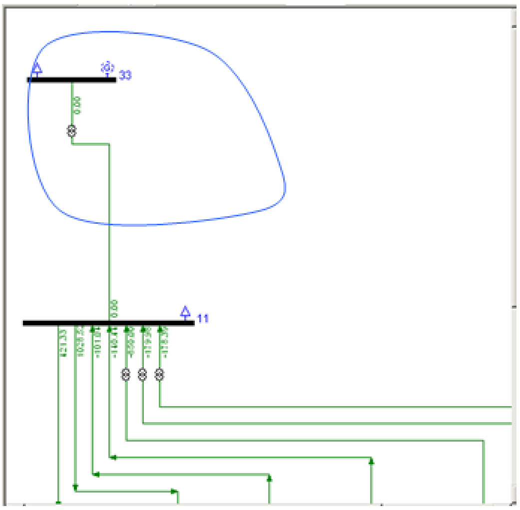


Fig. 4. A Connecting Cluster

There are three options to identify initiating events within the presented framework:

1. A list of N-1 and/or N-2 contingencies identified as a result of the "cluster" approach. It takes under one minute to identify potential initiating events in a 50,000-bus Eastern Interconnection planning model.
2. A user-specified contingency list containing NERC Category B, C, and D contingencies may be used as a pre-defined list of initiating events.
3. Combination of the above mentioned lists (1) and (2).

B. Simulation of Cascading Outages

Thermal violation occurs if the total power flow on a branch is at or above thermal limit:

$$S_{ij} \geq S_{ij}^{\max} \tag{1}$$

where

S_{ij} - is the total power flow on a branch *ij*

$S_{ij}^{\max}$ - is the thermal limit on a branch *ij*

If an initiating event causes branch(es) to become loaded above a certain line tripping threshold, protection schemes may initiate opening of overloaded branches:

$$\frac{S_{ij}}{S_{ij}^{\max}} > 100\% + \delta \tag{2}$$

where δ is the line tripping threshold value.

For this study, all overloaded branches are identified, but only those that are overloaded above the user-specified line tripping threshold are automatically tripped to simulate operation of protection schemes. Thus, tiers in the cascading chain are identified.

Following an initiating event (see Section III.A), branches are consecutively tripped until one of the following events occurs:

1. System fails to solve due to voltage instability;
2. Loss of load exceeds a user-specified threshold value;
3. Islanding with imbalance of load and/or generation within an island
4. A thermal violation is alleviated or drops below the line tripping threshold value.

The present study concentrates on cascading outages that lead to events (1) – (3) listed above.

Thus, cascading outages are N-*k* contingencies that cause stability violation, large loss of load, or islanding, where *k* is the cascading tier when either stability violation, islanding or large loss of load occurs.

The process of sequential contingency simulation is shown in Fig. 5.

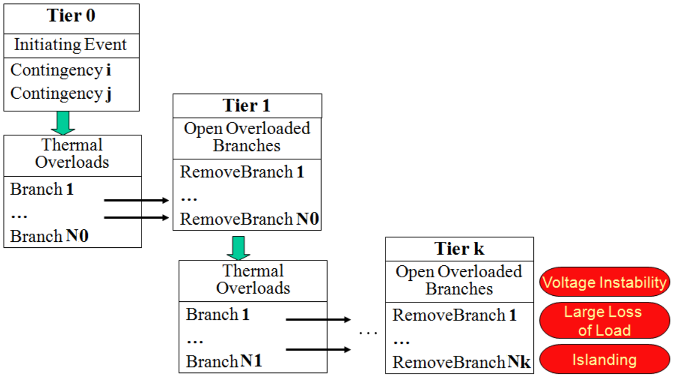


Fig. 5. Simulation of Cascading Outages

As a result of this process, potential cascading modes (PCM) in the power system network are identified.

C. Ranking Cascading Outages

After potential cascading modes are identified, the probability of each PCM may be estimated, and the impact of each PCM may be also estimated. A vulnerability index of cascading, which is based on the estimated likelihood and impact of the events, is computed [14, 15]. This index is further used to rank cascading outages. Ranking of cascading outages is performed in order to alarm operators and provide planners with the most severe potential cascading modes.

The probability of a potential cascading mode is:

$$P(PCM) = P(\text{Initiating Tier } 0) \times \prod_{TI=1}^{M} P(\text{Tier } TI) \qquad (3)$$

where

M is the number of tiers in the cascading chain;

TI is a cascading tier number;

For example, probability of a potential cascading mode that has two tiers is:

P(PCM) = P(initiating Tier 0) x P(Tier 1) x P(Tier 2) (4)

The probability of all the overloaded lines at a Tier TI tripping is:

P(Tier TI) = Probability of Trip of Line 1 (Loading of Line 1) x Probability of Trip of Line 2 (Loading of Line 2) x … x Probability of Trip of Line J (Loading of Line J) (5)

In this project, it is being assumed that when branch loadings increase above the branch limits, the probability of branch tripping increases and eventually flatten out to 100%, see Fig. 6.

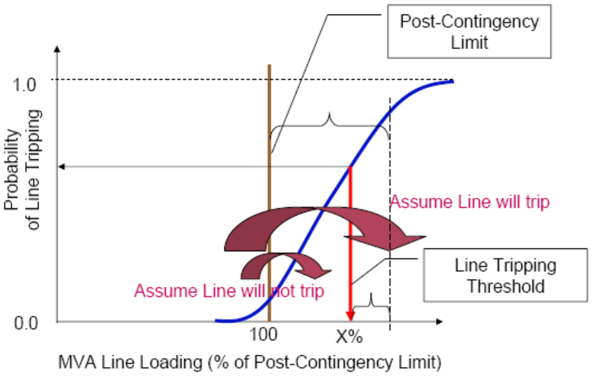


Fig. 6. Assumption on the Line Tripping Threshold

Probability of line tripping is a function of line loading with the following assumed probabilities (see Table 2):

Table 2. Assumption on Probability of Trip as a Function of Line Loading

Loading (% of Limit)	**Probability of Trip**
100	0.10
110	0.30
120	0.60
130	0.80
140	0.95
150	1.00

Thus, formula (5) assumes that each individual line at a Tier TI trips independently according to the probabilities listed in Table 2.

Then, for each initiating event, both the Impact at each tier and the total Impact at all tiers are computed.

The Impact is the sum of the following components:

1. Sum of MW Overload at each Tier.
   This is the sum of all overloads, including those that are less than line tripping threshold.
2. Sum of Load loss at each Tier.
3. Sum of Generation loss at each Tier.

Impact at a Tier at which voltage instability/islanding is not observed is specified by:

$$MW\_Impact = \sum Overload + \sum MW\ Load\ Loss + \sum MW\ Gen\ Loss \qquad (6)$$

Impact at a Tier at which voltage instability is observed is specified by:

MW_Impact = 2 x MW_Impact of Previous Tier (7)

Impact at a Tier at which islanding is observed is specified by:

MW_Impact = 2 x *T*, (8)

where

T is the sum of tie line flows before the island is formed

Then, the ranking index for potential cascading mode is:

PRI_{PCM} = P(PCM) x MW_Impact (9)

IV. STUDY RESULTS FOR ONE OF THE PROJECT PARTICIPANT'S NETWORK

A. *Input Data and Requirements*

Analysis of cascading outages was performed during this study on the 2007 Summer peak case consisting of approx. 50,000 buses and 65,000 branches.

A user-specified contingency list was also provided by the utility. The list contained N-1 contingencies, including stuck breakers, tower outages, etc. Contingencies from this list were combined into N-2 contingencies with the total number of combinations exceeding 31,000. These N-2 contingencies were treated as initiating events during assessment of cascading outages and processed through Potential Cascading Modes analysis.

Overloads on all elements above 13 kV in three control areas (the participants' footprint and two neighboring utilities) were monitored during the course of the analysis.

The line tripping threshold for tripping branches was set at 100% of Rate C, which is lower than that currently implemented at the participating utility. This value of the threshold was selected in order to perform a more extensive analysis of the system vulnerability to cascading in the course of this research project.

B. *Potential Cascading Modes*

The analysis of the participating utility's network showed that only 953 initiating events, out of over 31,000, caused branch overloads above the line tripping threshold.

In 915 situations the overloads were alleviated after the overloaded branch was tripped.

Only 38 initiating events, or less than 0.13% of all contingencies, lead to voltage instability as a result of cascading outages. These events are further analyzed in the present paper.

Each of these 38 initiating events is a combination of two N-1 contingencies. Some of the N-1 contingencies participate multiple times in 38 N-2 contingencies (e.g., initiating events) that further lead to cascading outages. Thus, these N-1 contingencies, in combination with other N-1 contingencies, are vulnerable to cascading. Frequency of N-1 contingencies participating in an N-2 Initiating Event is shown in Fig. 7.

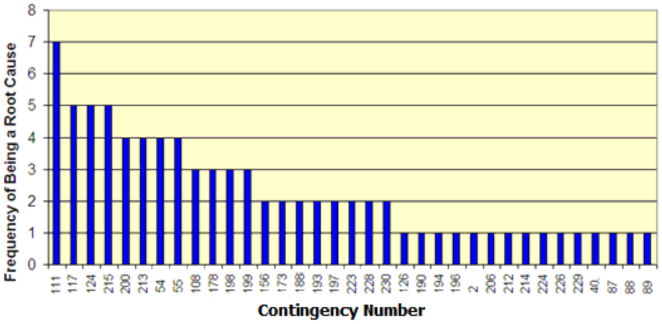


Fig. 7. N-1 Contingencies Participating in N-2 Initiating Events

Then, tiers in the cascading chains were analyzed. It was identified that cascading outages resulted in voltage instability in three or less tiers:

- 17 Initiating Events - in 1 tier
- 11 Initiating Events - in 2 tiers
- 10 Initiating Events - in 3 tiers

These are relatively "short" cascading chains.

The distribution of the potential cascading modes by the number of tiers in the cascading chain is given in Fig. 8.

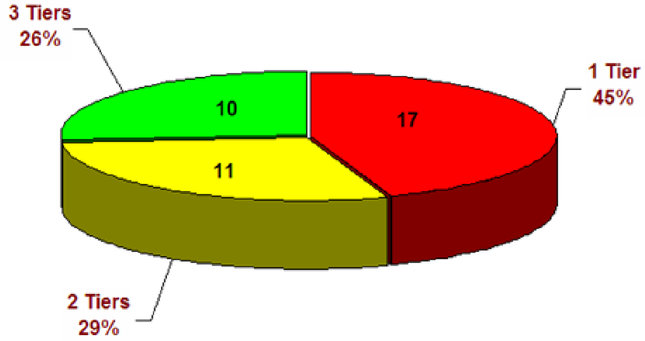
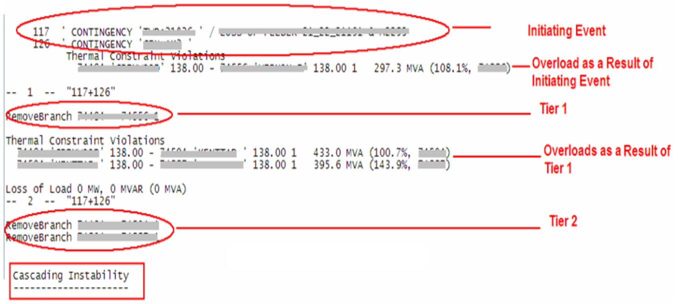


Fig. 8. Distribution of Cascading Events by Tiers

Another interpretation of Fig. 8 is:

- 38 initiating events have at least one tier;
- 21 events have at least two tiers;
- 10 events have at least three tiers.

An example of an initiating event that causes voltage instability in two tiers is shown in Fig. 9.



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  117  ' CONTINGENCY '[redacted]' / [redacted]
  126  ' CONTINGENCY '[redacted] '
        Thermal Constraint Violations
          [redacted]' 138.00 - [redacted]' 138.00 1   297.3 MVA (108.1%, [redacted])

-- 1 -- "117+126"
RemoveBranch [redacted]

Thermal Constraint Violations
  [redacted]' 138.00 - [redacted] ' 138.00 1   433.0 MVA (100.7%, [redacted])
  [redacted] ' 138.00 - [redacted] ' 138.00 1   395.6 MVA (143.9%, [redacted])

Loss of Load 0 MW, 0 MVAR (0 MVA)
-- 2 -- "117+126"
RemoveBranch [redacted]
RemoveBranch [redacted]

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Fig. 9. A 2-Tier Cascading Chain

C. *Analysis of Cascading Outages with 1 Tier*

The analysis of Tier 1 overloads showed that only 14 different branches were overloaded above the line tripping threshold as a result of 38 initiating events identified in Section IV.B. Thus, only 14 different branches were tripped at Tier 1. A 345 kV line, overloaded above the line tripping threshold in 9 instances, is the most frequently overloaded branch as shown in Fig. 10.

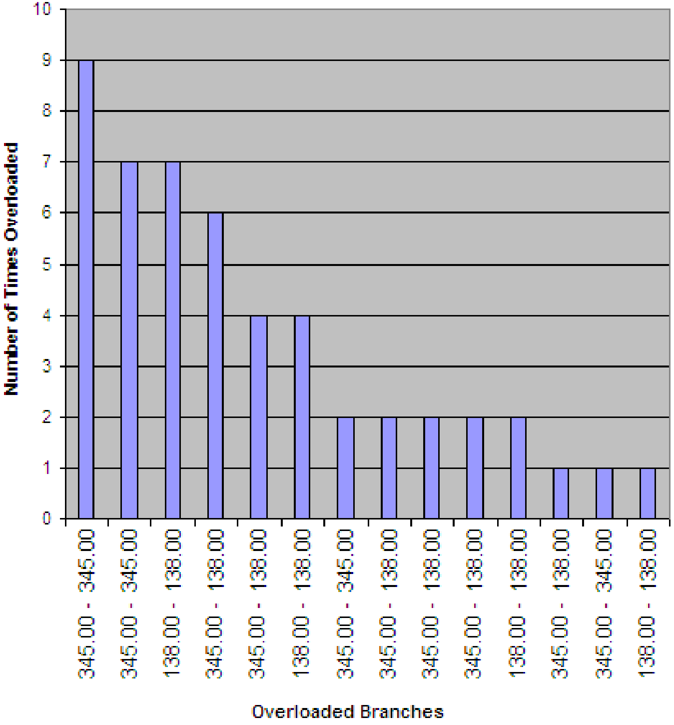

Fig. 10. Tier 1: Branches Overloaded as a Result of 38 Initiating Events

Over 40% of branches that are overloaded above the line tripping threshold and tripped at Tier 1 are 345/138 kV transformers, as shown in Fig. 11.

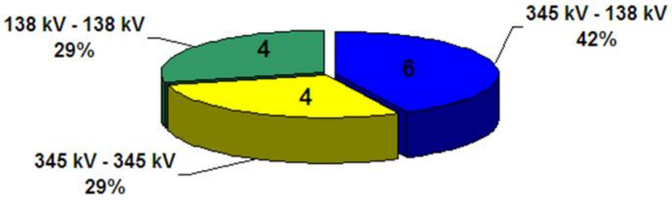

Fig. 11. Base Voltages of Branches Tripped at Tier 1

From 38 initiating events identified in Section IV.B, there are 17 initiating events that lead to voltage instability in just one tier, which is Tier 1 (see Fig. 8). An in-depth analysis of the branches that were overloaded above the line tripping threshold and tripped at this tier was performed.

These 17 initiating events caused overloads above the line tripping threshold at Tier 1 as follows:

- 11 Initiating Events caused 1 overload each
- 4 Initiating Events caused 2 overload each
- 2 Initiating Events caused 4 overload each

The analysis showed that initiating events cause a relatively small number of overloaded facilities at the next tier, see Fig. 12.

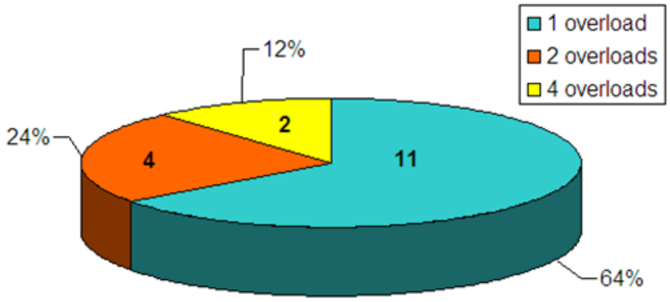

Fig. 12. Distribution of Initiating Events by the Number of Overloads Each Event Causes

D. Analysis of Cascading Outages with 2 Tiers

From 38 initiating events identified in Section IV.B, 17 events terminated in one tier (see Section IV.C), and the remaining 21 events cascaded to Tier 2 (see Fig. 8).

The analysis of Tier 2 overloads showed that only 13 different branches were overloaded above the line tripping threshold as a result of 21 initiating events that cascaded to Tier 2. Thus, only 13 different branches were tripped at Tier 2. Four branches are the same as switched at Tier 1 (but for different initiating events). These are shown in blue in Fig. 12. Nine branches are unique; e.g., they were not overloaded above line tripping threshold and tripped at Tier 1. They are shown in yellow in Fig. 13.

Four 138 kV lines, overloaded above the line tripping threshold in 8 instances each, are the most frequently overloaded branches (see Fig. 13).

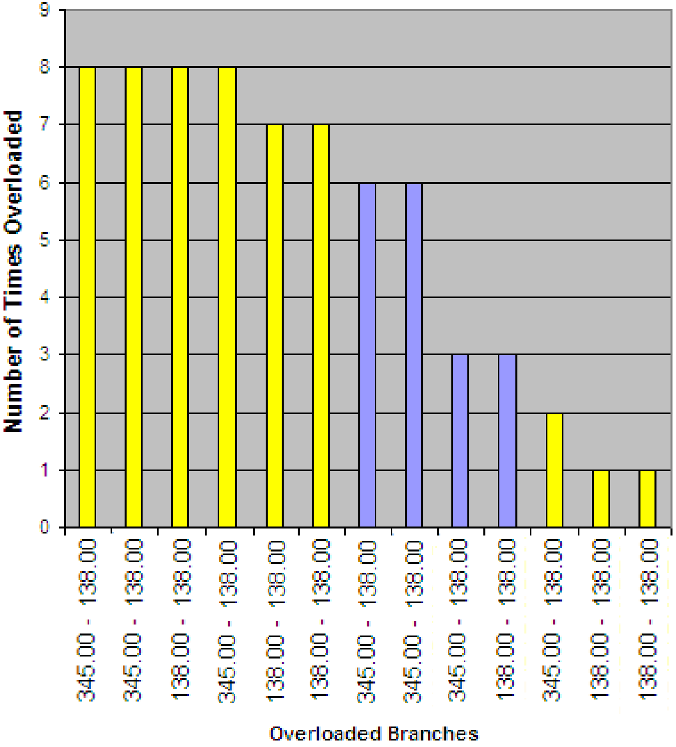

Fig. 13. Tier 2: Branches Overloaded as a Result of 21 Initiating Events

Seven branches that are overloaded above the line tripping threshold and tripped at Tier 2 are 345/138 kV transformers, and the remaining six branches as 138 kV lines, as shown in Fig. 14.

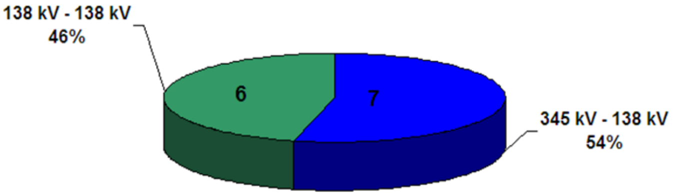

Fig. 14. Base Voltages of Branches Tripped at Tier 2

E. Analysis of Cascading Outages with 3 Tiers

From 38 initiating events identified in Section IV.B, 17 events terminated in one tier, 11 terminated in two tiers, and the remaining 10 events cascaded to Tier 3 (see Fig. 8).

The analysis of Tier 3 overloads showed that only two different branches were overloaded above the line tripping threshold as a result of 10 initiating events that cascaded to Tier 3. Thus, only two different branches were tripped at Tier 3. Both branches are unique; e.g., they were not overloaded above line tripping threshold and tripped at Tiers 1 or 2 (but for different initiating events).

A 345/69 kV transformer, overloaded above the line tripping threshold in 8 instances, is the most frequently overloaded branch (see Fig. 15).

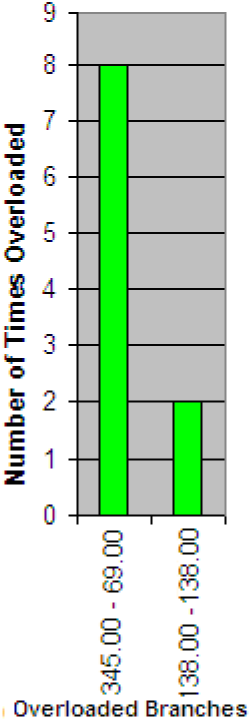

Fig. 15. Tier 3: Branches Overloaded as a Result of 10 Initiating Events

Analysis of the cascading outages for this participating utility shows that cascading chains have local spread, and involve a limited number of elements that are being tripped.

The initiating events and cascading chains are automatically displayed on the oneline diagram, see Fig. 16. The spread of cascading outages is animated in the oneline.

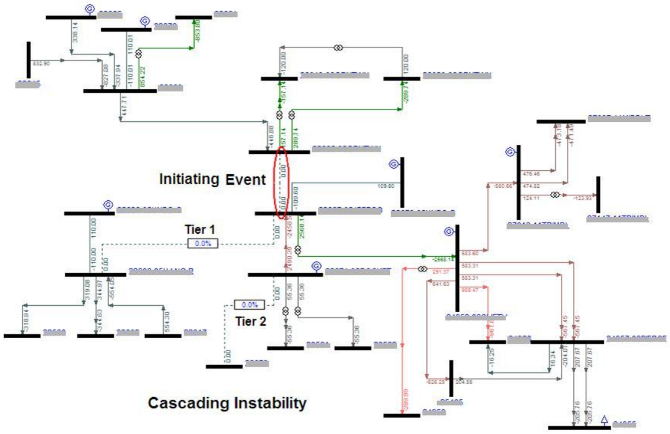

Fig. 16. Cascading Outages on the Oneline Diagram

If an island is formed as a result of a cascading outage, it is shown in the oneline. Four types of islands are displayed:

- Load only
- Generation only
- Generation greater than load (e.g., over-generated island)
- Generation less than load (e.g., under-generated island)

V. DISPLAYING THE RISK OF POTENTIAL CASCADING MODES

A bubble diagram display offers a practical view of the risk of the potential cascading modes, see Fig. 17.

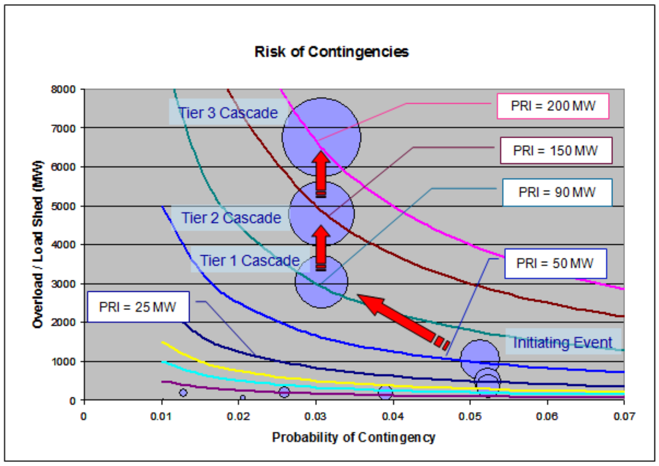

Fig. 17. Displaying Risk of Cascading Outages

The diagram is shown on the plane (*Probability*, *Impact*)

x- axis - probability of an initiating event

y- axis - MW Impact (MW Overload/Load Loss/ Generation Loss).

The size of the bubble is in proportion to the value of the ranking index for potential cascading mode, $\mathrm{PRI}_{\mathrm{PCM}}$, see Section III.C.

For each initiating event, each bubble corresponds to an impact at each tier, as specified in Section III.C. Bubbles for different tiers for the same initiating event are connected with arrows.

The diagram also displays hyperbolic curves –– equal-$\mathrm{PRI}_{\mathrm{PCM}}$ level lines.

This display is effective in showing the increasing risk of cascading outages under different stress levels.

VI. CONCLUSION

This present paper describes a process for evaluating cascading outages in order to comply with NERC recommendations.

The objectives for this study are:

- Identify initiating events that may lead to cascading outages
- Automatically determine how the cascading spreads, e.g., cascading chains.
- Automatically determine islands that are formed as a result of a cascading outage.
- Display initiating events/cascading chains on the oneline.
- Identify impact of cascading outages.
- Rank cascading outages based on the vulnerability index.

The study shows that the proposed approach is a fast practical method for analysis of cascading outages. It may be adopted as both an operational and a planning tool.

The benefits of such analysis include:

- A practical approach to identifying initiating events that may lead to cascading outages.
  These events might be located outside of a utility's footprint and not analyzed as a part of the routine analysis. However, they may spread into the utility's control area and cause a severe disturbance.
- Quick prediction of how the cascading event spreads.
  The cascading tiers are automatically identified and the process is shown in the oneline diagram.
- Islands, created as the result of cascading outages, are automatically identified and displayed on the oneline diagram.
- Implementing probabilistic assessment in order to rank cascading outages and visualize their impact.

At first, a "cluster" approach was implemented to perform a quick screening and identify potential initiating events that may lead to cascading outages. This automatically generated contingency list may be further combined with the user-defined "must run" contingency list in order to offer a master list of initiating events.

Then, for each potential cascading mode cascading tiers were automatically identified. Determining the impact of cascading outages and ranking them using a vulnerability index then follows.

The study was performed using the project participant's loadflow data to validate the approach.

Because this approach looks very promising, it may be extended to incorporate optimal mitigation measures to prevent and mitigate the impact of cascading outages.

VII. ACKNOWLEDGEMENT

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