Enhanced Multiple Element Contingency Screening and Cascading Analysis for NERC Compliance

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Abstract — This paper addresses enhancements of ATC's steady state multiple element contingency screening and cascading analysis for NERC compliance. The improvements include (1) changes to the ATC cascading analysis criteria; (2) automation of screening and cascading analysis simulations; (3) automation to find mitigations to restore the system to be within emergency and/or normal performance limits and (4) automation of the post-processing of results into spreadsheets. These enhancements allow the assessment of a larger number of multiple element contingencies for compliance with selected NERC transmission planning and security Reliability Standards. Another improvement was to develop a better definition of the total load at risk.

Index Terms — NERC compliance, multiple element contingency, screening analysis, cascading analysis, cascading tripping criteria, load loss, mitigation measures.

I. Introduction

AMERICAN Transmission Company (ATC) was founded in 2001, as a multi-state, transmission-only electric utility. ATC provides electric transmission service in an area from the Upper Peninsula of Michigan, throughout the eastern half of Wisconsin and into portions of Illinois. ATC has more than 9,480 miles of high-voltage transmission lines and 529 substations to provide communities with access to local and regional energy sources.

In recent years, ATC has improved its practices related to steady state multiple element contingency analysis to address the following business needs:

- To improve compliance support documentation for various NERC standards that involve multiple element contingency analysis. Applicable standards include: transmission planning standards TPL-003-0[1], TPL-004-0[2], and future TPL-001-4[3]; cyber security standard CIP-002-5[4]
- To effectively and efficiently assess a larger number of multiple element contingencies that may impact the ATC system to better identify which contingencies to categorize as "more severe"
- To improve the ATC screening and cascading analysis methodologies, including enhancing our cascading tripping criteria
- To automate a larger amount of post-processing of screening and cascading analysis results

In 2013, ATC engaged V&R Energy Research to develop special scripts to implement ATC's enhanced multiple element contingency screening and cascading process using the Physical and Operational Margins[5] – Optimal Mitigation Measures[6] (POM/OPM) software.

The scripts were used for the 2013 ATC NERC Category C compliance study and the results were used for the 2013 Midwest Reliability Organization / Reliability First Compliance Audit.

II. ENHANCED ATC CASCADING TRIPPING CRITERIA

The ATC cascading tripping criteria were enhanced to consider line circuits, transformers, cables, generator units, and interconnected loads.

1. Overhead Transmission Lines

In 2011, ATC's Base Assumptions Ratings Committee team established thermal transient limits (TTLs) for different transmission overhead line voltages. The TTLs are 30-minute load dump ratings. In the Planning horizon, we assume that thermal line loading above TTL would lead to tripping because it exceeds the line's thermal design and the response to the overload is unknown.

The thermal overload tripping criteria for overhead transmission lines are:

• 345-kV lines: 110% of the overhead line conductor summer emergency rating

• 115/138/161/230-kV lines: 105% of the overhead line conductor summer emergency rating

• 69-kV lines: 100% of the overhead line conductor summer emergency rating

2. Transformers and Cables

Thermal overload tripping criteria for transformers and cables were also developed:

• Transformers: 30-minute rating with 70% preload at an ambient temperature of 90 deg Fahrenheit

• Underground/submarine cables: 125% of the cable summer emergency rating

3. Loads and Generators

In addition to the thermal tripping criteria, two low voltage tripping criteria were also developed:

• Load low voltage tripping threshold: The selected value of 0.8 p.u. is used as a reasonable tripping level based on the materials from C.W. Taylor, Power System Voltage Stability[7], McGraw-Hill, International Editions 1994.

• Generator low voltage tripping threshold: if a low voltage tripping value was provided by a generator owner, it is used. Otherwise, an assumed value of 0.9 p.u. is used, which is based on voltage ride-through time duration curve in Attachment 2 of NERC PRC-024-1[8].

III. TOTAL LOAD AT RISK

A "**Total Load at Risk**" was defined by ATC to evaluate and prioritize the system impact of a multiple element contingency. It is the sum of the following three types of load loss, which are identified and recorded in the multiple element contingency screening and cascading studies:

• **Consequential load loss** (NERC definition [9]): "All Load that is no longer served by the Transmission system as a result of Transmission Facilities being removed from service by a Protection System operation designed to isolate the fault".

• **Subsequent cascading load loss**: The load outaged as a result of the subsequent outages during the remaining cascading tier analysis. This type of load loss is a result of either load tripping when load buses are below 0.8 p.u. or load islanding due to lines/transformers tripping.

• **Expected load shed**: The sum of the load curtailment that may need to be performed by manual or automatic control to restore the system to be within emergency limits and the additional load curtailment that may need to be performed by manual or automatic control to restore the system to be within normal limits.

ATC selects a Total Load at Risk value to classify which contingencies are "more severe" and also selects a Total Load at Risk value as a criterion to help better define NERC Cascading.

IV. ENHANCED SCREENING ANALYSIS METHODOLOGY

The enhanced screening analysis methodology includes two stages.

Stage 1 – Steady State Screening Analysis without Mitigation (Fig.1.): The primary aim of Stage 1 analysis is to screen a selected set of contingencies and identify any contingencies that fall into one of these three post-contingency Outcomes:

1. Potential steady state voltage instability
2. Any ATC cascading tripping criteria were met
3. Any emergency or normal thermal or voltage limits were exceeded

In order to determine Outcomes, the power flow models need to include normal ratings, emergency ratings and tripping ratings for lines, transformers and cables.

The contingencies in Outcomes 1 and 2 will be reviewed further in the Stage 3 Cascading Analysis. The contingencies in Outcome 3 will be reviewed further in the Stage 2 Steady State Screening Mitigation Analysis.

The Stage 1 script automatically sends the following results and tabulates them in spreadsheets: contingency name and type; thermal circuit loadings compared to normal, emergency and tripping ratings; bus voltages compared to normal and emergency limits; load/generator bus voltages compared to tripping limits; and a list of potential voltage instability contingencies.

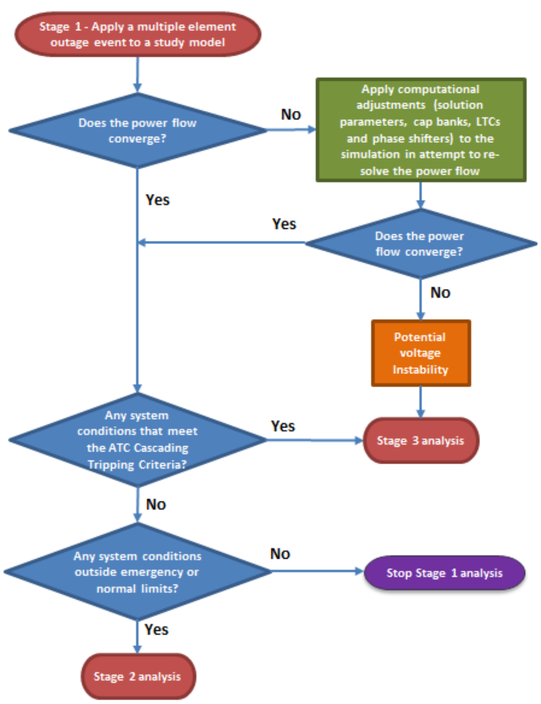

Fig. 1. Stage 1 Flow Chart - Steady State Screening without Mitigation

Stage 2 – Steady State Screening Mitigation Analysis (Fig.2.): The primary aim of Stage 2 analysis is to determine potential mitigation measures using OPM to alleviate post-contingency thermal overloads and bus voltages outside of emergency or normal limits.

Step 1a - For thermal overloads or bus voltages outside of emergency limits, the following measures are used to restore the system to be within emergency limits. The mitigation measures are applied in following order:

- Capacitor and inductor switching
- Transformer LTC adjustment
- Phase shifter adjustment
- System reconfiguration
- Load curtailment

Step 1b - After the mitigation measures identified in Step 1a are applied, Step 1b checks whether there are any thermal overloads or bus voltages outside of normal limits. For thermal overloads or bus voltages outside of normal limits, the mitigation measures are applied in same order except that generation redispatch is included between system reconfiguration and load curtailment.

Step 2 - This step is performed for contingencies that only result in bus voltages above their high voltage limits. The following measures are used to restore the system to be within emergency and normal limits. The mitigation measures are applied in following order:

- Capacitor and inductor switching
- Transformer LTC adjustment
- Generation voltage schedule
- Phase shifter adjustment
- System reconfiguration

The Stage 2 script automatically tabulates the results and outputs them into spreadsheets:

- A summary file containing the total consequential load and generation loss due to the initial outage, the total expected load shed /generation redispatch during each step of the mitigations. And, the Total Load at Risk after all steps are completed.
- A results file containing the detailed mitigation measures determined at each step of the mitigation process
- A results file containing the detailed load and generation loss information due to the application of system reconfiguration measures recorded at each step of the mitigation process
- A results file containing the post-contingency and post-mitigation thermal loading information calculated at each step of the

mitigation process

• A results file containing the post-contingency and post-mitigation bus voltage information calculated at each step of the mitigation process

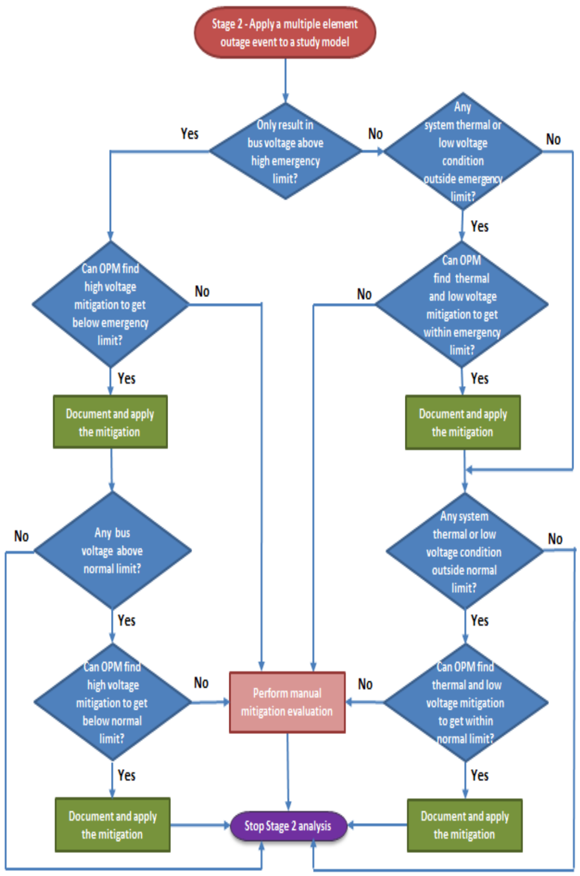

Fig. 2. Stage 2 Flow Chart - Steady State Screening Mitigation Analysis

V. ENHANCED CASCADING ANALYSIS METHODOLOGY

Stage 3 - Cascading Analysis (Fig. 3. and Fig.4.) The primary aim of Stage 3 analysis is to model, monitor and report cascading analysis based on ATC's tripping criteria and record the three types of load loss on a bus basis, a tier basis and an aggregate basis. Stage 3 includes two parts:

1. **Cascading Tier Analysis**: The cascading simulation is performed on a tier-by-tier basis. Each tier includes the simulation of applicable tripping and the evaluation of the results against the cascading criteria.

Cascading Tier Analysis is stopped by any one of the following four criteria:

a. The Total Load at Risk threshold is exceeded

b. No more tripping criteria are met

c. The number of Bulk Electric System (BES) lines tripped threshold is exceeded

d. Potential voltage instability - at any tier that the power flow does not converge, computational adjustments are attempted to resolve the non-convergence. If resolved, cascading simulation is continued. If not, then OPM "Load Curtailment" measure is used to identify optimal load curtailments that may allow the power flow to converge. Otherwise, the Cascading Analysis is stopped and manual evaluation is performed.

During Cascading Tier Analysis, the Stage 3 script automatically sends the results into the following files:

• A results file containing the detailed, tier-by-tier, line thermal loading information. All lines listed in this file exceed their tripping ratings on a certain tier.

• A results file containing the detailed, tier-by-tier, load and generator bus voltage information. All load and generator buses listed in this file are below their voltage tripping criteria at a certain tier. It also identifies whether any generators or loads are already out of service.

• A results file containing the detailed, tier-by-tier, load and generation loss information. It also identifies whether any load or generator loss is due to line tripping or due to an associated bus voltage below its tripping criterion.

• A results file containing OPM "Load Curtailment" details when voltage instability occurred on a certain tier and was successfully alleviated

• A summary results file containing, tier-by-tier, the total consequential load and generation loss due to the initial outage and total subsequent cascading load/generation loss

2. **Post-Cascading Mitigation Analysis**: When the Cascading Tier Analysis is stopped by any one of the first three criteria, Post-Cascading Mitigation Analysis is performed using the OPM and same mitigation measures discussed in Stage 2 to restore the system to be within emergency and normal limits.

Results related to this part of the Stage 3

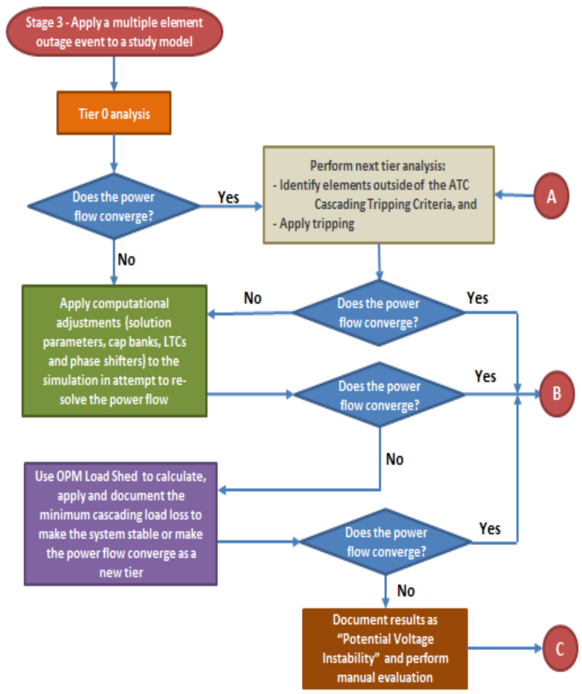

Fig.6. Stage 3 Flow Chart Part 1

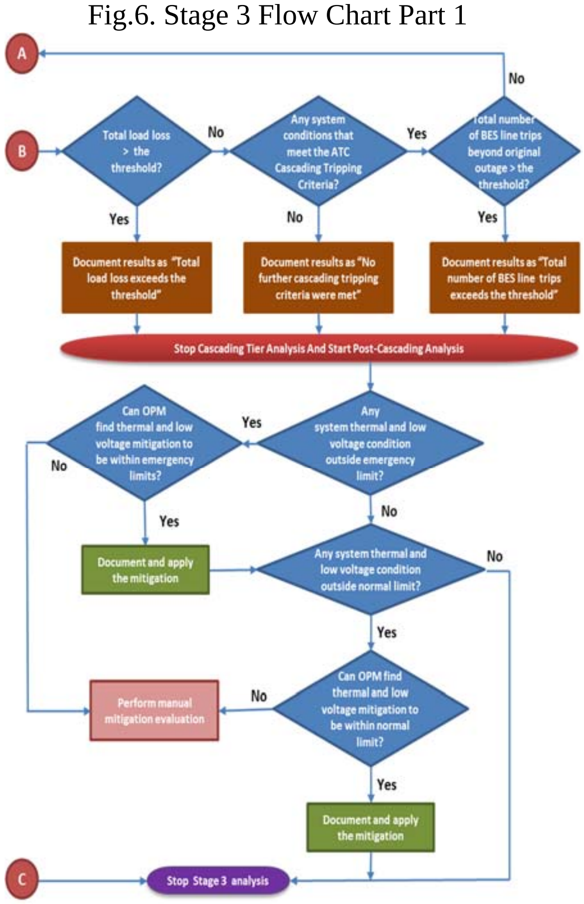

Fig.7. Stage 3 Flow Chart Part 2

analysis are same as the Stage 2 results except that an overall Cascading Analysis summary file is generated. This file contains the total consequential load and generation loss due to the initial outage and the total subsequent cascading load/generation loss. It also includes the total number of BES line tripped, the total number of tiers and the reason for stopping the cascading. In addition, it provides the Total Load at Risk to restore the system to be within emergency and normal limits.

VI. Script Performance

Based on the ATC 2013 NERC Category C compliance study, typical running times including both contingency simulation and result tabulation for each of the three stages were recorded.

- Stage 1- Steady State Screening Analysis without Mitigation

    ~250,000 number of contingencies
    ~25 hours running time

- Stage 2 – Steady State Screening Mitigation Analysis

    ~14,000 number of contingencies
    ~10 hours running time

- Stage 3- Cascading Analysis

    ~800 number of contingencies
    ~2 hours running time

Other factors that significantly impact running time are: computer speed, number of iterations needed to solve the power flow, and number of buses modeled.

VII. Conclusion

The efforts to develop a more fully defined steady state screening and cascading analysis process proved to be very beneficial. Some of the favorable outcomes were:

- More effective and efficient screening and cascading analysis process details were developed and documented, which formed the foundation for automating a significant portion of the analysis tasks.
- The cascading tripping criteria were expanded to include load /generator low voltage tripping thresholds and more detailed tripping thresholds were developed for overhead lines,

transformers, and cables.

• The definition of Total Load at Risk was enhanced to allow better evaluation and prioritization of the system impact of a multiple element contingency.

• New screening analysis and cascading analysis considerations were identified and addressed including the development of methods to resolve non-convergence conditions and cascading simulation stop criteria.

A substantial portion of the screening and cascading analysis was automated. The scripts allow transmission planning engineers to perform screening or cascading analysis on more extensive or comprehensive sets of candidate contingencies. The time that a planning engineer spends performing screening and cascading analysis, as well as post-processing with the scripts, is a small fraction of the time needed to perform the analysis manually. However, a small number of contingencies still require manual evaluation.

Although the enhancements in this paper were developed primarily to support compliance with NERC TPL-003-0 and TLP-004-0 Reliability Standards, they will also be helpful to support compliance with the TPL-001-4 standard, which becomes effective in 2015. The enhancements were also useful for CIP-002-5 Reliability Standard analysis and various transmission operation assessments.

The automation scripts that were created to work with the POM/OPM program software achieved the desired results.

Planning Coordinators, Transmission Planners, Reliability Coordinators, and Transmission Operators would benefit from developing similar enhancements for their multiple element analysis screening and cascading analysis activities.

VIII. FUTURE WORK

The following enhancements to the ATC Cascading Tripping Criteria and the screening/cascading analysis process are under consideration:

• Enhancing the cascading tripping criteria for overhead lines, transformers, and cables by considering terminal equipment ratings

• Developing high voltage tripping criteria for generators

• Improving cascading analysis by determining the sequence in which elements should be tripped and when elements should be tripped together

• Replacing the element-based tripping in the cascading analysis with automated breaker-to-breaker tripping

• Incorporating the simulation of SPS or loadability relay actions into the automated screening and cascading analysis

IX. REFERENCES

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