Expanding Transmission Planning Capabilities for NERC Standard TPL-001-2 Compliance

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Abstract—North American Electric Reliability Corporation (NERC) Standard TPL-001-2 has been adopted by the NERC Board of Trustees and will become effective in the near future. The TPL-001-2 standard was developed to identify events which will cause reliability violations and more severe system impacts including cascading. It also requires simulation of protection system actions in contingency analysis and development of corrective actions for system deficiencies and possible preventive actions to reduce the likelihood of cascading and mitigate the consequences. To meet the compliance with this Standard, an innovative transmission planning method is developed which includes: (1) identification of contingencies which will cause reliability violations or produce more severe system impacts including cascading; (2) development of corrective actions to achieve required system performance, and identification of actions to prevent the spread of cascading outages, or to mitigate the cascading consequences; and (3) ranking of the severity of the events and evaluation of cascading-causing events.

Index Terms—Cascading, Compliance, Contingency analysis, Corrective action, NERC Standard, Preventive action, Reliability violation, Severity ranking, System performance, Transmission planning

I. INTRODUCTION

North American Electric Reliability Corporation (NERC) Standard TPL-001-2 has been adopted by the NERC Board of Trustees and will become effective in the near future. The purpose of this Standard is to “Establish Transmission planning performance requirements within the System planning horizon to develop a Bulk Electric System (BES) that will operate reliably over a broad spectrum of System conditions and following a range of probable conditions and following a wide range of probable System actions in contingency analysis and development of corrective actions for system deficiencies and possible preventive actions to reduce the likelihood of cascading and mitigate the consequences. To meet the compliance with this Standard, an innovative transmission planning method is developed which includes: (1) identification of contingencies which will cause reliability violations or produce more severe system impacts including cascading; (2) development of corrective actions to achieve required system performance, and identification of actions to prevent the spread of cascading outages, or to mitigate the cascading consequences; and (3) ranking of the severity of the events and evaluation of cascading-causing events.

The TPL-001-2 Standard is developed to [1]:

- identify planning events which cause “an inability of the System to meet the performance requirements in Table 1” [1] (Requirement R2.7)
- develop Corrective Action Plan(s) to achieve required System performance for the listed System deficiencies (Requirement R2.7)
- simulate the actions of the Protection System, automatic controls, and Special Protection System (SPS) in contingency analyses (Requirement R3.3)
- identify the planning events and extreme events in Table 1 which are expected to produce more severe System impacts, and evaluate their consequences including Cascading (Requirements R3.4-R3.5)
- conduct a cascading evaluation to develop possible actions to reduce the cascading likelihood or “mitigate the consequences and adverse impacts” (Requirement R3.5)

Cascading is defined by NERC as: “The u ncontrolled successive loss of system elements triggered by an incident at any location. Cascading results in widespread electric service interruption that can not be restrained ed from spreading beyond areas predetermined by studies.” [2] According to [3], the number of blackouts which cause load loss of more than 1,000 MW doubled every 10 years. Several recent large blackouts in the US caused by cascading include the Arizona-Southern California blackout in September, 2011; the Midwest and Northeast US and Ontario, Canada blackout in August, 2003; and two WECC blackouts in July and August, 1996.

Protection systems play a significant role in NERC events; in fact, they were significant in 73.5% of 49 evaluated NERC events [4]. It is very important to simulate the actions of relays and SPS in contingency analyses. Protective relays can be distance relays, over-current relays, under-voltage relays on induction motors, differential relays, etc. SPS is designed to detect abnormal system conditions and take automatic corrective actions to maintain system reliability [2]. SPS actions may result in reduction in load or generation, or HVDC system change, or changes in system configuration, etc.

A cascading failure generally involves the sequential outage of power system facilities and automatic or manual operations dependent on previous sequence of system states.
Cascading failures following a contingency usually occur in one of two frequent scenarios [5]:

1. Branches are heavily overloaded and/or generator bus voltages are well below limits, causing the protection system to initiate trip ping of overloaded branches and/or under-voltage generators;
2. Reactive power is deficient, causing significant voltage drop. At buses where voltages are well below the limits, generators are tripped and induction motors are stalled or tripped.

To study the development and consequences of cascading, power flow equations will be solved many times in successive modes, to mimic the system dynamics. The system dynamic reactions include contingencies; branch, generator, or load tripping or reduction due to protection system automatic actions; system separation (islanding) due to contingencies or tripping; automatic redispatch of generation due to system load and generation imbalance or even system separation (islanding) due to contingencies or tripping; automatic redispatch of generation to balance system load and generation.

IEEE Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures has done tremendous work on reviewing status quo methodologies and tools on risk assessment of cascading outages [6]-[9]. In this paper, an innovative transmission planning method based on a well-defined used power system software program [10] is developed for compliance with NERC Standard TPL-001-2. The new transmission planning method includes three main functions: (1) identify panning events and extreme events which will cause reliability violations or p reduce m ore severe syste m impacts including cascading; (2) develop corrective actions to achieve required system performance, and identify actions to prevent the spread of cascading outages and mitigate the cascading consequence; and (3) rank the severity of events and identify cascading root cause.

II. IDENTIFY EVENTS CAUSING RELIABILITY VIOLATIONS AND MORE SEVERE SYSTEM IMPACTS INCLUDING CASCADING

NERC Standard TPL-001-2 classifies single and multiple contingencies into “Planning Events” and “Extreme Events.” The planning events are in Category P0–P7, including “same time” events (P0–P2, P4–P5, and P7) and two independent single contingencies with a period in-between where system adjustments are performed (Category P3 and P6, also called Category P.N-1-1 contingencies).

To identify planning and extreme events which will cause system reliability violations, and/or may produce more severe system impacts including cascading, AC contingency analysis will be performed. Consequential load or generation loss may occur after the contingency (or after the tripping by the protection system as discussed in Section III). This will cause system load and generation imbalance, or even system separation (islanding). All the system load and generation an d islanding will be recorded for event evaluation and ranking as discussed in Section IV.

To simulate the expected automatic operation of devices designed to provide system steady-state control (Requirement R3.3.2 in [1]) and to facilitate the power flow solution, automatic generation redispatch is simulated. This redispatch can be in proportion to: [11]

- (Pmax – Pgen) or (Pgen – Pmin)
- Pmax
- Machine inertia
- Governor droop

If a network island is created after the contingency or tripping, the following system controls will be taken [11]:

- The island will be shut down and the total consequential load loss in the island will be recorded if there is no online generator in the island;
- If the online generation is efficient, increase online generation while observing Pmax limits. If generation is still deficient, shut island loads proportionally while maintaining the same load power factor. Once the generation and load balance is achieved, the island power flow solution will be calculated;
- If the online generation is excessive, decrease online generation while observing Pmin limits. If generation is still excessive, the island will be shut down.

The total number of single contingencies (Category P1-P2 in [1], also called Category B contingencies in [12]) and their combinations (Category P3, P6, and extreme events), and multiple co-continuities (Category P4, P5, P7, and extreme events) is enormous in a large interconnected system. It is essential to rank contingencies from the most to least severe before the actual AC contingency analysis is performed.

DC contingency analysis can be performed to rank all the contingencies. An overload Contingency Severity Index (CSI) measures the severity of a contingency, based on post-contingency overloads and loss of load and generation [13]. This can be calculated as:

\[ Overload\ CSI = \sum_i \left( P_i - P_{lim} \right)^2 + LossOfLoad^2 + LossOfGen^2 \]  \hspace{1cm} (1)

Where:
- \( P_i \): post-contingency branch \( i \) active flow
- \( P_{lim} \): branch \( i \) rating
- \( LossOfLoad \): total loss of load caused by the contingency
- \( LossOfGen \): total loss of generation caused by the contingency

A voltage CSI measures increased reactive power consumption in all branches due to increased loadings, which indicates voltage depression [11]:

\[ Voltage\ CSI = \sum_i X_i P_{i,\text{active}} \]  \hspace{1cm} (2)

Where:
- \( P_i \): post-contingency branch \( i \) active flow
\( X_i \): branch \( i \) reactance

The overload CSI and voltage CSI can be combined with weighting factors to rank contingencies. In an example of combinations of two Category B contingencies (N-2, or N-1-1), the primary contingencies will be ranked from the most to least severe in system in a common condition. The secondary contingencies will be ranked after the primary contingency is simulated (N-2), or after each primary contingency is simulated and the system adjustments are taken (N-1-1). Therefore each primary contingency will have its own ranked secondary contingency simulating from the most to least severe. Under each primary contingency, if there are any consecutive specified number of secondary contingencies for which cause no reliability violations, the entire AC contingency analysis will stop simulating the remaining secondary contingencies and continue simulating the next primary contingency and its ranked secondary contingencies. If there are a consecutive specified number of primary contingencies with their consecutive specified number of secondary contingencies not causing any reliability violations, the entire AC contingency analysis is finished. Through these steps of the contingency ranking method, the time for completing the entire AC contingency analysis is greatly reduced.

For N-1-1 contingencies, system adjustments will be taken after the primary contingency and before ranking the secondary contingency. If branch loadings or bus voltages are beyond normal limits but below emergency limits under a primary-level contingency, either corrective or action will be taken to bring the branch loadings or bus voltages to normal limits, or preventive actions will be taken for system adjustments and preparation for the next Category B contingencies. Th is represents the system adjustments with a period in-between.

Preventive Security Constrained Optimal Power Flow (PSCOF) is used to identify and perform preventive actions to ensure system security in preparation for the next contingency. This step is performed before ranking the next Category B contingencies. It is represented as system adjustments with a period in-between.

Induction motor loads can be explicitly modeled as single or double cage induction motors in the power flow. They can be automatically tripped or stalled during the power flow solution due to low terminal voltages. These include contingencies which have thermal or voltage violations over applicable limits, but may not lead to cascading (below the protection tripping threshold).

After the AC contingency analysis is finished, the contingencies will be classified in three categories:

- Category 1: Events which cause "an inability of the System to meet the performance requirements in Table 1" [1]. These include contingencies which have thermal or voltage violations over applicable limits, but may not lead to cascading (below the protection tripping threshold);
- Category 2: Events which cause "whic h are expected to produce more severe System impacts" [1]. These include contingencies which have thermal or voltage violations above the protection tripping threshold. These contingencies may lead to cascading;
- Category 3: Planning events and extreme events which lead to a divergent power flow due to voltage collapse, or contingencies which cause consequential load loss or generation loss above a threshold, or large scale islanding with total load above a threshold.

III. DEVELOP CORRECTIVE ACTIONS FOR MITIGATION AND IDENTIFY ACTIONS TO PREVENT CASCADING

The criteria for cascading failure include the following events:

- Power flow diverges due to voltage collapse;
- Consequential load loss (with contingency or tripping) exceeds a threshold, or controlled load shedding exceeds a threshold;
- Islanding with total load exceeding a threshold;
- Consequential generator loss (with contingency or tripping) exceeds a threshold;
- Total number of tripped branches (by protection system) above a certain voltage level exceeds a threshold.

For the contingencies which fall into Category 1, corrective actions can be taken to mitigate the event. The objective is to minimize the control adjustments for the removal of thermal or voltage violations. The constraints include equality and inequality constraints, such as power flow equations and limits of controls and operation conditions.

Corrective actions may include transformer tap adjustment, switched shunt cont rollor, phase shifting angle adjustment, generation re-dispatch, system reconfiguration, generator controlled voltage adjustment, offline generator control, load shedding, etc. To ensure that the most effective and economic corrective actions are taken first, different types of corrective actions are assigned different cost coefficients, with controlled load shedding as the most expensive corrective action.

For the contingencies which fall into Category 2, automatic tripping actions (including tripping, generation reduction, load switching, system configuration change, etc.) representing the actions taken by protective relays and SPS will be simulated if they meet the tripping criteria. Branches can be tripped if the loadings are above the threshold, generators can be tripped due to low or high voltages, and load (not explicitly modeled as induction motors) can be tripped due to low voltages. To mimic the relay settings, different tripping thresholds can be specified for transmission lines and transformers at different voltage levels and locations, generators of different MW size.
During a cascading event, multiple lines, generators, and loads may meet the tripping threshold at the same stage. The order in which facilities are tripped can greatly influence the cascading progression [15]. To help the power flow convergence, it is better to trip one facility each time and then solve the power flow rather than tripping all the facilities simultaneously. A tripping priority table can be predefined, which sets the tripping priorities among different branches. Overloading levels at different voltage levels, and different generator over/under-voltage levels at different sizes. Usually, load at low voltage levels should be tripped after all overloaded branches and over/under-voltage generators are tripped. This will ensure the most severe scenario in the event simulated.

Branch tripping should be from breaker to breaker to represent the actual relay action. Planning models are typically in bus-branch representation without detailed breaker modeling. To implement the breaker-to-breaker tripping, buses and their multi-terminal branches can be pre-specified in a “Dictionary”, which can be easily searched during the tripping period.

After the tripping actions are finished, results are compared against the criteria for cascading failure. If the cascading failure criteria are not violated, corrective actions are identified and performed before tripping all loads and voltages within the applicable emergency limits.

If a contingency in Category 2 violates any of the cascading failure criteria, the power flow solution will be stopped and the contingency will be classified as a cascading event causing generator overload at low voltage levels should be tripped last, after the total thermal violations during the event, number of buses with voltage violations during the event, and number of cascading events (number of power flow solutions).

\[
S = a_i \times V_{C_i} + a_i \times L_{SH_i} + a_i \times L_{CL_i} + a_i \times G_{LCL_i} + a_i \times V_{V_i} + a_i \times T_{V_i} + a_i \times N_{j_i}
\]

where different weighting factors \(a_i\) can be assigned.

For the contingencies which initiate cascading, the number of times the same branch or generator trips occurs in
the cascading event can also be cumulated. This gives a list of frequent branches and generators involved in the cascading events.

Similarly, branches and generators involved in the contingencies at tipping where the event will have consequential load loss or require controlled load shedding are also counted. All of these can help identify system weaknesses and indicate necessary system upgrades.

V. CONCLUSIONS

This paper discusses the new requirements in NERC TPL-001-2 Standard which includes: (1) identification of contingencies which will cause reliability violation, or produce more severe system impacts including cascading; (2) simulation of automatic action by protection system and automatic controls in contingency analysis; (3) development of automatic action plans to achieve system performance and automate controls upon the occurrence of contingencies; (4) development of possible actions to reduce the likelihood of cascading or mitigate cascading consequences.

To meet compliance with NERC TPL-001-2 Standard, this paper proposes an innovative transmission planning method which includes: (1) identification of contingencies which will cause reliability violations, or produce more severe system impacts including cascading; (2) development of corrective actions to achieve required system performance and evaluate the possibility of cascading; and (3) ranking of the severity of the event and evaluating system weaknesses.

The implementation of this new planning method is based on a widely used power system software program [10]. Some advanced techniques are implemented which include: (1) DC contingency analysis for contingency ranking, which considers “same time same multiple events” and “two independent simultaneous contingencies”; (2) development of corrective actions to achieve required system performance and evaluate the possibility of cascading; and (3) ranking of the severity of the event and evaluating system weaknesses.

VI. REFERENCES

[27] Siemens PTI, ”PSS®E 33.2 program operation manual,” July 2012.