CANA

AESO Engineering Studies

Failure Containment Loads for

502.2 Bulk Transmission Line Technical Requirements

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1 Background

CANA High Voltage was requested by the AESO to prepare a report documenting the various inputs and criteria evaluated by the Transmission Rules/Tower Review Working Group (the Technical Committee) in choosing the failure containment criteria specified in the current draft of the Section 502.2 Bulk Transmission Line Technical Requirements as of April, 2016.

In preparation of this report, Technical Committee minutes, correspondence, and other references within the ISO Rules and Information documents were reviewed. These findings are summarized within this report. The Technical Committee reviewed transmission standards, documents, and practices of other Canadian utilities to assess a state of the art of transmission design for failure containment.

Failure containment measures are taken to reduce the likelihood of a cascading structural failure. This refers to the progressive collapse of transmission line structures extending well beyond the source of the original failure. This may take one of three mechanisms (or combinations thereof):

- Transverse;
- Vertical;
- Longitudinal.

An initial failure triggers subsequent failures on its adjacent structures which progress in a domino-like fashion and can extend for great distances. These basic mechanisms are explained in further detail in the following discussion.

1.1 Transverse Cascading Failures

A transverse cascading failure typically occurs as a result of extreme (high intensity) wind events or combined wind and ice (wet snow) events. They are usually triggered with the failure of a single structure in the transverse direction increasing loads on its adjacent structures as it pulls the conductors over, off the transmission line centerline. If these adjacent structures are already approaching their transverse capacity, the skewed conductor tensions can initiate a transverse cascading failure extending for a great distance.

The tendency for a transmission line to experience a transverse cascading failure increases for taller structures and with shorter spans. With the failure of a single structure, a greater transverse load can be applied to adjacent structures when there is insufficient slack in short a span to avoid large conductor tension increases with conductor displacement. Conductors are pulled further off-center with failure of a taller structure – particularly in the event of a failure near ground line.

Failure of a single structure in a high intensity wind event is not common; there are often multiple adjacent structures which also fail. While this is sometimes attributed to a broad gust front, it is more probably the result of a transverse cascading failure.

Such failures have occurred in Alberta:

a) The wet snow event in 1986 resulted in widespread damage to transmission facilities. One of the heavily effected lines was 924L where the failure of forty structures was experienced. Half (20 of 40) structure failures were attributed to a transverse cascade.

b) In 1987 the loss of an approximately 8 km stretch of double circuit 240kV line in Southern Alberta in 1987 was attributed to a transverse cascading failure. The initiation point was thought to be a foundation failure occurring on the windward side of a tangent tower. The failure propagated in both directions from the assumed initiation point until it terminated at structure types with sufficient transverse strength to halt the failure progression.

1.2 Vertical Cascading Failure

Vertical cascading failures are usually initiated by severe ice loading events. This typically takes the form of attachment (hardware, insulator) failures, or structure arm failures over an extended group of structures.

The failure of a tower arm under a heavy vertical load due to iced conductor, for example, would immediately transfer additional vertical load to the arms of its neighboring supports as they pick up additional conductor weight span. If they were already at or near their maximum load capacity, a cascading failure may be initiated which could proceed a considerable distance past the initiating failure, in either direction, before stopping at a more lightly loaded structure or at a structure with greater load capacity.

Where multiple vertical failures have been reported in Alberta they are more typically accompanied by longitudinal or transverse cascading failures resulting from heavy combined (ice and wind) loading. No records attributing a purely vertical cascading failure to multiple structures were found at the time of writing this report.

1.3 Longitudinal Cascading Failure

Longitudinal failures have historically been the most problematic and costly examples of cascading failures. Many legacy transmission lines in Alberta and elsewhere in the world were never designed for any more than a nominal capacity in the longitudinal direction. Their primary function was the resistance of transverse and vertical loads.

Longitudinal failures are normally initiated during an extreme weather event with the failure of a structural element maintaining tension in conductor. Loss of a single phase conductor assembly can result in a progressive torsional failure effecting arms or complete structures. Loss of more phases and shield wires can result in complete structure collapse for an extended distance.

In Alberta's 1986 wet snow storm, about half of the structure failures on 924L (20 of 40 structures) resulted from a longitudinal cascade initiated by the tensile failure of the sub-conductors in one phase. The other half was attributed to a transverse cascade, as described previously.

2 Failure Containment Provisions in Standards & Specifications

Following some fairly disastrous longitudinal failures in the US and elsewhere, many utility, national, and international standards have been updated to partially address containment of longitudinal cascading failures.

Some of these specify the use of Residual Static Load (RSL) referenced in several discussions below. This is the structure load resulting from the remaining conductor tension in the spans adjacent to the failed span after stabilizing – it does not consider dynamic loads occurring momentarily after the failure. RSL loads are dependent on the rigidity of the support structure and on the free-swinging length of the shield wire and conductor suspensions.

2.1 International Requirements

The most commonly applied international standard to transmission lines is the IEC 60826, Third Edition (2003). Its security or failure containment provisions are as summarized in Table 3-1:

Load Type	Basis	Description
Torsional	Broken Conductor	Complete Broken Phase or Shield Wire in adjacent span at any one attachment; application of Residual Static Load. At "sagging temperatures", with no wind or ice load.
Longitudinal	Conductor Load Imbalance	Bare conductor on one side, loaded conductor on other side with loaded conductor unit weight equal to twice the unit weight of the bare conductor. Temperature -5°C
Other	Suggested Options for High Security Lines	Increase RSL by a factor of 1.5, or; Apply RSL loads at any two points of conductor or OHSW attachment, or; Insertion of anti-cascading towers at every tenth structure.

Table 3-1: IEC 60826: 2003 Failure Containment Provisions

This standard is applied in some form for much of transmission line design and construction outside North America.

2.2 American NESC Requirements

US requirements for transmission line design are summarized in the National Electrical Safety Code (NESC)[1]. This is a voluntary standard but has been adopted by many regulatory agencies in the USA. It does not contain specific requirements for failure containment, but clause 252. C. 6. states, "It is recommended that structures having a longitudinal strength capability be provided at reasonable intervals along the line." No other specific requirements for failure containment are noted.

2.3 ASCE 74 Provisions

Other important references are contained in guidelines published by the American Society of Civil Engineers for structural loading of transmission lines[2], ASCE 74. While guidelines documents such as this are not mandatory, they provide a standard of practice which can be used for comparison against the design approaches used in the case of a failed transmission line facility.

ASCE 74 discusses three design approaches to deal with failure containment (security). They propose one of the following approaches:

- Design all structures with some longitudinal load capacity
  - Suggests use of Residual Static Load (RSL) through application of a Longitudinal Load Factor which applies to pre-failure conductor tensions. No meteorological conditions specified (ice/wind load or temperature). For a single circuit line the loads are applied at any single phase attachment, or shield wire attachment. For a double circuit line the loads are applied at any two phases or shield wire attachments.
- Install failure containment structures at specified intervals
  - Notes that no rule is universally applied but that intervals up to 10 miles are common.
- Install release mechanisms
  - Installation of limited slip clamps on tangent structures; no specifics on availability of such devices nor if this has even been installed on actual facilities.

ASCE 74 also references the Bonneville Power Administration approach in Appendix I which was said to accept the failure of one tower on either side of the initiating failure using loading conditions generated from parameters as follows:

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[1] IEEE C2-2007 National Electrical Safety Code, Published by the Institute of Electrical and Electronics Engineers, Inc., Approved by the American National Standards Institute

[2] American Society of Civil Engineers (ASCE), "Guidelines for Electrical Transmission Line Structural Loading", third edition, ASCE Manuals and Reports on Engineering Practice No. 74 (2010)

- One phase or shield wire broken;
- Break occurs during "everyday" load (no ice, no wind, temp 30°F (-1.1°C));
- Initial sag/tension (no creep).

2.4 Canadian Requirements and Practices

The 2010 version of the Overhead Systems portion of the Canadian Electrical Code[3] is referenced in the Alberta Electrical Utility Code (AEUC) with specified exceptions. Unless specifically exempted in the AEUC, the provisions of the Canadian Electrical Code are then presumed to be legal requirements for overhead lines in the Province of Alberta. The current version of the AEUC does not reference the more recently published version of CSA C22.3 (2015) but this is expected to be updated in its next edition.

This mandatory document has no specific requirements for failure containment.

The more recent practice of reliability based design is covered in CAN/CSA-C22.3 No. 60826:06[4]. This basically is an acceptance of IEC 60826 as a Canadian standard with some noted exceptions. This standard is not mandatory in Alberta.

With regard to failure containment, the reliability based design standard specifies only one exception to IEC 60826; it exempts wood pole structures if the broken conductor load requirements are considered "impractical". Its requirements are summarized in Table 3-2.

Load Type	Basis	Description
Torsional	Broken Conductor	Complete Broken Phase or Shield Wire in adjacent span at any one attachment; application of Residual Static Load. At "sagging temperatures", with no wind or ice load.
Torsional	Broken Conductor, CSA Wood Pole Exemption	As above, or: Anti-cascade structures, capable of resisting all static broken bare conductor tensions at 0°C, inserted every 10 structures, or as justified by study.
Longitudinal	Conductor Load Imbalance	Bare conductor on one side, loaded conductor on other side with loaded conductor unit weight equal to twice the unit weight of the bare conductor. Temperature -5°C
Other	Optional for High Security Lines	Increase RSL by a factor of 1.5, or; Apply RSL loads at any two points of conductor or

[3] CAN/CSA C22.3 No.1-10, "Overhead Systems", Canadian Standards Association, July, 2010
[4] CAN/CSA-C22.3 No. 60286:06, "Design Criteria of Overhead Transmission Lines", Canadian Standards Association, October, 2006

		OHSW attachment, or; Insertion of anti-cascading towers at every tenth structure.

Table 3-2: CAN/CSA 60826:06 Failure Containment Provisions

2.5 Design Practice at Canadian Utilities

Technical Committee members provided information on common design practices, as conferred in confidence to them, by Canadian utilities outside Alberta. Such information is difficult to obtain as they do not, in general, make their design practices publicly available and distributed documents are often protected by non-disclosure agreements.

2.5.1 CEATI Survey of Canadian Utilities

The Centre for Energy Advancement through Technological Innovation (CEATI) conducted a survey of Canadian Utilities' design practices in 2006. The final report distribution was largely restricted to members and is not generally available to the public. However, it was partially reprinted in an appendix to CIGRE TB 515[5] and provided an informative summary of Canadian utility design practices. Those which would be applicable to failure containment are summarized in Table 3-3.

Load Type	Basis	Responses	Survey Question (Paraphrased for space)
Containment	Unspecified	12 Yes	Containment provisions made to limit damages in case of exceeding design loads?
Torsional	Broken Conductor	6 Yes 4 No	Broken conductor under ice load considered?
Torsional	Broken Conductor	0 Yes 11 No	Consideration of dynamic load effect on tower?
Torsional	Broken Ground Wire	9 Yes 2 No	Load cases considered by the utilities in determining longitudinal load due to broken wires?
Torsional	Broken Single Conductor Loads	11 Yes 0 No	As above
Torsional	Broken Insulator or Hardware	4 Yes 6 No	As above

[5] CIGRE TB 515, "Containing Cascading Failures and Mitigating Their Effects", Working Group B2.22, Mechanical Security of Overhead Lines

Torsional	Bundled Conductors One Sub-conductor broken	4 Yes 4 No	As above
Torsional	Bundled Conductors All Sub-conductors broken	6 Yes 4 No	As above

Table 3-3: Responses to CEATI Survey of Canadian Utilities

While there are various interpretations and speculations as to the distribution of responses, it is clear that the great majority of Canadian utilities:

- consider some form of failure containment;
- consider broken conductor load conditions, and;
- do not consider dynamic load effects of broken conductors and shield wires on supporting towers.

2.5.2 Hydro One (Formerly Ontario Hydro)

As reported by members of the Technical Committee, Hydro One uses a tower loading which is not common among most utilities. It has historically applied a load to both ends of the same arm for their double circuit towers. The loads are applied in opposite directions such that the load case is referred to as a "double twist" condition.

For the "double twist" condition the conductor is presumed to be in its final load/creep state, under every day conditions (annual mean temperature, light winds).

One practical disadvantage of the "double twist" loading condition is that very few, if any, tower test sites in the world are equipped to test this condition. Longitudinal loads are typically applied in only one direction at tower test sites.

2.6 Failure Containment Provisions of ISO 502.2

The Section 502.2 Rules document in effect at the time of writing specifies failure containment loading which must be considered for bulk transmission lines. One of two approaches must be used:

- Design longitudinal strength into all suspension-type structures, or;
- Construct anti-cascade structures every 10km for 138-144 kV structures, every 5 km for 240kV and above.

Anti-cascade structures must be designed to withstand residual static load due to the breakage of all wires on one side of the structure under final conductor tensions at zero degrees Celsius.

Load parameters used to establish longitudinal capacity for the first option are as summarized in table 3-4 for suspension structures.

Load Type	Condition	Environmental Load
Single Circuit, Torsion	RSL loading from single broken phase or shield wire applied at support.	Bare wire, no wind, final tension, 0^{o} Celsius
Double Circuit, Torsion	RSL loading from two broken phases, or one phase and one shield wire, or two shield wires applied at their respective supports.	Bare wire, no wind, final tension, 0^{o} Celsius
Longitudinal	Unbalanced wet snow loading on one side of the structure, on one or more phases, or shield wires, with bare conductor on adjacent span; all wires intact.	Radial Wet Snow as per AESO Maps, no wind, -20^{o} C,

Table 3-4: Section 502.2 Technical Requirements for Failure Containment Loads

In all cases in table 3-4, the residual and unbalanced load computation is to account for insulator swing and structure deflection.

3 Conclusions and Recommendations

3.1 Conclusions

The current version of AESO 502.2 provides a reasonable balance between international standards, Canadian standards, and common Canadian utility practice. It does not adopt the most severe criteria, nor is it the most permissive; it adopts portions of each.

Adoption of failure containment provisions is prudent in Alberta, where cascading transverse and longitudinal failures have been experienced.

The AESO 502.2 provisions for failure containment are reflective of common utility practice in Canada.

3.2 Technical Committee Recommendations

The general consensus of the Technical Committee was to retain the current 502.2 standard provisions for failure containment with one revision. Clause 10(8)'s exemption of wood poles from anti-cascading provisions (subject to study) should be expanded to include wood, steel, composite, or laminate poles. This accounts for the natural flexibility of this structure style and the ability for pole-type structures to greatly reduce residual static loads through deflecting into the load imbalance without pole failure.

In the opinion of the Technical Committee, this recommendation is consistent with Alberta utility operating experience with 138kV wood pole lines; they have experienced very few, if any, longitudinal cascading failures.