CANA
HIGH VOLTAGE

Alberta Electric System Operator

S1: 240 kV Galloping Cost Impact Study

Final Report

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APEGA Permit Number:		P07302

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2 Executive Summary

With recent 240 kV transmission project expenses, questions have been raised as to the cost efficiency of the RA, RB, RC, and RD series of 240kV latticed steel towers and, in particular, if the galloping requirements of the ISO Rules, Division 502, Section 502.2 Bulk Transmission Technical Requirements (Section 502.2) are contributing substantially to additional costs.

An initial study documented in a draft report submitted to the Section 502.2 committee in April, 2014 reviewed the tower configurations and the design requirements used for their development to assess how much influence the galloping criterion had on their configuration. In addition, historical outage data was reviewed to see if the frequency of galloping or potential galloping occurrences justified its consideration in transmission line design for Alberta.

An analysis of the towers designed for use in AESO Zones A, B, C, and D did not show that the structure cost was likely to be reduced substantially as a direct result of removing the galloping criterion. The majority of tower head dimensions were dictated by insulator swing and other clearances to address hot line maintenance. Removal of the galloping criterion would introduce a need for ice unloading or similar criteria between the middle and upper or lower phases. Consideration of ice unloading conditions may become a governing factor for tower configuration should the galloping criterion be removed, limiting the perceived benefits.

A secondary analysis was undertaken in the initial study to identify problem areas for galloping. After plotting galloping occurrences on a map of Alberta, the region extending east from Calgary was identified as a high frequency area, with possible galloping occurrences extending as far North as Swan Hills.

The findings of this report did not provide economic support for removal of the galloping requirements of Section 502.2.

3 Background

The Alberta Electric System Operator (AESO) requested CANA High Voltage (CHV) to conduct a study looking into the impact of designing for galloping mitigation on the installed 240 kV transmission cost.

The first component of the study involved an analysis of 240 kV tangent tower designs to determine if removal of the Section 502.2 galloping requirements would enable configuration changes resulting in a noticeable reduction to the cost of double circuit 240 kV towers. The RA22A, RB22A, and RC22A 240 kV tower designs were examined, taking all criteria into consideration as specified in the original tower design requirement documents provided by the AESO.

The second part of the study consisted of a review of historical AESO outage data to determine the frequency of outage occurrence by area which may be attributed to galloping. Information involving outage cases concerning potential or confirmed galloping was compiled from the historical outage data, with the locations being plotted on a map of Alberta for frequency analysis.

Following review of the initial draft report for the first two parts, additional components for analysis were requested by the Section 502.2 committee. The committee expressed their interest in the following scenarios:

a) If tower arm offsets are shortened to minimally accommodate Section 502.2 galloping methodology (in the case of the RA22A and RA22B);
b) If tower arms are further shortened to accommodate a phase to phase separation less than the galloping criterion permits; establish this phase-to-phase separation requirement.

The cost saving for each of the first two comparisons was to be evaluated based on the assumption of tower weight saving without re-optimizing the towers.

In addition, the AESO requested addition of the RD22A tower to this study for similar evaluation.

4 Analysis Procedure

4.1 Model for Line Analysis

For the towers being studied, a PLS-CADD model was constructed consisting of 30 spans and having a ruling span of 365 meters. The model incorporated wires specified in Revision 8 of the AESO 240 kV Tower "Backbone" Design Criteria Summary (the design criteria document for the RA, RB, and RC series towers).

- Conductor was a 2 bundle 1240.2 kcmil Type 13 Curlew-TWD ACSR-TW ("Yukon");
- Fibre optic ground wire AFL CC-75/528 48f OPGW;
- Shield wire ½" Grade 220 Steel OHSW.

For the RD tower, the analysis incorporated the wires specified on the Design Requirement Drawings (DRDs) provided by the AESO. These were:

- Conductor was 2 bundle 795 kcmil ACSR ("Drake");
- Fibre optic ground wire was AFL CC-75/528 48f OPGW;
- Shield wire was ½" Grade 220 Steel OHSW.

A creep condition of 4 degrees Celsius with no wind and a load condition of CSA Heavy were implemented in the model construction. The use of CSA Heavy as the load stretch condition rather than the extreme wet snow was due to the improbability that a line in service would have experienced the structural design limit of a 1 in 100 year AESO Wet Snow and Wind. CSA Heavy was considered a more probable load-stretch condition.

Modelled wires were initially sagged using the tension limiting criteria detailed in the design criteria documents for the original tower designs.

4.2 Tower Geometry Investigation

Galloping ellipse parameters were manually calculated using the previously specified conductors and sag-tension criteria. The AFL CC-75/528 48f OPGW was chosen over the ½" Grade 220 Steel OHSW for development of galloping ellipses due to its greater sag when tensioned to the limiting parameters. This deeper sag produced a lower and larger galloping ellipse for comparison to the phase ellipses.

Insulator Swing Clearances

Insulator swing angles and required air gaps specified on the AESO tower DRDs were superimposed onto the PLS-Tower models provided to CHV by the AESO for this analysis in order to discern which elements of tower geometry were being governed by insulator swing requirements.

Insulator Swing and other operational clearances for each structure are shown on Sketches A1, B1, C1, and D1 (Appendix A).

Havard Galloping Ellipses

Galloping ellipse parameters were found using Dr. Havard's modified CIGRE method detailed in Section 502.2 Appendix A. The ellipses were applied on the PLS-Tower model image, with the air gaps between ellipses being measured against the required 60Hz flashover value for both phase to phase and phase to ground cases.

Havard galloping ellipses for each structure are illustrated on Sketches A2, B2, C2, and D2 (Appendix A).

CIGRE and REA Galloping Ellipses

Following the approach previously outlined for checking the tower designs against the Havard galloping ellipses, parameters were calculated for ellipses according to both the CIGRE [1] and the REA[2] methods, as well. The air gaps specified within Section 502.2 for phase-to-phase and phase-to-ground were used. Although these analyses are not required by the AESO technical requirements, they are in common industry use and are included for the sake of relative comparison.

Cigre and REA galloping ellipses for each structure are shown on Sketches A3-D3 and A4-D4 respectively (Appendix A).

4.3 Outage Record Review

Historical AESO outage data collected between 2006 and 2014 was reviewed for events attributed to potential or confirmed galloping. All instances of directly suspected or confirmed galloping were recorded, with approximate locations, on a map of Alberta (Sketch 5, Appendix B) for an area-based frequency analysis.

In addition to cases where galloping was specifically mentioned, the data contained references to outages with either unknown or weather related causes. Those outages attributed to weather (snow, ice, etc.) occurring in the months where galloping was possible, were plotted on a second map of Alberta (Sketch 6, Appendix B) to aid in the area based frequency analysis.

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[1] Cigre Technical Bulletin 322, "State of the Art of Conductor Galloping", Task Force B2.11.06, June, 2007.

[2] U.S. Department of Agriculture Rural Utilities Service Bulletin 1724E-200, "Design Manual for High Voltage Transmission Lines", May 2009 revision

4.4 Ice Unloading Analysis

As directed by the AESO a further study was conducted presuming that, in the absence of galloping clearances, some other horizontal offset would be desired between the phases. It was expected this would be required to prevent line trips resulting from loss of separation following ice unloading of lower phases.

Ice Unloading

The effect of losing one span of ice on the lower phase of a thirty (30) span section of transmission line was evaluated using PLS- SAPS finite-element software. The resulting static configuration of the phases following such an event was evaluated to see if their vertical clearance was sufficiently reduced that some horizontal offset would be required to maintain flashover clearances. This was analyzed for clearance between the lower and middle phases, and the upper phase to the OPGW.

Two ice loading criteria were evaluated as follows:

- Section 502.2 specified vertical load of 40mm radial ice with a density of 350 kg/m^3 and;
- CSA Heavy Loading (ice only).

Minimum 260kV Phase to Phase Air Gap

Members of the Section 502.2 committee acknowledged that an ice unloading event could leave one phase conductor unloaded for an extended period of time before nearby phases or shield wires similarly unload. Accordingly, CHV concluded that air gap clearances for this type of event should accommodate system overvoltages and switching surges.

CHV used a methodology consistent with IEEE 1313.2[3] to establish a 2.65m criterion for 260kV phase to phase clearance under a sustained condition. There are a number of assumptions made in deriving this number and these are summarized in Appendix C.

The largest challenge was the assessment of a switching surge to be used for establishing a reasonable phase to phase overvoltage. Ultimately, the treatment of phase to phase switching surge factors in the EPRI Red Book[4] was used in development of the required air gap.

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[3] IEEE 1313.2 "Guide for the Application of Insulation Coordination", IEEE Power Engineering Society, 1999.

[4] "Transmission Line Reference Book, 345kV and Above", Second Edition, Electric Power Research Institute

5 Summary of Findings

5.1 Electrical Clearance and Operational Impact on Tower Head

Insulator Swing and Maintenance Air Gaps

Insulator swing conditions and the specified air gaps for each were taken from the original design requirement drawings for each of the RA, RB, RC and RD tower series. For all four towers, the length of the top and bottom arms is governed by the requirement for a minimum specified air gap of 2.3m with an additional 1.0m climbing clearance against the tower body under weather conditions possible during such operations.

Insulator Swing and other operational clearances for each structure are shown on Sketches A1, B1, C1 and D1 (Appendix A) to assist in the visualization of their impact on tower head design.

The RD22A tower was designed for phase to ground air gaps of 2.3m, as with the other towers, but did not provide the extra 100mm allowance for member thickness, protruding flanges, and step bolts noted on the design requirements for the RA, B, and C series tangents.

Operational Requirements Governing Tower Head

For all four towers, the height between the upper conductor arm and the middle arm was governed by operational requirements. The minimum air gap between a maintenance “buggy” positioned on the top phase and the middle arm dictated the vertical separation between the top arm and the middle arm. For the RD22A conductor buggy clearance between the upper phase and the middle arm appears marginally deficient, particularly in the absence of an allowance for protruding members.

A combination of operational “hand clearance” beneath the arms and insulator swing under moderate wind dictate the use of hangers under the arms of the RA series tangent tower. This adds to overall tower height.

5.2 Tower Head Configuration for Galloping

On both RA22A and RB22A towers it was found that the Havard galloping ellipses (Sketches A2 and B2, Appendix A), were easily accommodated. Spacing on these towers exceeded the specified minimums by more than 1m in all cases. The Havard galloping analysis did not govern the offset distance of the middle arm for these towers.

The RC22A and RD22A tower middle arm offsets were governed by the Havard galloping criterion. The RD tangent used a 1m larger vertical spacing between the mid and bottom arm, but was otherwise similar to the RC22A tower in overall configuration.

5.3 Ice Unloading

Analysis of a theoretical, thirty span transmission line was conducted to determine phase separation after ice unloads from the lower phase of a single span in the middle. Two cases were examined:

- CSA Heavy Loading
- AESO Vertical Loading Case (40mm Wet Snow)

For the RA22A and B towers under CSA Heavy Loading, the lower phase stabilized at a vertical separation of 1.4m below the middle phase. For the AESO vertical case, the lower phase stabilized 2.1m above the middle phase. Similar spacing issues were observed between the middle to upper phase although, due to increased vertical spacing between these tower arms, the problem was not as severe. Clearances on the RC and RD towers were worse.

		Residual Vertical Spacing	
Tower	**Horizontal Arm Offset**	**Section 502.2 Heavy Vertical**	**CSA Heavy (Ice Only)**
RA22A	5.0	-2.1	1.4
RB22A	5.0	-2.1	1.4
RC22A	4.0	-2.4	1.0
RD22A	3.65	-2.5	1.5

Table 5.1: Vertical Separation (m) after Ice Unloading (Lower to Middle Phase)

		Residual Vertical Spacing	
Tower	**Horizontal Arm Offset**	**Section 502.2 Heavy Vertical**	**CSA Heavy (Ice Only)**
RA22A	1.40	2.2	7.3
RB22A	1.40	2.1	7.3
RC22A	1.40	2.0	7.1
RD22A	0.35	-0.6	5.1

Table 5.2: Vertical Separation (m) after Ice Unloading (Top Phase to OHSW)

It is clear from the values in table 5.1 that vertical spacing between the phases will not be sufficient to prevent phase-to-phase flashover. Some of the existing horizontal offset must be retained to maintain reliability.

For the RA, B, and C series towers, clearance from the OPGW shield wire to the upper phase has sufficient vertical separation under either of the ice unloading conditions to maintain phase to ground flashover clearance under similar switching surge conditions applied for the phase to phase. The RD series tower does not have sufficient vertical phase to ground clearance in the event of an AESO-Heavy ice unloading event. Clearances are summarized in table 5.2.

5.4 Arm Length Reduction

It was presumed that arm lengths could be shortened if the Section 502.2 galloping criterion was removed. However, this is with the provision that horizontal spacing is provided to maintain adequate air gaps in the event of ice unloading. Since phase conductors were actually crossing side-by-side, the minimum permissible horizontal separation was computed as:

2650mm flashover + 500mm bundle spacing + 50mm conductor/spacer radius = 3200mm

			Possible Arm Length Reduction	
Tower	**Horizontal Arm Offset**	**Minimum for Flashover (m)**	**For Galloping Limit (m)**	**For Ice Unloading Limit (m)**
RA22A	5.0	3.20	1.0	1.80
RB22A	5.0	3.20	1.0	1.80
RC22A	4.0	3.20	0.1	0.80
RD22A	3.65	3.20	0	0.45

Table 5.3: Potential For Reduction in Arm Length Offset

PLS-Tower models of each of the towers were modified to shorten the middle arms by the amounts shown in table 5.3 and the tower was re-analyzed with the shorter arms. Reduction in tower weight was recorded from the analysis output.

5.5 Outage Record Review

Data provided by the AESO for the period from 2006 to 2014 was examined for instances of conductor galloping. Ten events of suspected or confirmed galloping were reported, with the approximate locations being plotted on a map of Alberta (Sketch 5, Appendix B) to determine if there was a predominant area. Examination of the plotted points shows a prevalence of galloping in the south-eastern portion of Alberta, with the area just east of Calgary showing the most occurrences in the 8 years of collected data.

The provided data also reported a number of outages that occurred under circumstances where galloping could have occurred without being reported. The approximate locations of these outages were plotted on a map of Alberta (Sketch 6, Appendix B) for an area based frequency analysis. Examination of the plotted points reinforced the initial indications and showed a large number of potential galloping cases occurring in the region extending east out of Calgary. In all, the review noted 87 separate instances, some affecting multiple lines, over the 8 year span.

6 Conclusions and Recommendations

6.1 Conclusions

Tower Geometry Analysis

Conclusions are as follows:

1. Havard galloping ellipses (requirement of Section 502.2) do not govern any component of the RA22A and RB22A tower designs. Based upon comments provided by AltaLink, it is understood that the RA and RB series towers were originally designed for galloping using the more stringent CIGRE method, which remains a common industry standard. Accordingly, their arm spacing was greater than that provided for the RC and RD series structures developed after adoption of the Havard method.

2. Most tower head configuration dimensions are being driven by insulator swing or other operational clearance requirements. However, the galloping criterion does appear to govern the middle arm offset for the RC22A and RD22A towers.

3. There is nothing in the Section 502.2 rules document which would require the extended middle arm length used for the RA22A and RB22A designs; the middle arms could be shortened by about 1m while meeting the present Section 502.2 galloping criteria. This would permit minor shortening of the OHSW arms, as well, due to shielding reduction.

4. Vertical phase spacing of the RA, RB, RC, and RD towers is not sufficient to provide phase to phase flashover clearances in the event of ice loading for the criteria checked in this report. Some horizontal separation would be required to maintain necessary air gaps.

Outage Record Review

1. Lines in the area extending east of Calgary to the Saskatchewan boundary show multiple occurrences of reported and suspected galloping. The city of Calgary showed the highest frequency of reported galloping.

2. Areas outside the major centers did not report galloping as frequently. Cause of events was often not reported or simply attributed to “weather” or “snow”. This was particularly true in the more remote service areas of Northern Alberta. The lack of reporting was partially attributed to the fact that, under weather conditions conducive to galloping, access to remote areas for observation and confirmation of galloping would be very difficult.

3. Although much less frequent, there were cases of suspected galloping or ice-related outages extending as far North as Ft. McMurray.

Cost Saving for Removal of Galloping

1. A suitable air gap for phase to phase separation incorporating switching surge overvoltage was found to be 2.65m. Allowing for bundle spacing and spacer hardware, a minimum middle arm offset was found to be 3.20m. If the Section 502.2 galloping requirement was replaced with ice shedding requirements, the middle arms of the towers could be reduced by:
   - RA22A tower 1.80m;
   - RB22A tower 1.80m;
   - RC22A tower 0.80m;
   - RD22A tower 0.45m.

2. Analysis of tower weight reduction assuming shortened middle arms without further optimization of the towers indicated weight savings in the order of those illustrated in table 6.1. Note that this table does not report true tower weights, but the percentage reduction should be representative.

Tower	Arm Length Reduction (m)	Theoretical Tower Wt.* (kg)	Weight* Reduction (kg)	% Reduction for Theoretical* Tower
RA22A	1.80	18,075	251	1.4
RB22A	1.80	15,450	212	1.4
RC22A	0.80	13,660	87	0.5
RD22A	0.45	8,290	22	0.2
**Note: Theoretical weight is not true weight of tower and arms; it is structural model only and does not include gussets, some redundants, bolts, and galvanizing.*				

Table 6.1: Potential For Reduction in Arm Length Offset

3. In most cases OHSW arm length reductions would place the shield wires directly above the upper phase of the transmission lines. While this could be accommodated if only static ice unloading is considered, there are other considerations which may prevent such a modification to the towers. Consequently, OHSW arms were not shortened for this analysis. Vertical or near-vertical alignment of tower arms for Canadian utilities in areas subject to ice loading would be a very uncommon present-day practice.

4. Additional savings may be available through reduction of right-of-way width due to a reduced tower width. While individual TFO practices vary, there is potential for land cost reductions where right of way width is determined by conductor swing criteria.

6.2 Recommendations

The following recommendations are made for the consideration of the AESO and the Transmission Rules/Towers Committee:

1. An approximate review of the effect of shortening the middle arms of the RA and RB towers showed that only minimal cost saving could be achieved by revising their design. We recommend against this approach on the basis of galloping alone, as we believe the savings are unlikely to justify the cost of a tower series re-design.

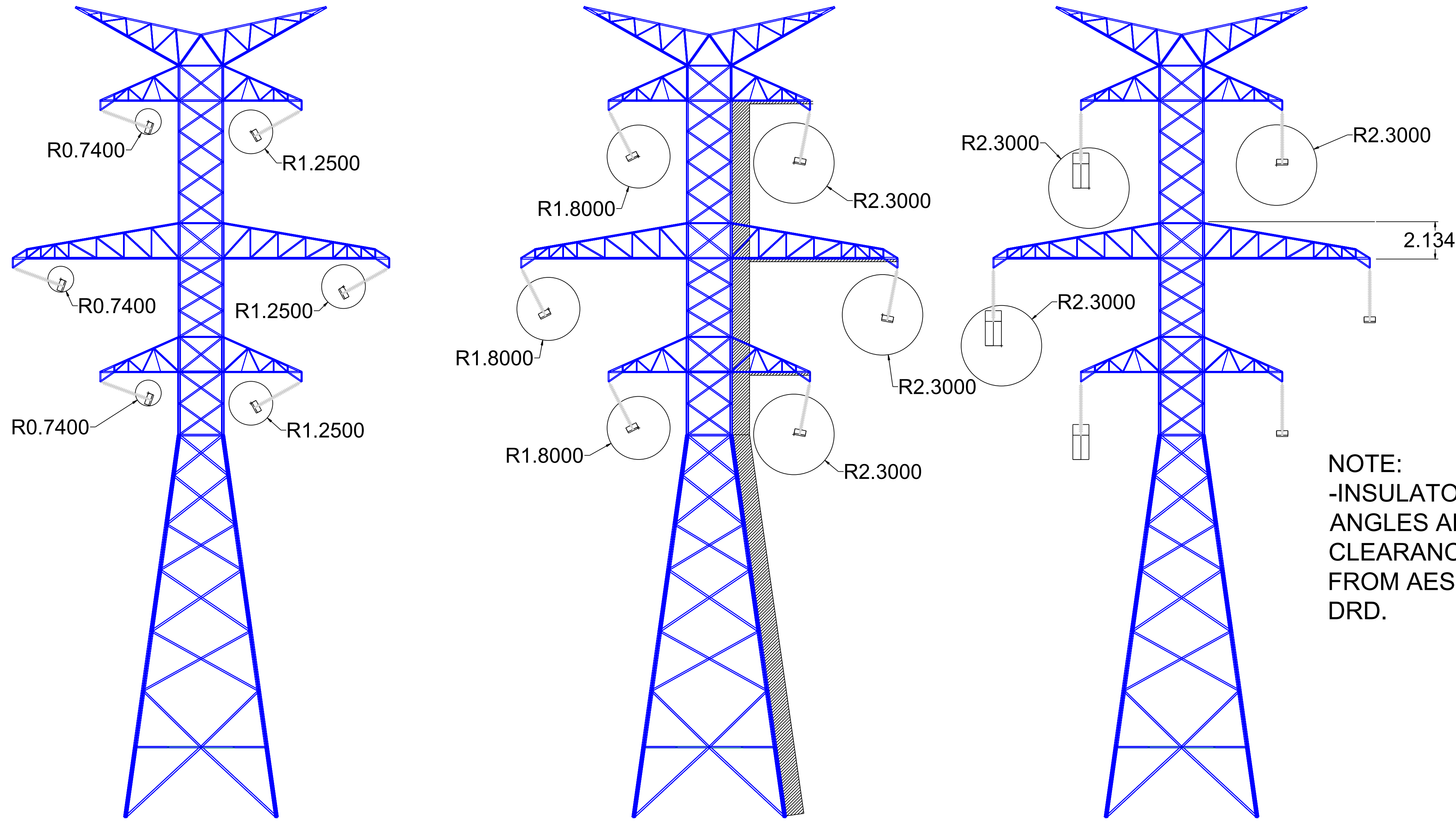
2. If the galloping requirement is removed, another standardized criterion to account for ice unloading is strongly advised. Outages attributed to frost, ice, and snow have been widely experienced in the province on transmission facilities constructed prior to the current Section 502.2 galloping criterion. Even if galloping is controlled by other means, and the galloping clearance criterion removed from Section 502.2, some provision should be made for phase separation in the event of ice unloading.

Appendix A

Governing Criteria; Tower Head Configuration

The following appendix contains three series of drawings illustrating clearance criteria which govern the tower head design for the R-series towers:

- Sketches A1, B1, C1, and D1 illustrate tower clearance for required air gaps under insulator swing conditions. Sketches show scaled representations of tower configurations and circular clearance envelopes which must be maintained to prevent flashover. Shaded areas represent clearances for climbing and other operations.
- Sketches A2, B2, C2, and D2 are scaled drawings showing conductor motion envelopes for galloping using the Havard modified CIGRE method (Havard method) specified in SECTION 502.2. Minimum achieved clearances are shown for comparison against requirements assuming maximum design span length.
- Sketches A3, B3, C3, and D3 also show galloping clearances, similar to the previously noted sketches, but with CIGRE method used to determine conductor motion envelopes. This method is not a requirement of SECTION 502.2 but is a common industry standard. Again, maximum design span was used to determine sag characteristics for this illustration.
- Sketches A4, B4, C4, and D4 show galloping clearances using the REA method which is commonly used for distribution circuits and lower voltage transmission lines. It would not typically be used for the long spans typical of 240kV construction in Alberta and, as is evident from the sketches, REA-style clearances cannot be maintained with current tower configurations.



NOTE:
-INSULATOR SWING ANGLES AND CLEARANCES TAKEN FROM AESO TOWER DRD.

70°
5 YEAR GUST REQUIRED AIR GAP: 0.74 M

61°
COLD TEMPERATURE REQUIRED AIR GAP: 1.25 M

27°
CSA STEADY STATE REQUIRED AIR GAP: 1.8 M

11°
MAINTENANCE REQUIRED AIR GAP: 2.3 M + 0.15 M (X-ARM) 1.00 M (BODY)

WITH CONDUCTOR BUGGY

ARM MAINTENANCE REQUIRED AIR GAP: 2.3 M + WALKOUT

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-04-16	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:
RA22A INSULATOR SWING

CLIENT:
TDC TRANSMISSION DESIGN CONSULTANTS

DRAWING NUMBER
SKETCH A1 | A

Drawing: SKETCH A1
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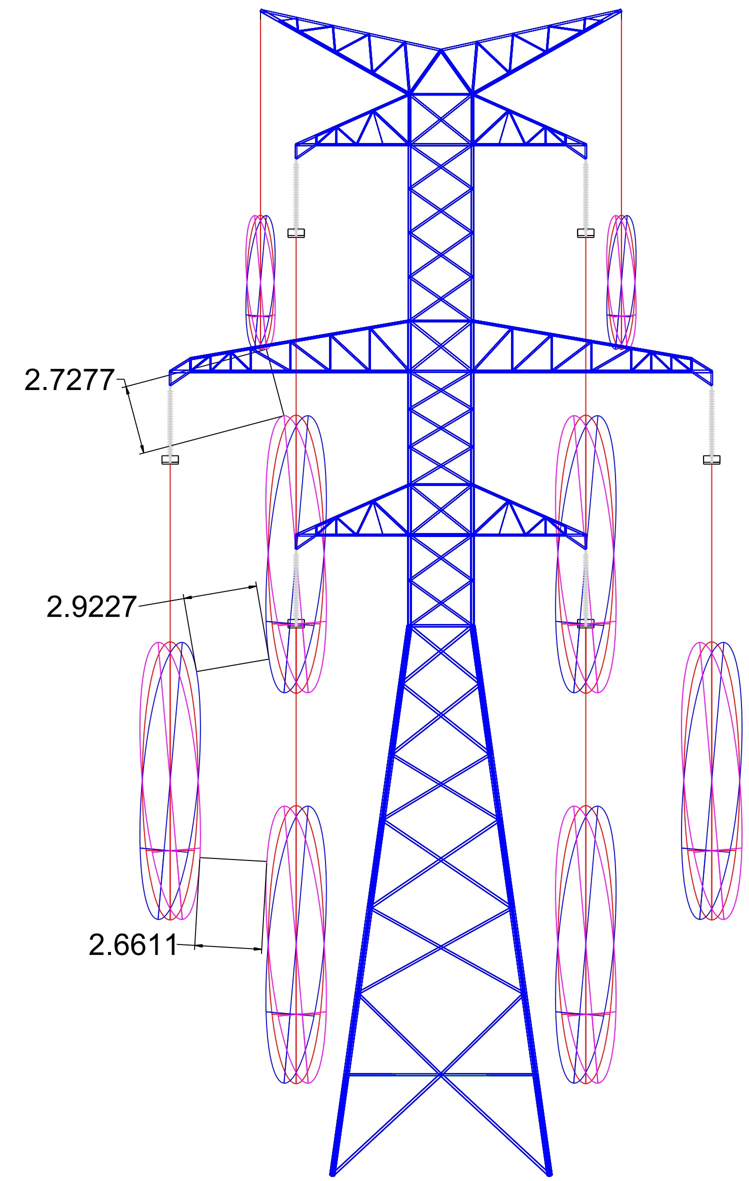
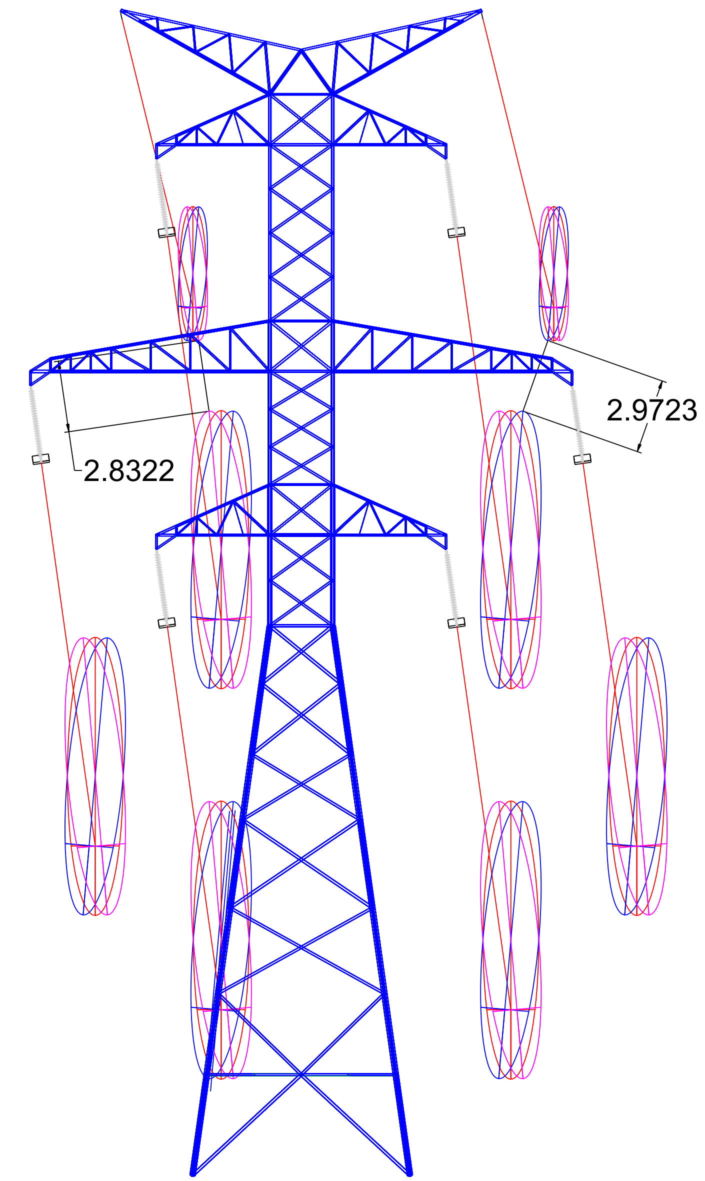
Date Plotted: 4/17/2014 Plotted By: smith.zheng



0° SWING

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
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SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:
RA22A - HAVARD

CLIENT:
CANA HIGH VOLTAGE

DRAWING NUMBER
SKETCH A2 | A

Drawing: SKETCH A2 - ra22a galloping HAVARD
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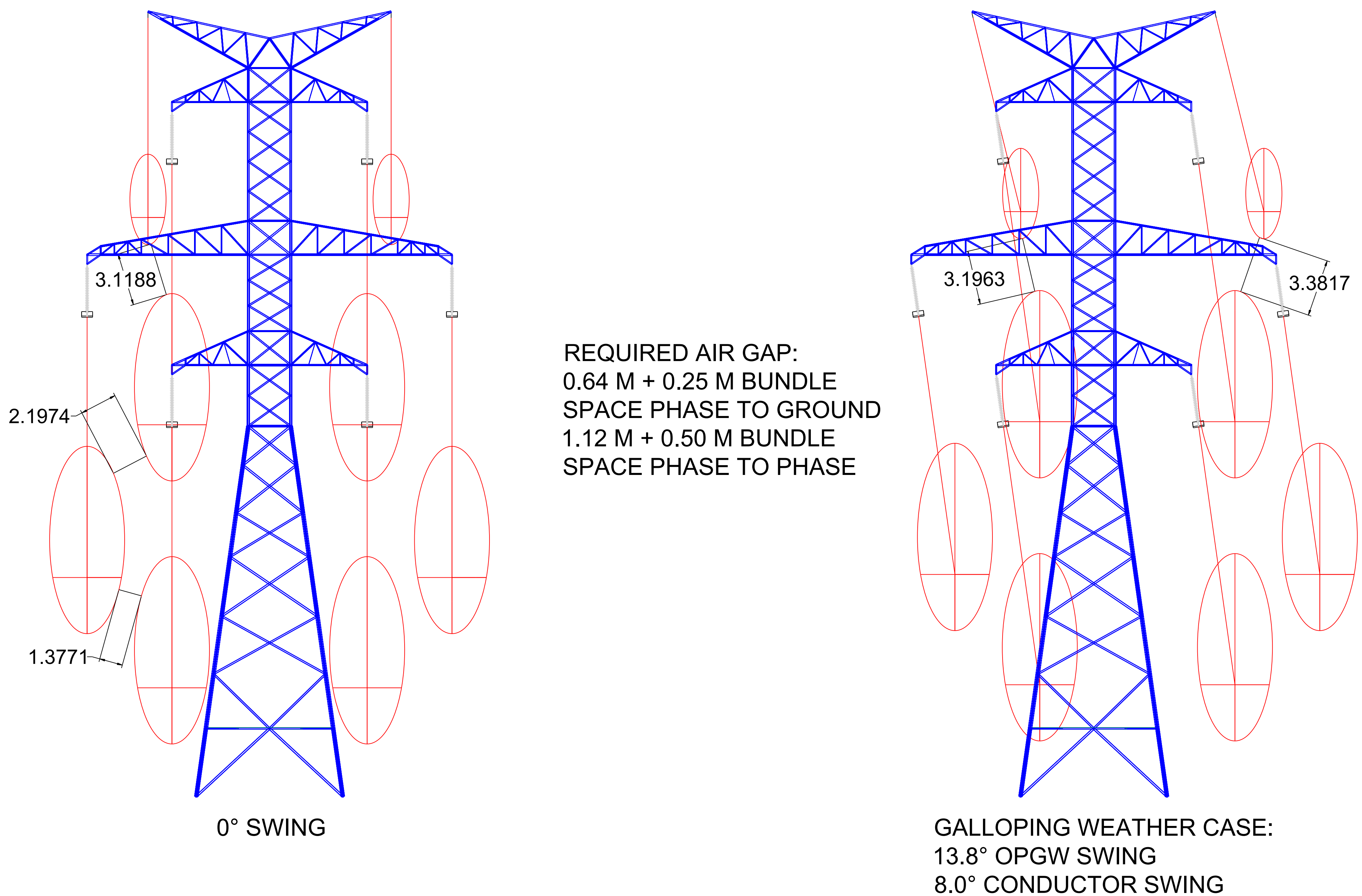
Date Plotted: 8/28/2014 Plotted By: zhengs



NO.	DATE	REVISION	DWN	DES	CHK	APPD
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SCALE: 1:300

DRAWN: X. ZHENG

DESIGNED: B. MURPHY

CHECKED: O. PERRY

APPROVED: O. PERRY

TITLE:

RA22A - CIGRE

CLIENT:

CANA HIGH VOLTAGE

DRAWING NUMBER

SKETCH A3 A

Drawing: SKETCH A3 - ra22a galloping CIGRE
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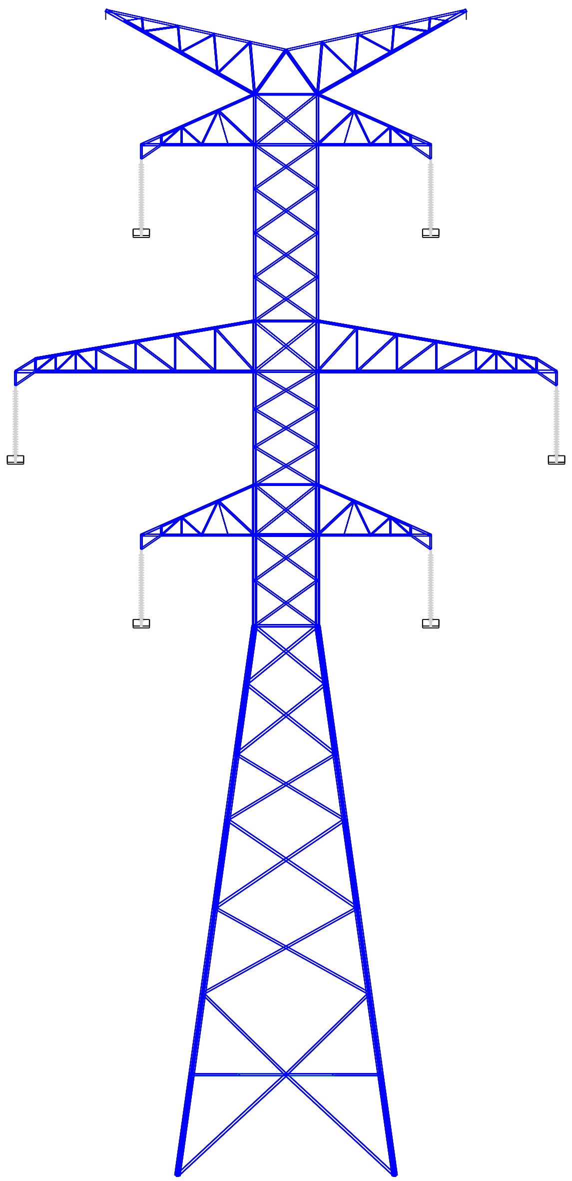
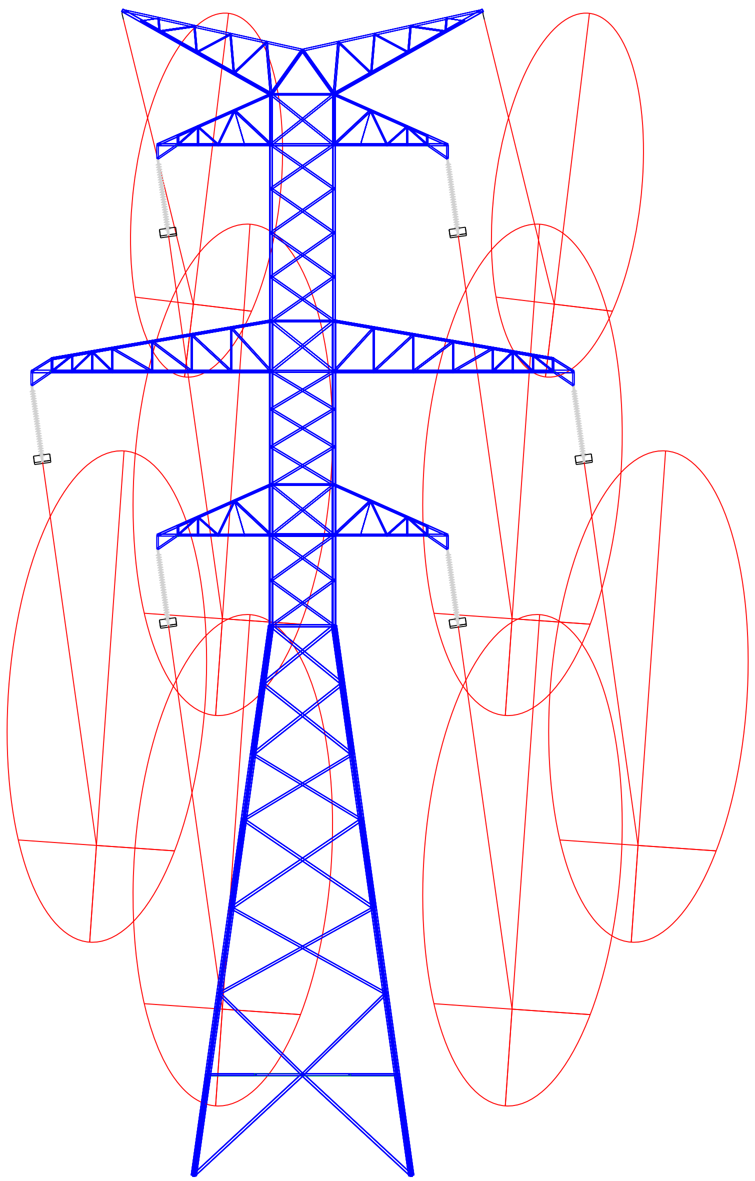


0° SWING
(NOT APPLICABLE)

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:
RA22A - REA

CLIENT:
CANA HIGH VOLTAGE

DRAWING NUMBER
SKETCH A4 | A

Drawing: SKETCH A4 - ra22a galloping REA
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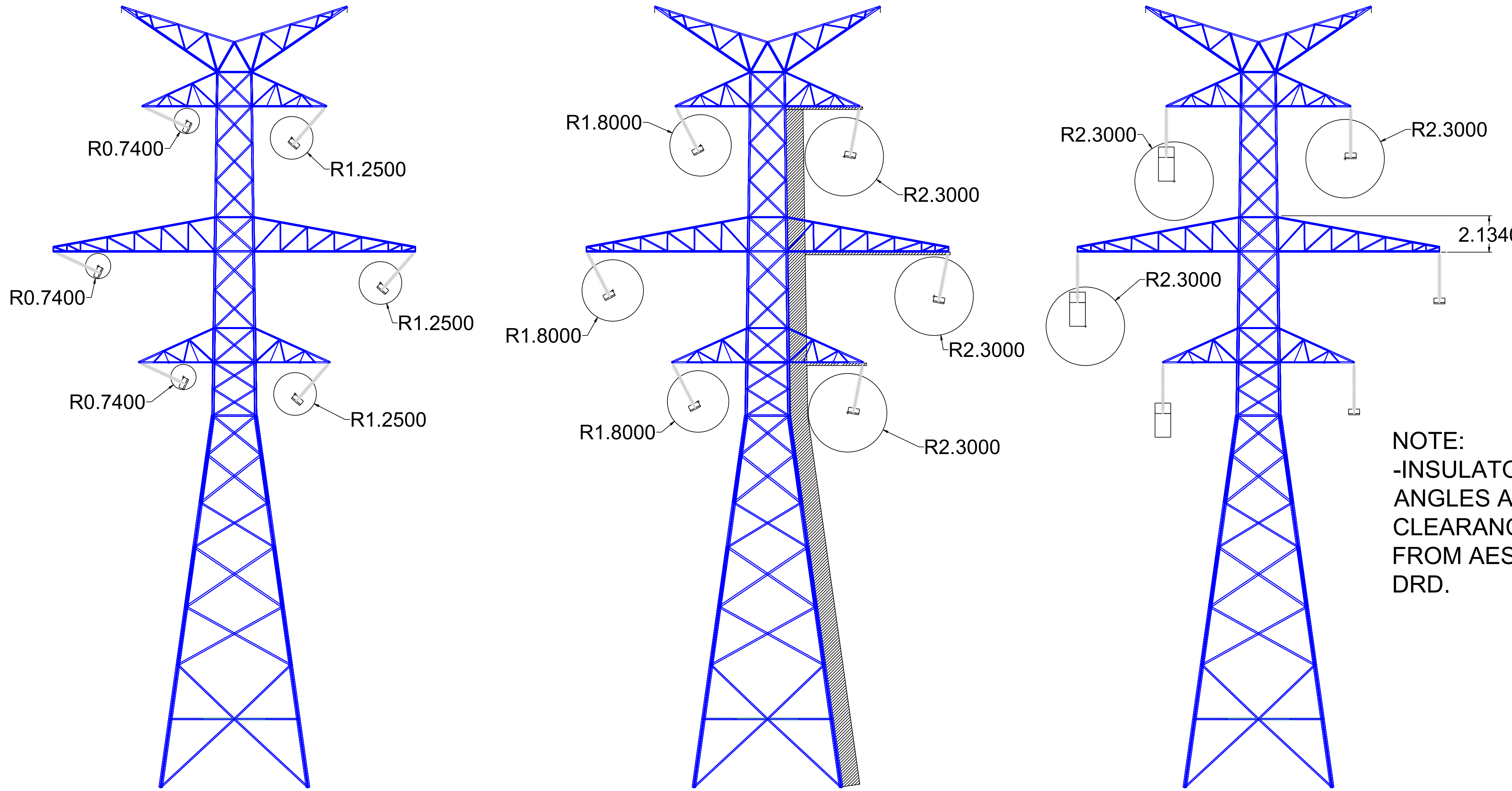
Date Plotted: 8/28/2014 Plotted By: zhengs



NOTE:
-INSULATOR SWING ANGLES AND CLEARANCES TAKEN FROM AESO TOWER DRD.

65°	41°	27°	11°		
5 YEAR GUST REQUIRED AIR GAP: 0.74 M	COLD TEMPERATURE REQUIRED AIR GAP: 1.25 M	CSA STEADY STATE REQUIRED AIR GAP: 1.8 M	MAINTENANCE REQUIRED AIR GAP: 2.30 M + 0.15 M (X-ARM) 1.00 M (BODY)	WITH CONDUCTOR BUGGY	ARM MAINTENANCE REQUIRED AIR GAP: 2.3 M + WALKOUT

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-04-16	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:

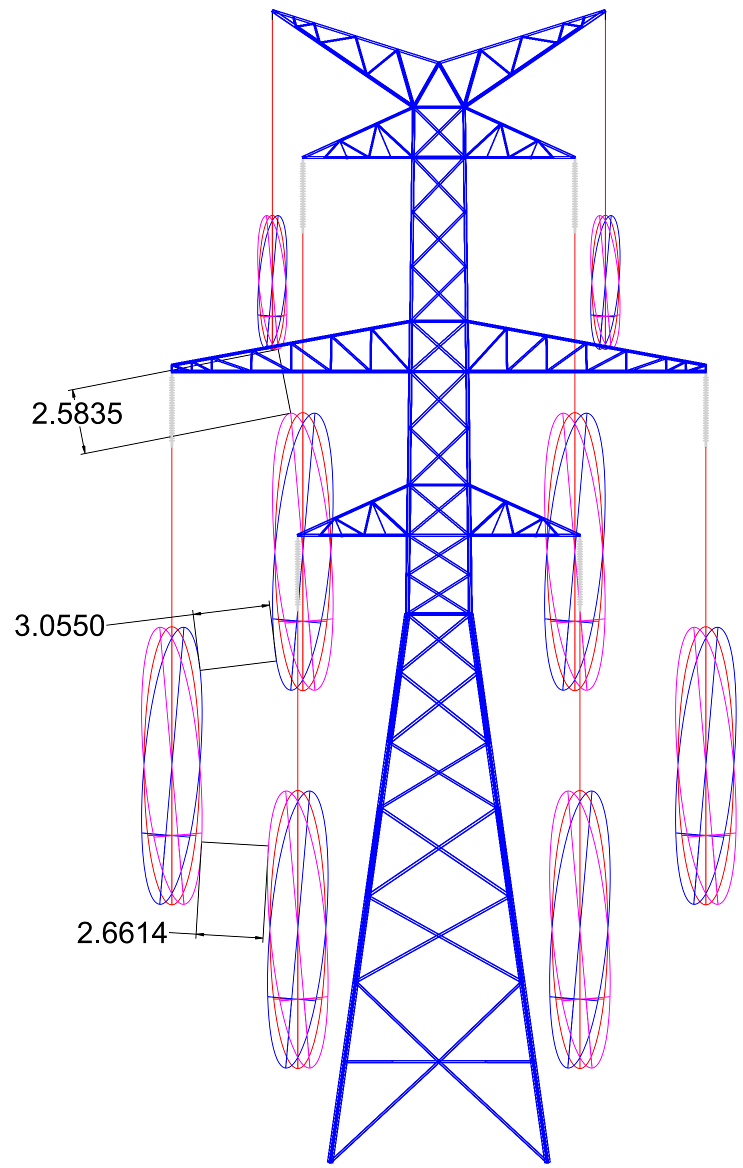
RB22A INSULATOR SWING

CLIENT:

TDC TRANSMISSION DESIGN CONSULTANTS

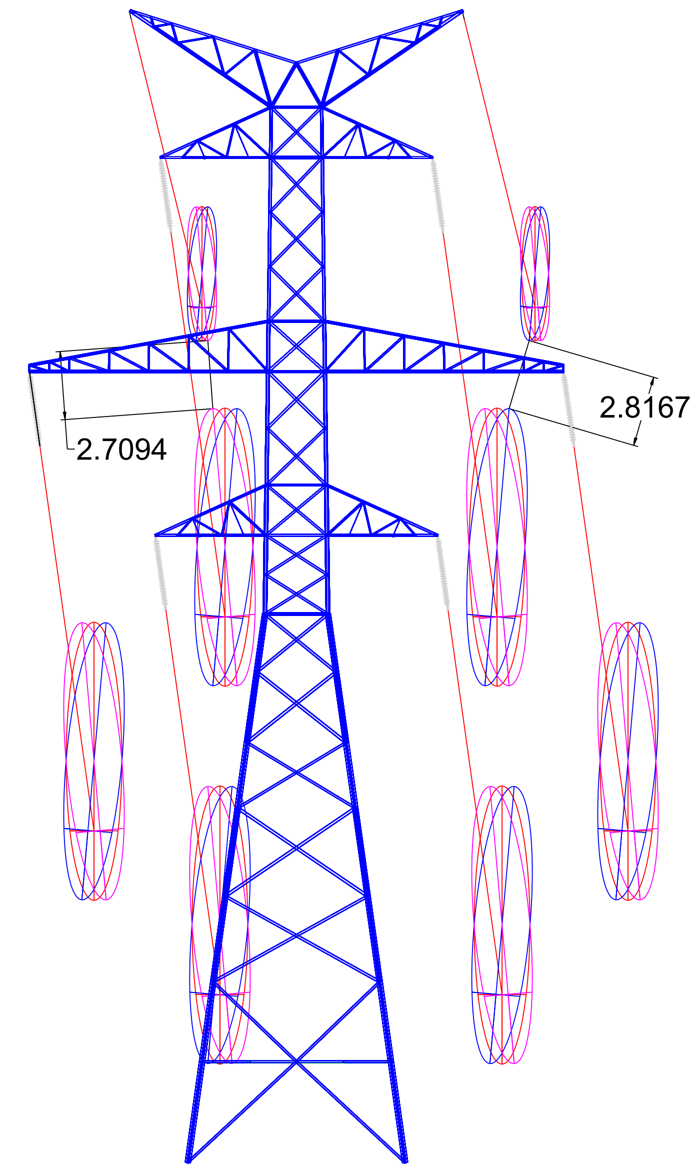
DRAWING NUMBER

SKETCH B1 | A



0° SWING

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

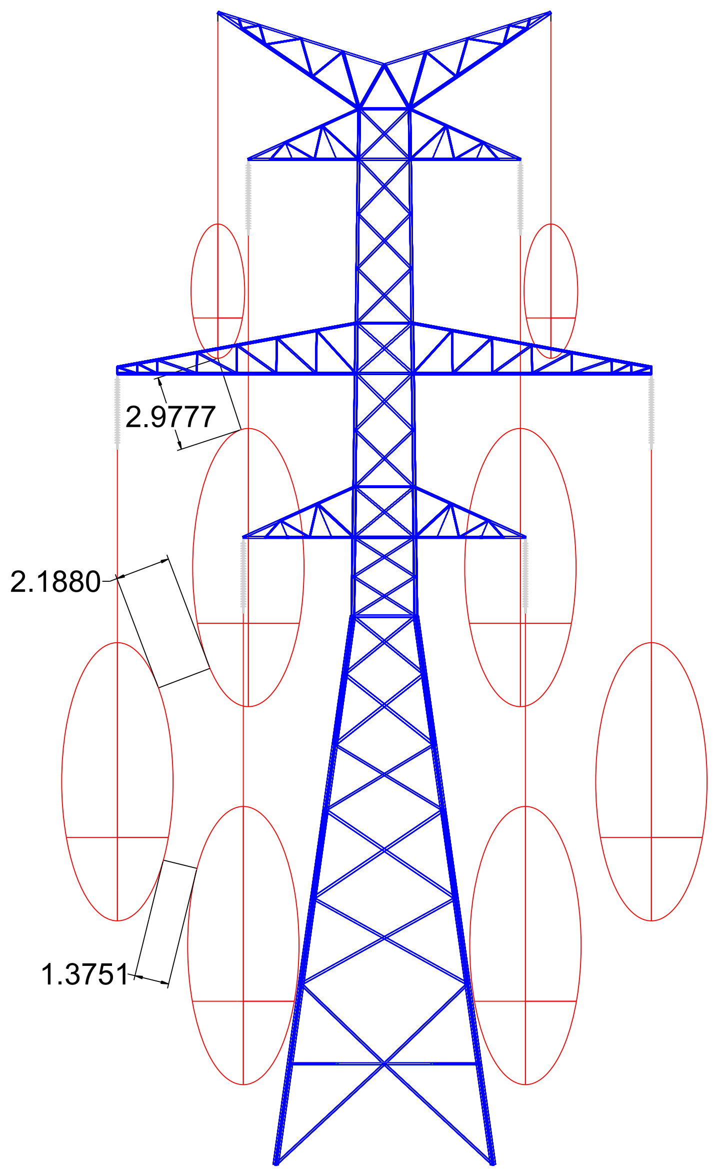
SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:
RB22A - HAVARD

CLIENT:
CANA HIGH VOLTAGE

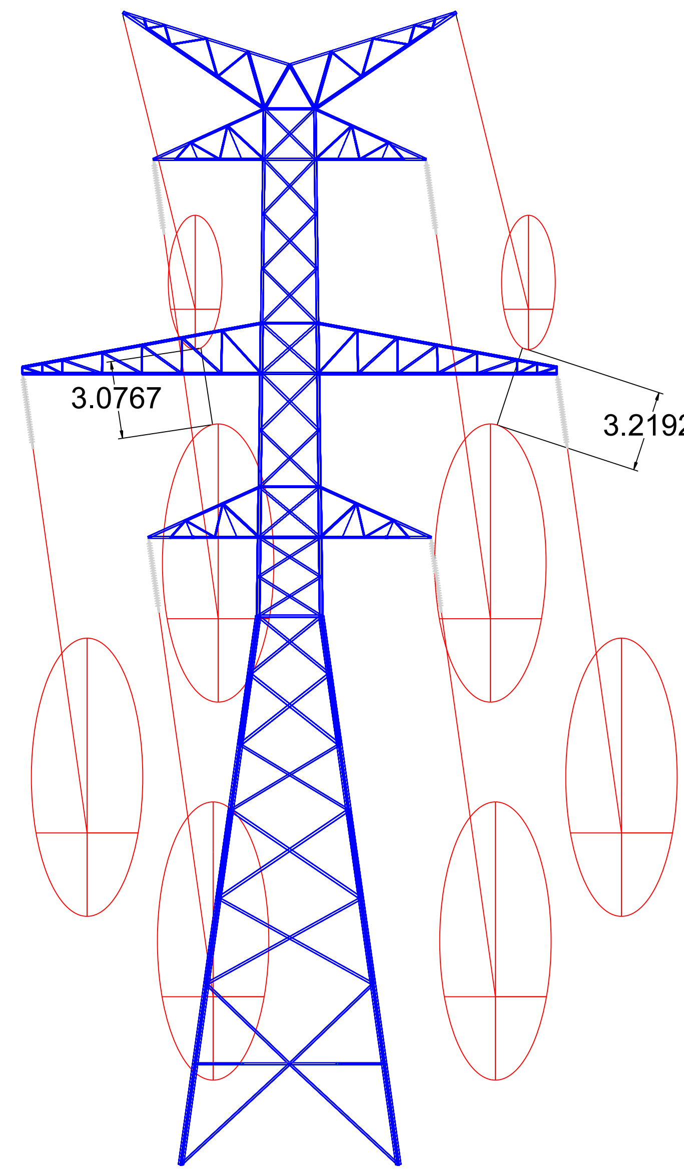
DRAWING NUMBER
SKETCH B2 A

Drawing: SKETCH B2 - rb22a galloping HAVARD
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH B2 - rb22a galloping HAVARD.dgn
Date Plotted: 8/28/2014 Plotted By: zhengs



0° SWING

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

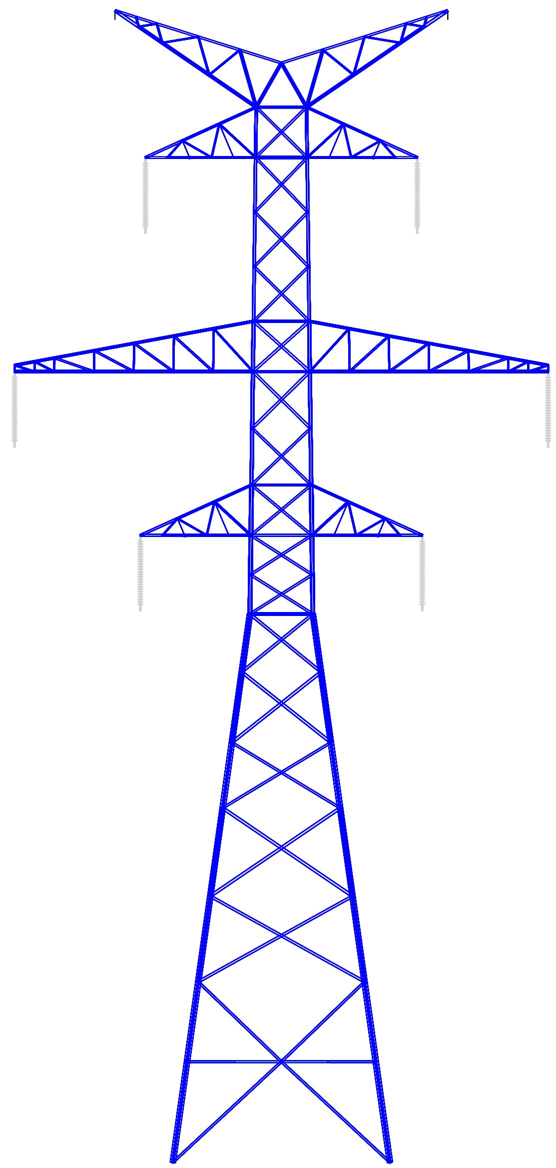
SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:
RB22A - CIGRE

CLIENT:
CANA HIGH VOLTAGE

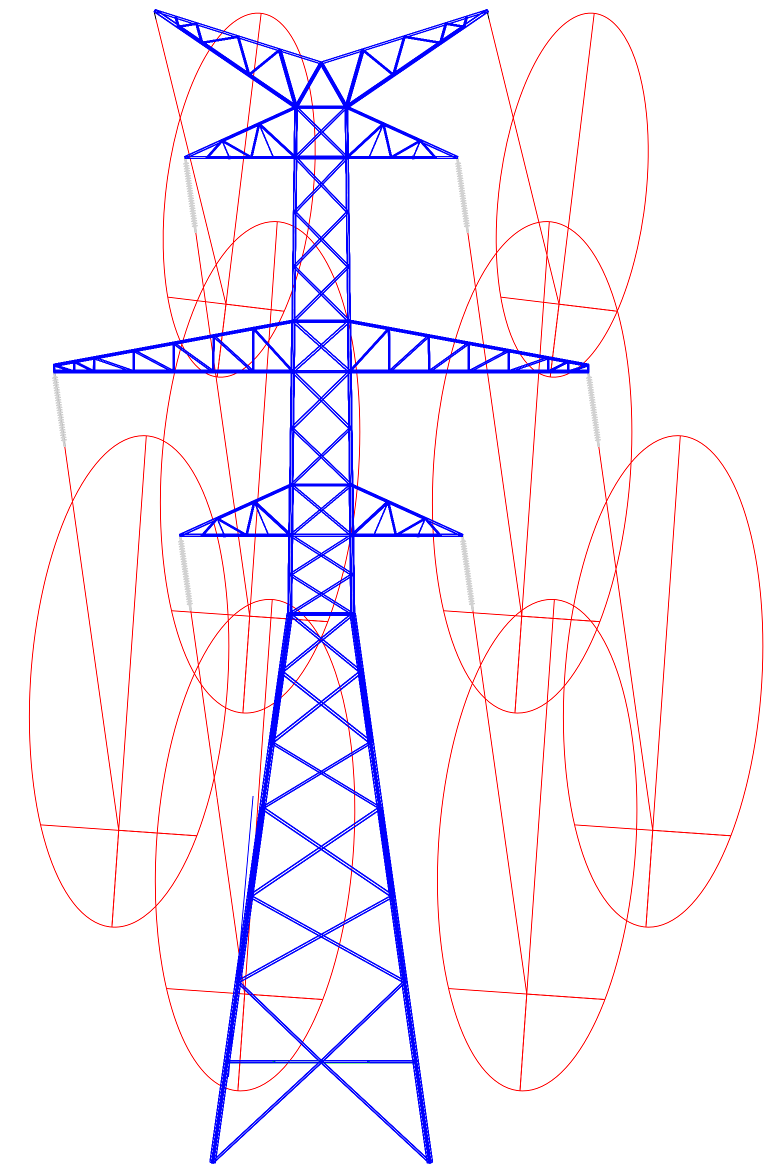
DRAWING NUMBER
SKETCH B3 A

Drawing: SKETCH B3 - rb22a galloping CIGRE
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH B3 - rb22a galloping CIGRE.dgn
Date Plotted: 8/28/2014 Plotted By: zhengs



0° SWING
(NOT APPLICABLE)

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300

DRAWN: X. ZHENG

DESIGNED: B. MURPHY

CHECKED: O. PERRY

APPROVED: O. PERRY

TITLE: RB22A - REA

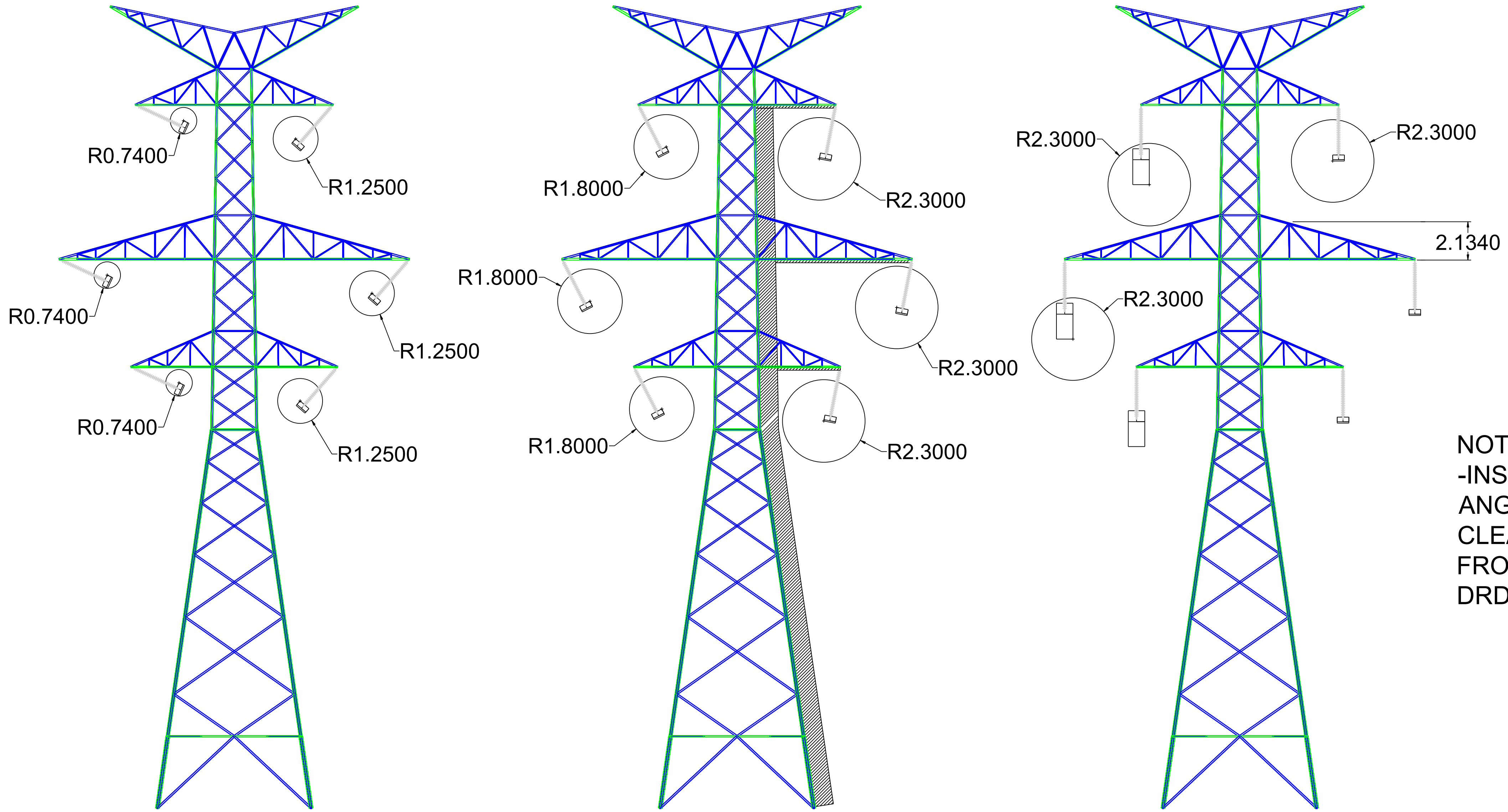
CLIENT:

CANA HIGH VOLTAGE

DRAWING NUMBER

SKETCH B4 A

Drawing: SKETCH B4 - rb22a galloping REA
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH B4 - rb22a galloping REA.dgn
Date Plotted: 8/28/2014 Plotted By: zhengs



65°	41°	27°	11°		
5 YEAR GUST REQUIRED AIR GAP: 0.74 M	COLD TEMPERATURE REQUIRED AIR GAP: 1.25 M	CSA STEADY STATE REQUIRED AIR GAP: 1.8 M	MAINTENANCE REQUIRED AIR GAP: 2.30 M + 0.15 M (X-ARM) 1.00 M (BODY)	WITH CONDUCTOR BUGGY	ARM MAINTENANCE REQUIRED AIR GAP: 2.3 M + WALKOUT

NOTE:
-INSULATOR SWING ANGLES AND CLEARANCES TAKEN FROM AESO TOWER DRD.

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-04-16	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

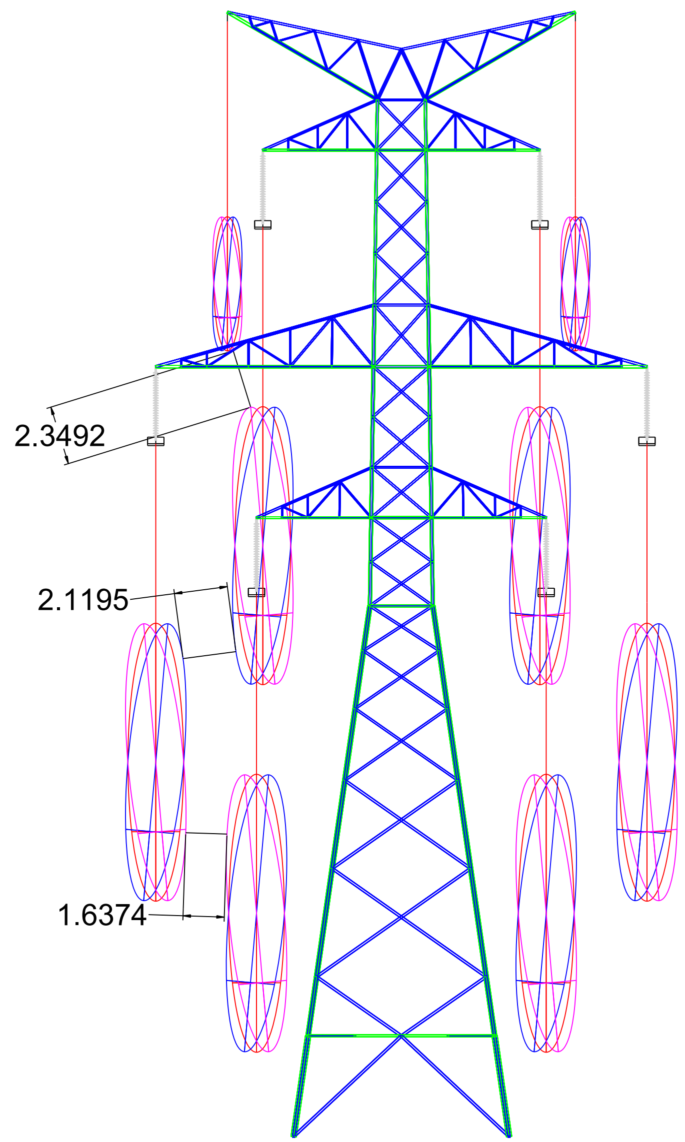
TITLE:
RC22A INSULATOR SWING

CLIENT:

TDC TRANSMISSION DESIGN CONSULTANTS

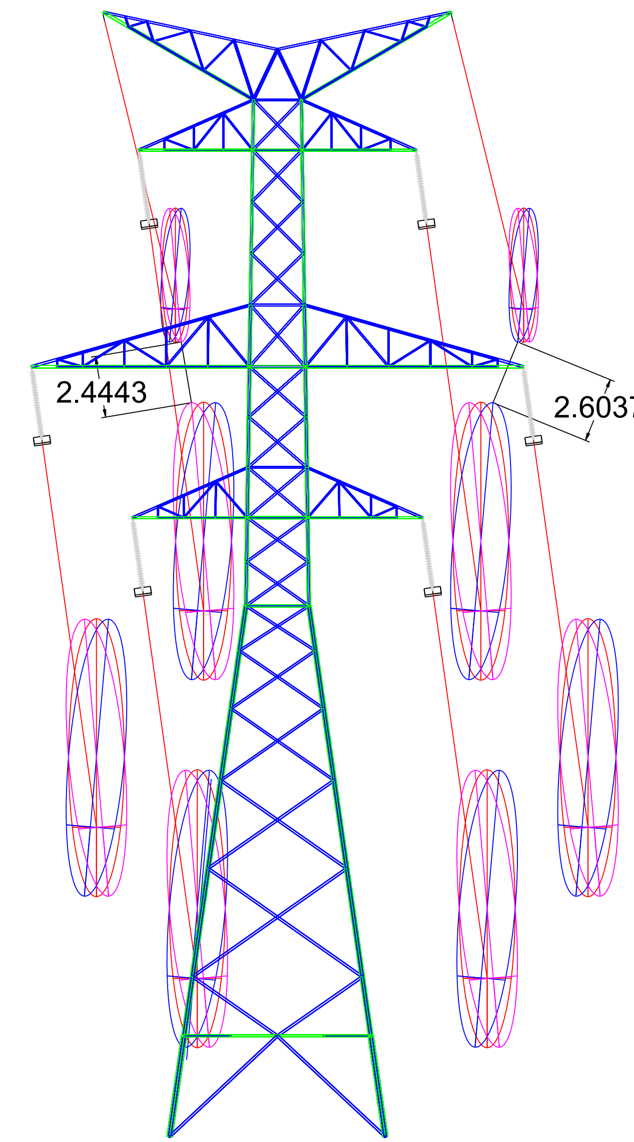
DRAWING NUMBER
SKETCH C1 A

Drawing: SKETCH C1
CADD Filename: X:\Project Drawings\TDC-1401-025-AESO\1-Client\12-rc22a insulator swings.dgn
Date Plotted: 4/17/2014 Plotted By: smith.zheng



0° SWING

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

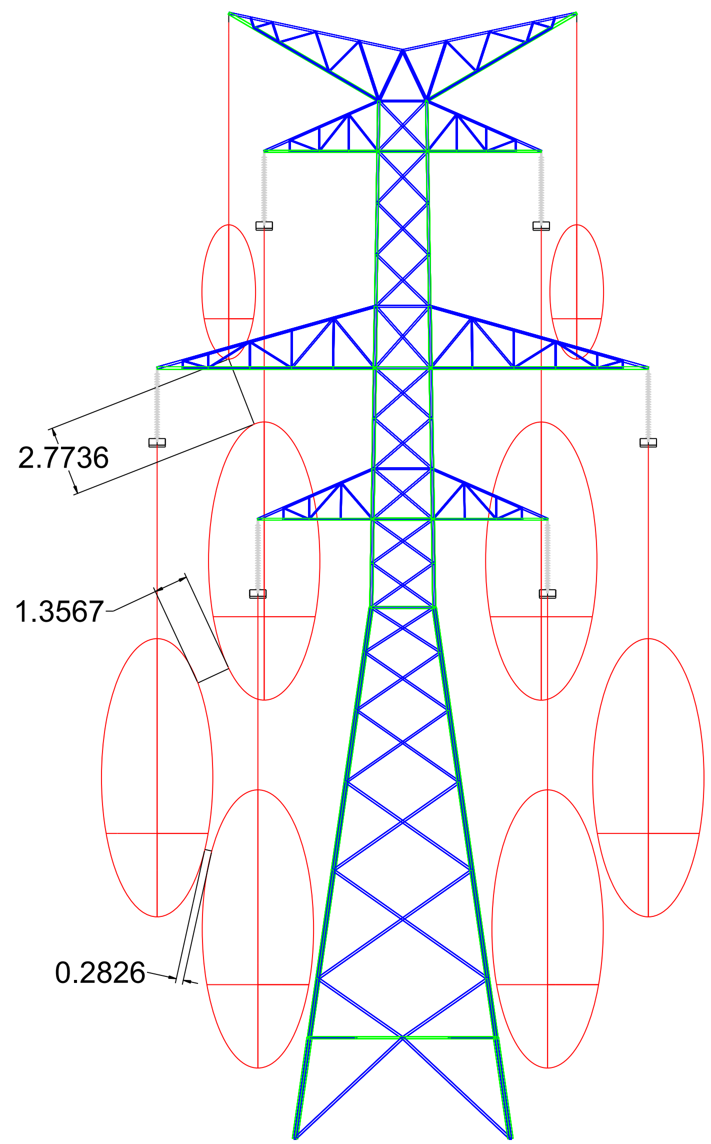
SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:
RC22A - HAVARD

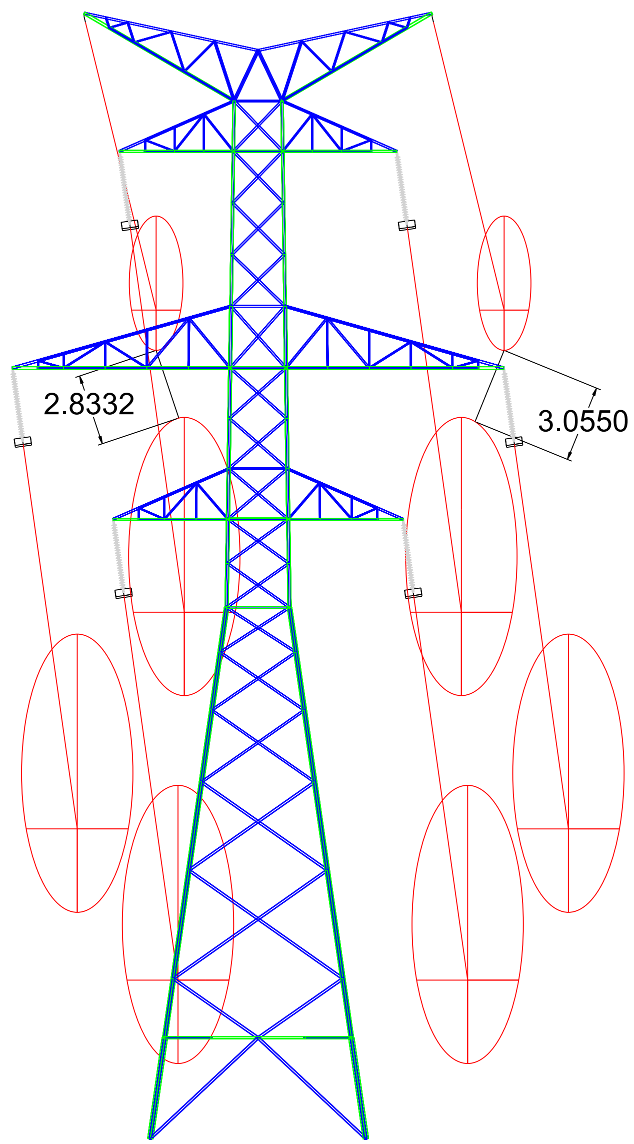
CLIENT:
CANA HIGH VOLTAGE

DRAWING NUMBER
SKETCH C2 A

Drawing: SKETCH C2 - rc22a galloping HAVARD
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH C2 - rc22a galloping HAVARD.dgn
Date Plotted: 8/28/2014 Plotted By: zhengs



0° SWING



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:

RC22A - CIGRE

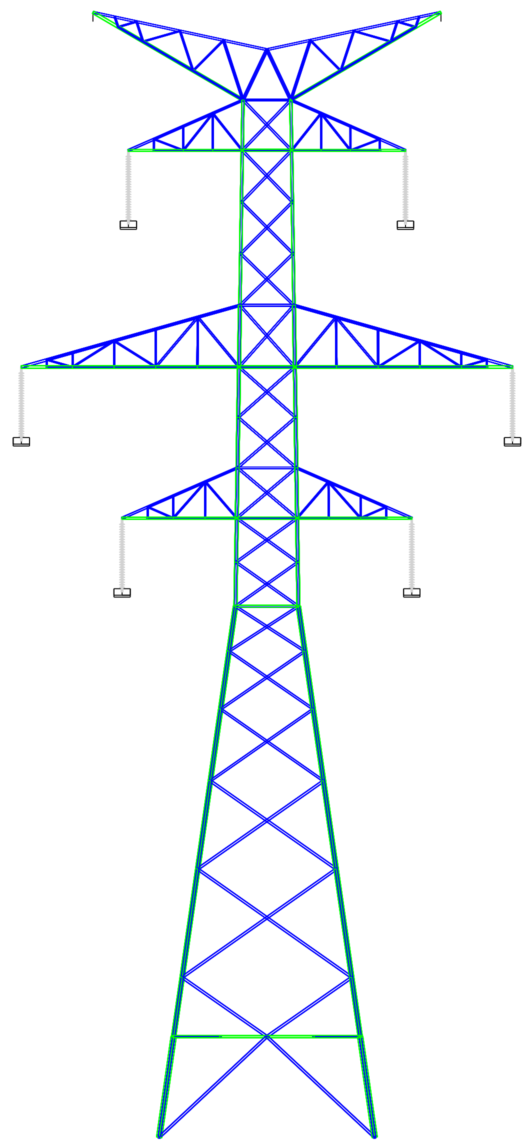
CLIENT:

CANA HIGH VOLTAGE

DRAWING NUMBER

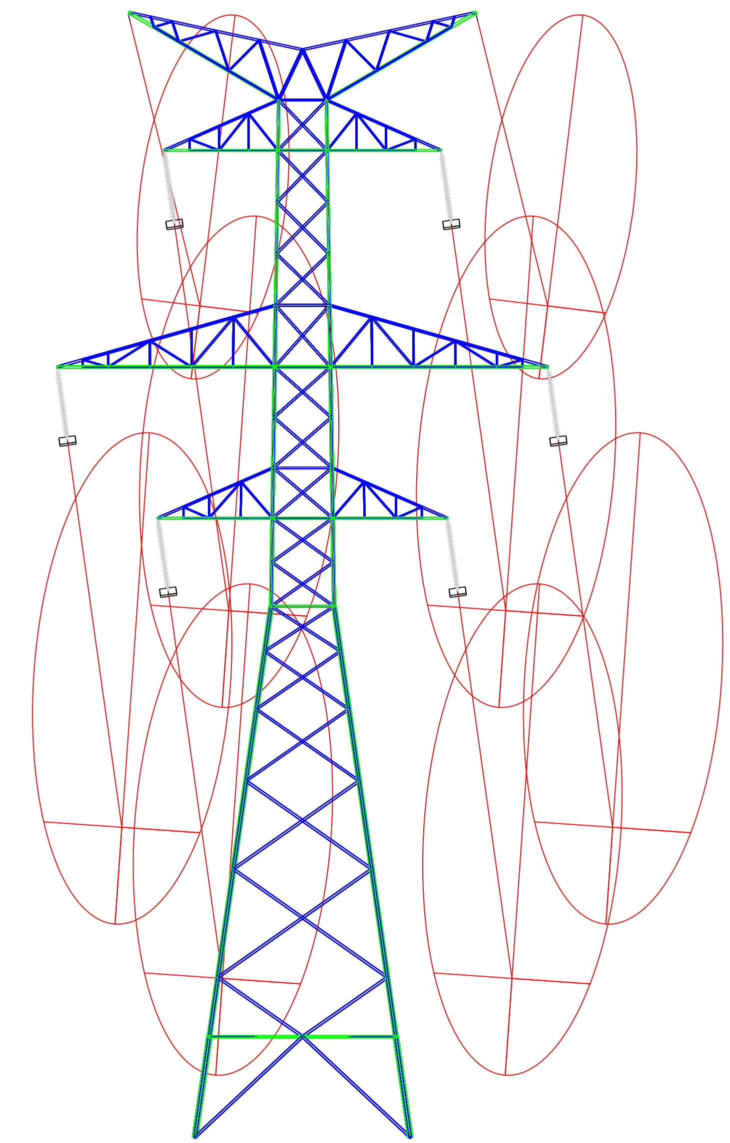
SKETCH C3 | A

Drawing: SKETCH C3 - rc22a galloping CIGRE
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH C3 - rc22a galloping CIGRE.dgn
Date Plotted: 8/28/2014 Plotted By: zhengs



0° SWING
(NOT APPLICABLE)

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
8.0° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300

DRAWN: X. ZHENG

DESIGNED: B. MURPHY

CHECKED: O. PERRY

APPROVED: O. PERRY

TITLE:

RC22A - REA

CLIENT:

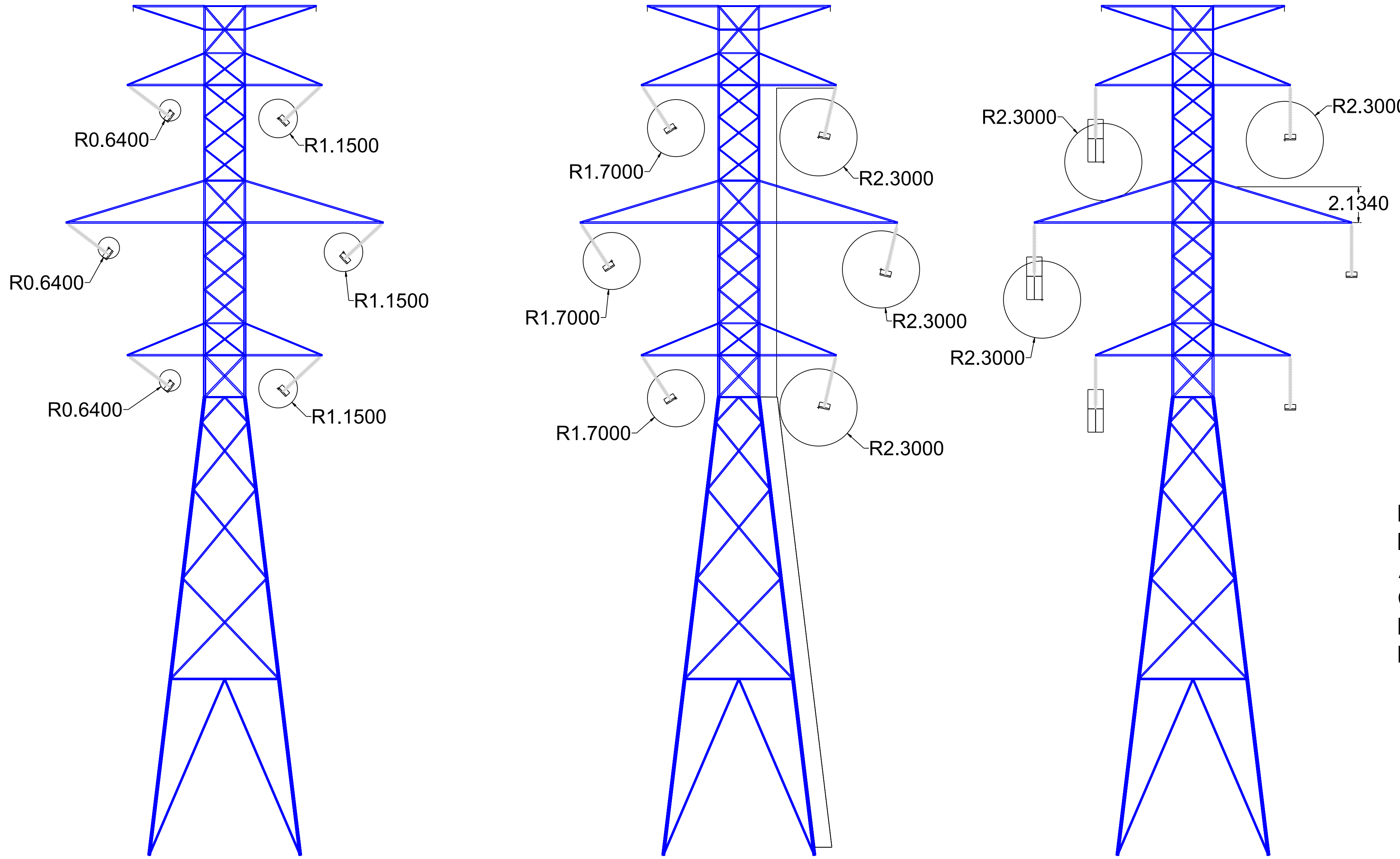
CANA HIGH VOLTAGE

DRAWING NUMBER

SKETCH C4

A

Drawing: SKETCH C4 - rc22a galloping REA
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH C4 - rc22a galloping REA.dgn
Date Plotted: 8/28/2014 Plotted By: zhengs



NOTE:
INSULATOR SWING ANGLES AND CLEARANCES TAKEN FROM AESO TOWER DRD.

53°
5 YEAR GUST REQUIRED AIR GAP: 0.64 M

47°
COLD TEMPERATURE REQUIRED AIR GAP: 1.15 M

33°
CSA STEADY STATE REQUIRED AIR GAP: 1.7 M

13°
MAINTENANCE REQUIRED AIR GAP: 2.30 M + 0.15 M (X-ARM) 1.00 M (BODY)

WITH CONDUCTOR BUGGY

ARM MAINTENANCE REQUIRED AIR GAP: 2.3 M + WALKOUT

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

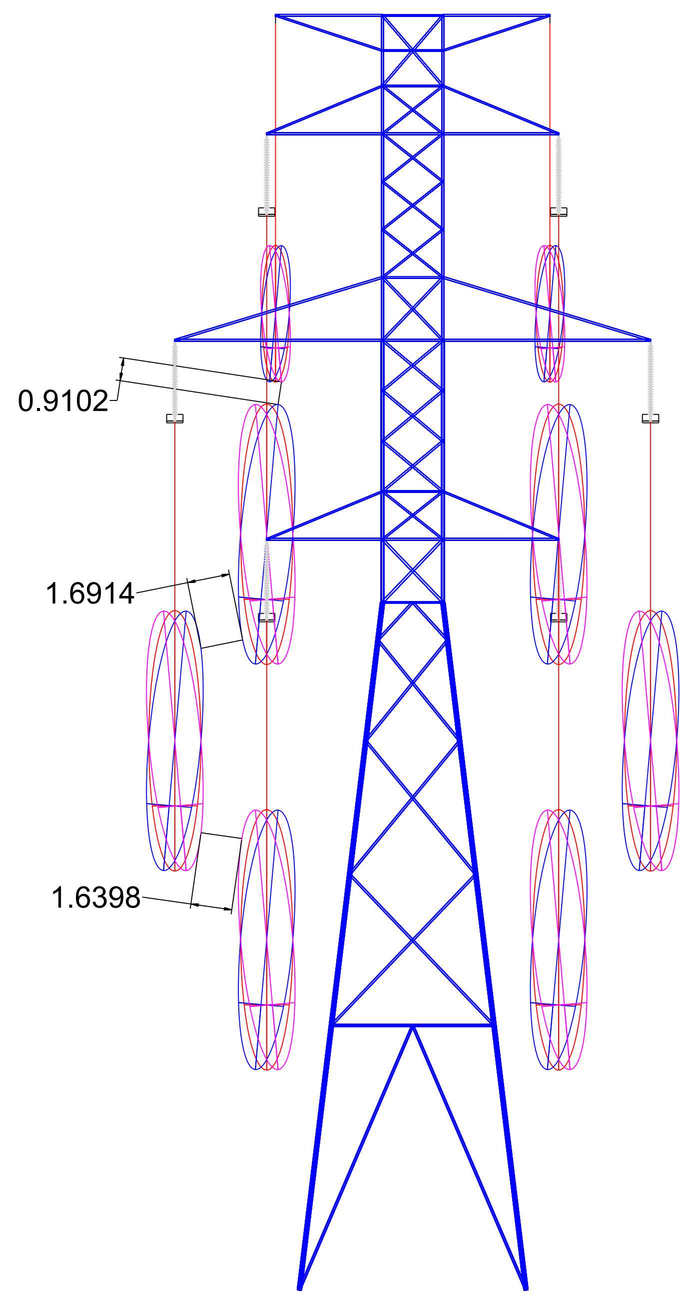
SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:
RD22A - INSULATOR SWINGS

CLIENT:
CANA HIGH VOLTAGE

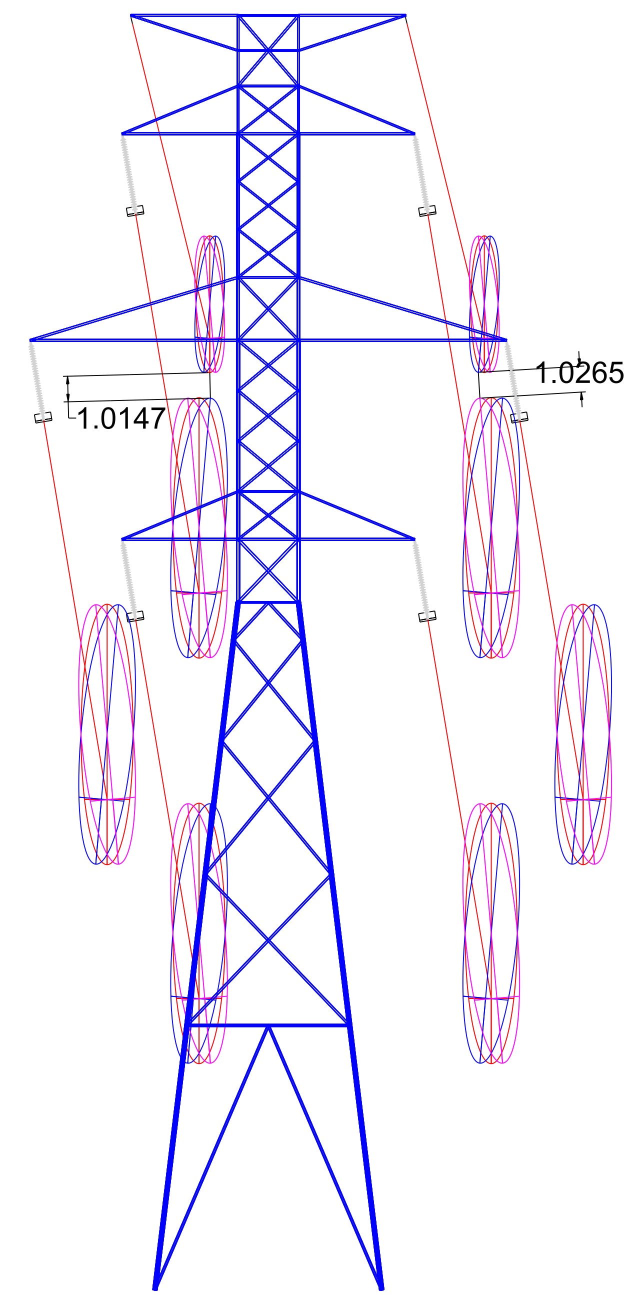
DRAWING NUMBER: SKETCH D1 — A

Drawing: SKETCH D1 - rd22a insulator swings
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH D1 - rd22a insulator swings.dgn
Date Plotted: 8/28/2014 Plotted By: zhengs



0° SWING

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
9.5° CONDUCTOR SWING

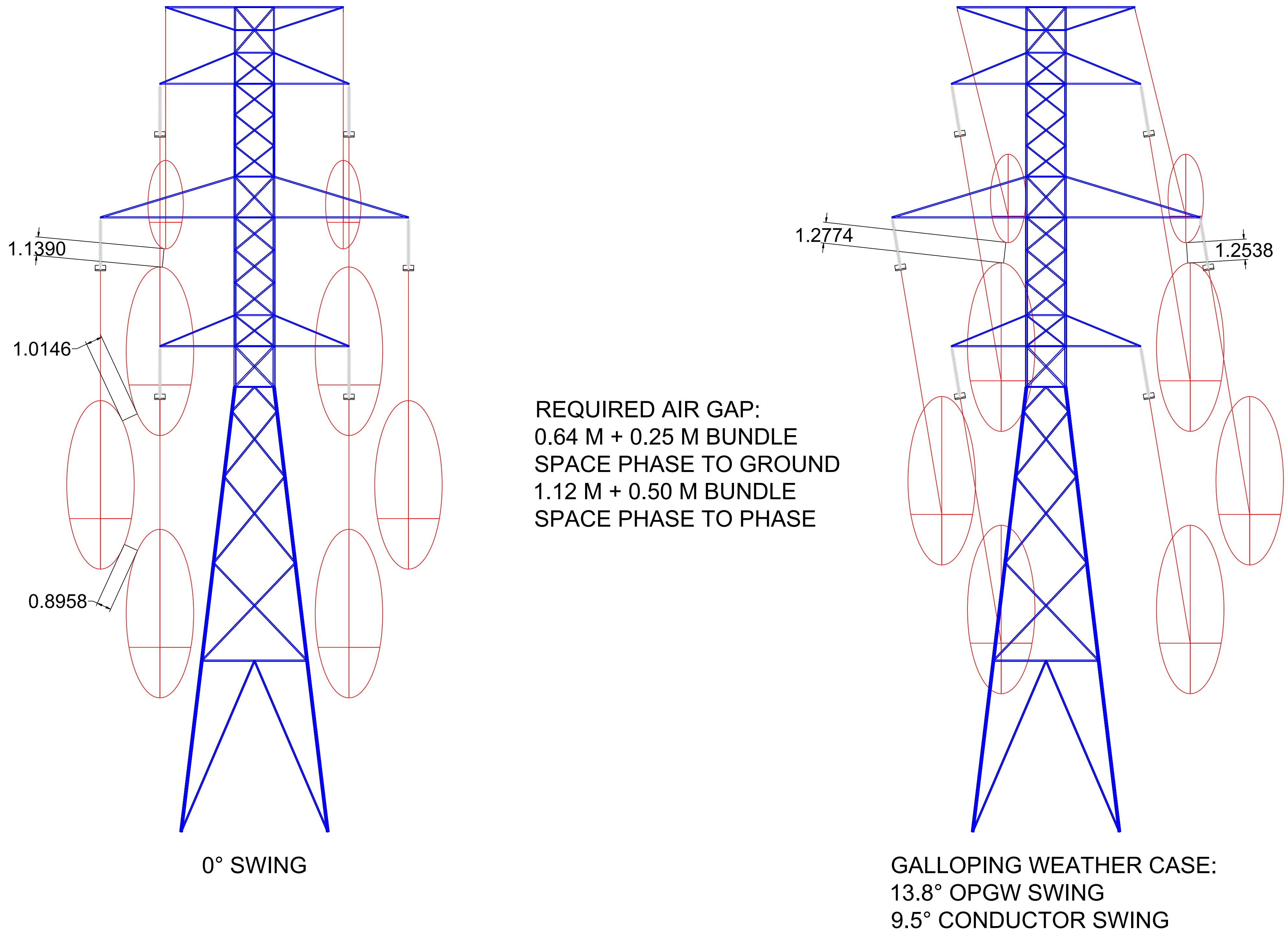
NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300
DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE: RD22A - HAVARD

CLIENT: CANA HIGH VOLTAGE

DRAWING NUMBER: SKETCH D2 A



NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300

DRAWN: X. ZHENG

DESIGNED: B. MURPHY

CHECKED: O. PERRY

APPROVED: O. PERRY

TITLE: RD22A - CIGRE

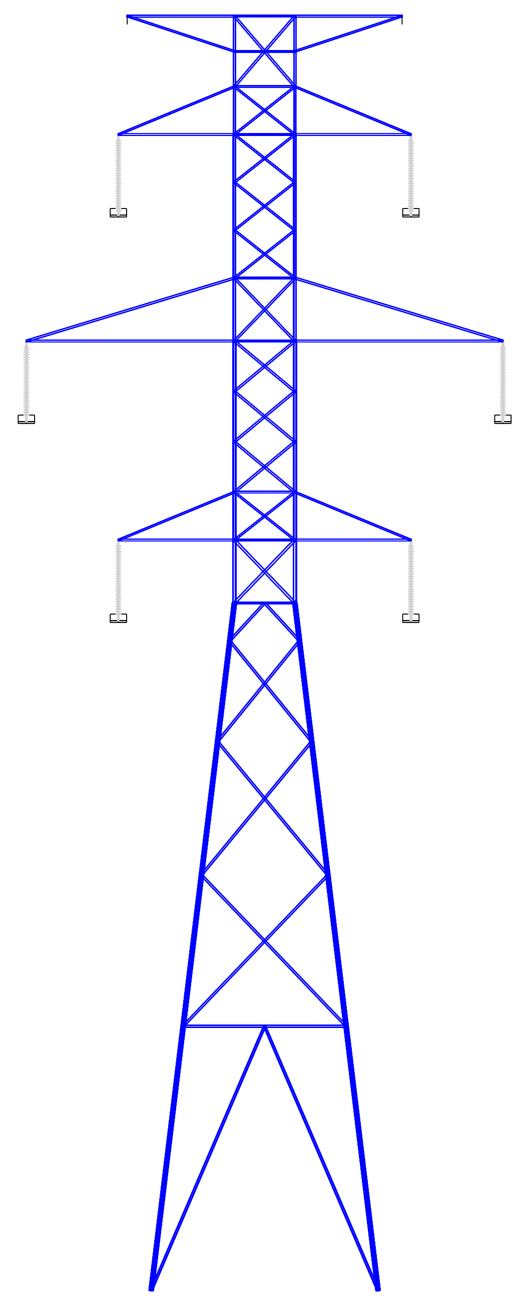
CLIENT: CANA HIGH VOLTAGE

DRAWING NUMBER: SKETCH D3 A

Drawing: SKETCH D3 - rd22a galloping CIGRE

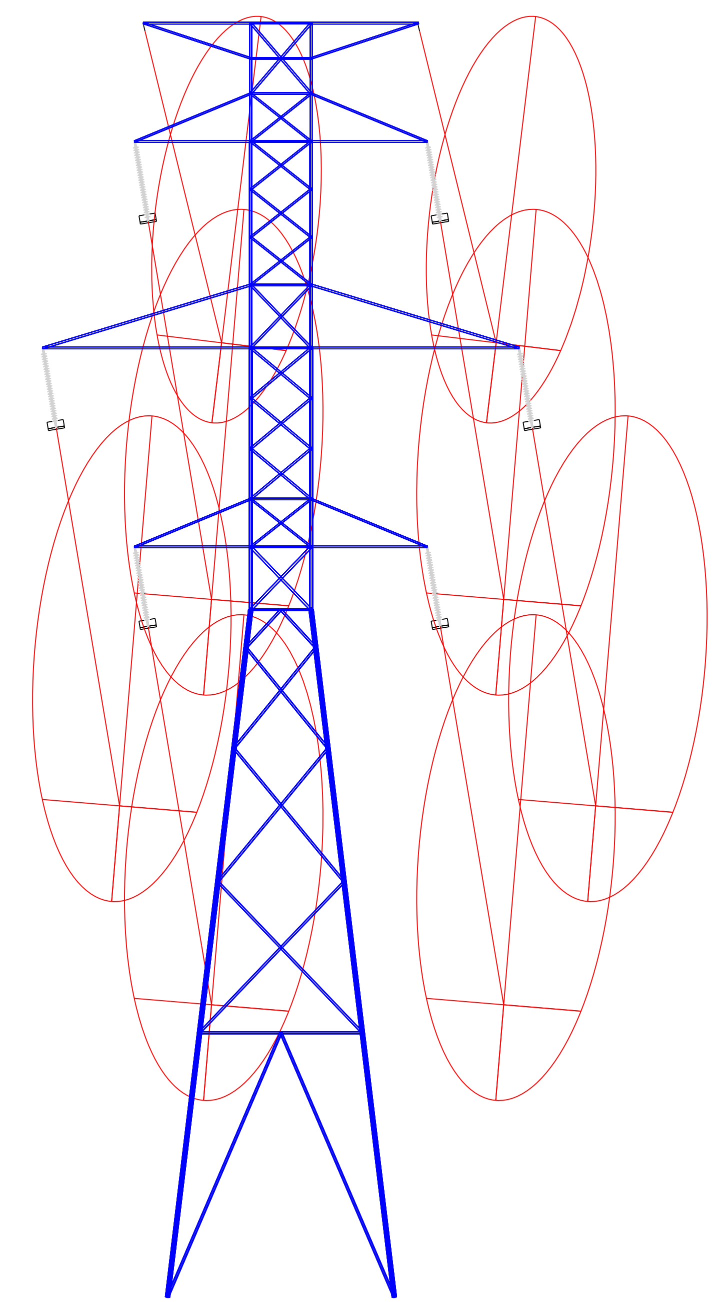
CADD Filename: S:\Dwgs\TDG Drawings\Project Drawings\TDC-1401-025-AESO\1-Client\DXFs FOR DRAFTING AUGUST 14th 2014\SKETCH D3 - rd22a galloping CIGRE.dgn

Date Plotted: 8/28/2014 Plotted By: zhengs



0° SWING
(NOT APPLICABLE)

REQUIRED AIR GAP:
0.64 M + 0.25 M BUNDLE
SPACE PHASE TO GROUND
1.12 M + 0.50 M BUNDLE
SPACE PHASE TO PHASE



GALLOPING WEATHER CASE:
13.8° OPGW SWING
9.5° CONDUCTOR SWING

NO.	DATE	REVISION	DWN	DES	CHK	APPD
A	14-08-26	ISSUED FOR INFORMATION	XZ	BM	OP	OP

SCALE: 1:300

DRAWN: X. ZHENG
DESIGNED: B. MURPHY
CHECKED: O. PERRY
APPROVED: O. PERRY

TITLE:

RD22A - REA

CLIENT:

CANA HIGH VOLTAGE

DRAWING NUMBER

SKETCH D4 | A

Appendix B

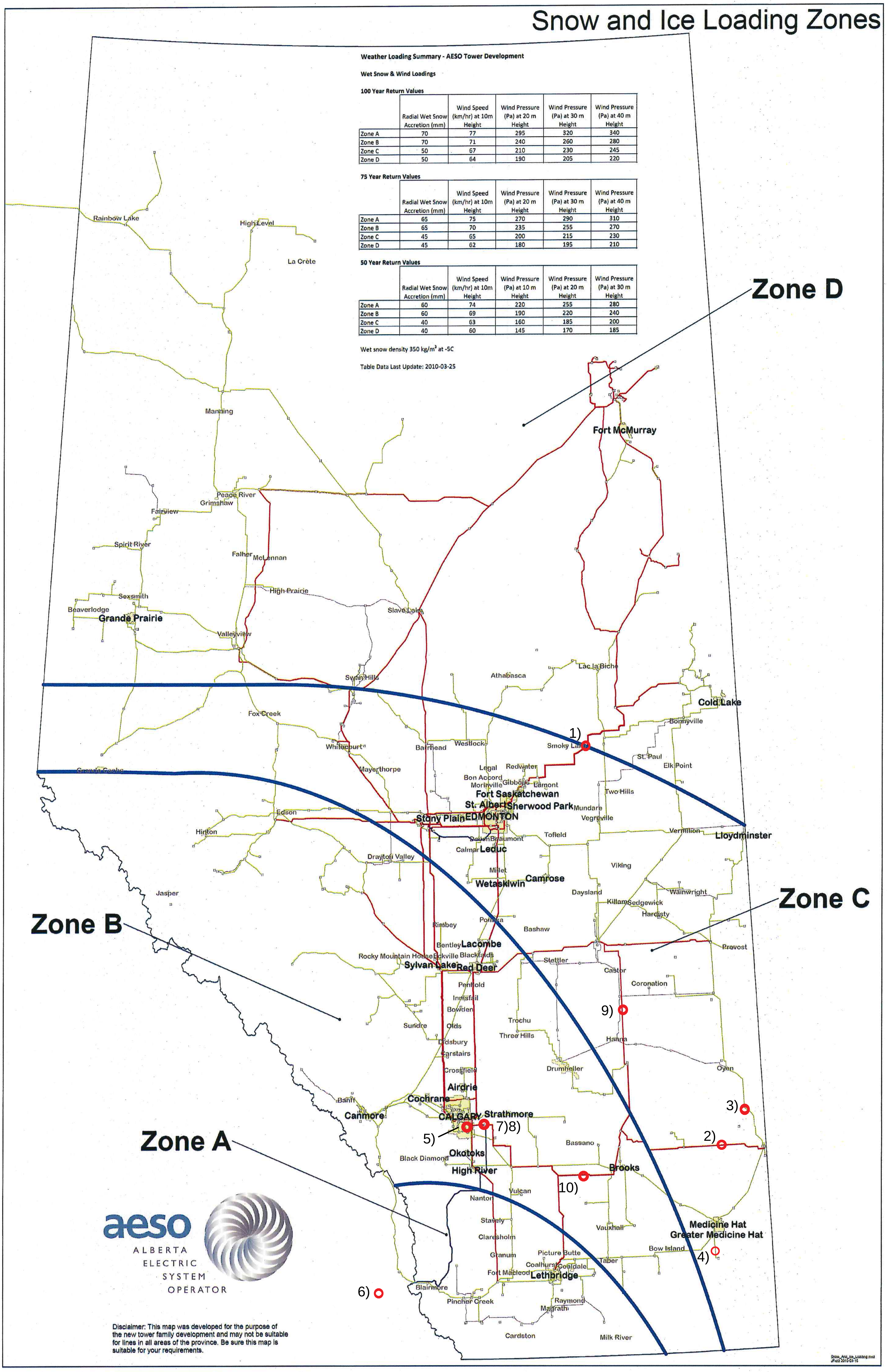
Distribution of Galloping Related Outages

The following appendix contains two drawings illustrating the general location and frequency of outages either related to galloping or occurring under circumstances which could be galloping related:

- Sketch 5 illustrates events directly attributed to galloping in operations reports.
- Sketch 6 shows outage events occurring during a season where galloping was a possibility, and attributed to ice or snow accretion. Other events attributed to wind or uncategorized but occurring during the spring or fall seasons were noted in different colours.

To record events, the identified line facility was given a marker although the exact location was not known. Where multiple instances occurred, the marker was given a frequency designation (ie: if two occurrences on that line, x2 if three occurrences, x3 etc.)

SKETCH 5: HISTORICAL OUTAGES ATTRIBUTED TO CONFIRMED OR SUSPECTED GALLOPING 2006-2014



Weather Loading Summary - AESO Tower Development

Wet Snow & Wind Loadings

100 Year Return Values

	Radial Wet Snow Accretion (mm)	Wind Speed (km/hr) at 10m Height	Wind Pressure (Pa) at 20 m Height	Wind Pressure (Pa) at 30 m Height	Wind Pressure (Pa) at 40 m Height
Zone A	70	77	295	320	340
Zone B	70	71	240	260	280
Zone C	50	67	210	230	245
Zone D	50	64	190	205	220

75 Year Return Values

	Radial Wet Snow Accretion (mm)	Wind Speed (km/hr) at 10m Height	Wind Pressure (Pa) at 20 m Height	Wind Pressure (Pa) at 30 m Height	Wind Pressure (Pa) at 40 m Height
Zone A	65	75	270	290	310
Zone B	65	70	235	255	270
Zone C	45	65	200	215	230
Zone D	45	62	180	195	210

50 Year Return Values

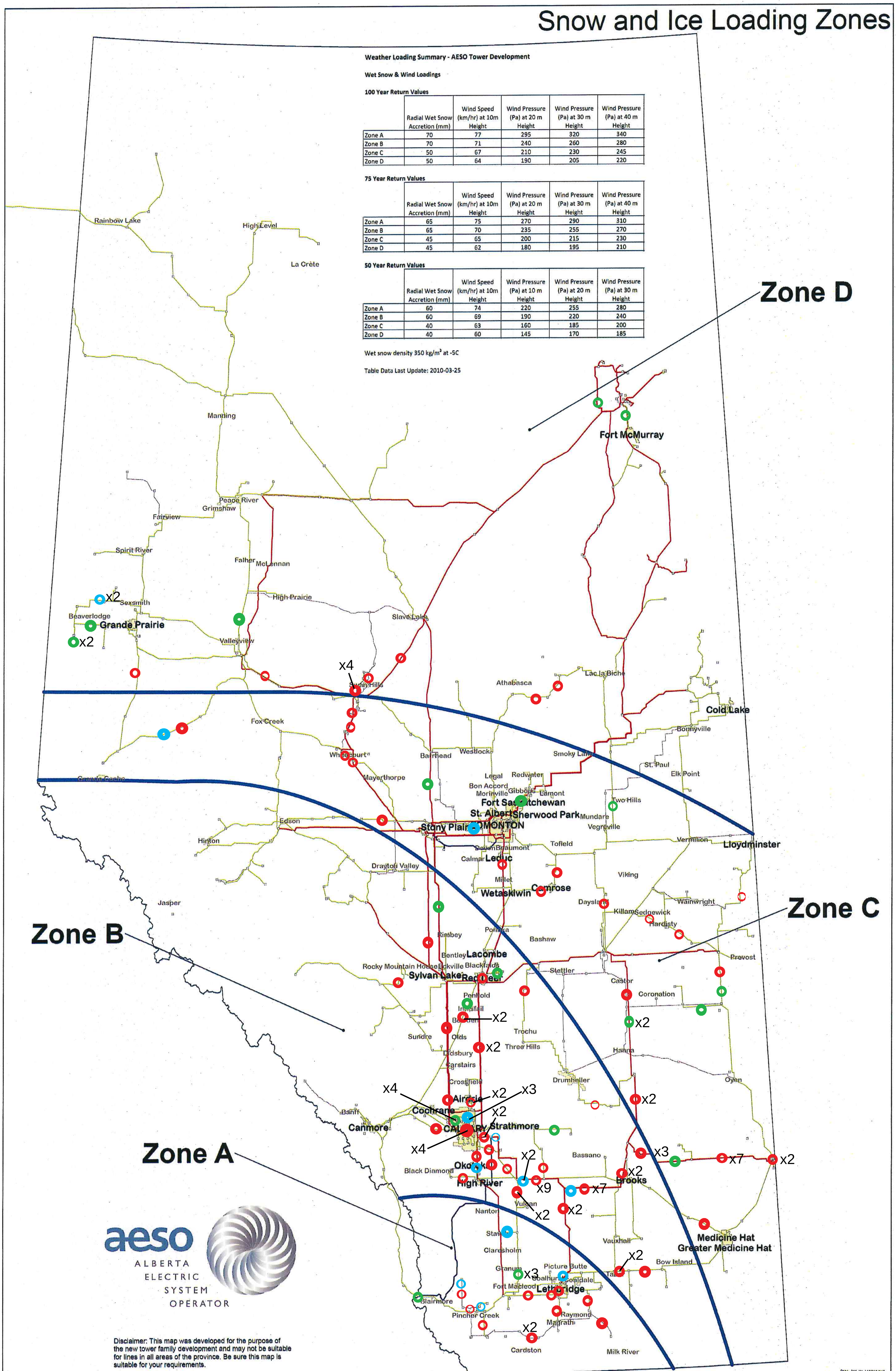
	Radial Wet Snow Accretion (mm)	Wind Speed (km/hr) at 10m Height	Wind Pressure (Pa) at 10 m Height	Wind Pressure (Pa) at 20 m Height	Wind Pressure (Pa) at 30 m Height
Zone A	60	74	220	255	280
Zone B	60	69	190	220	240
Zone C	40	63	160	185	200
Zone D	40	60	145	170	185

Wet snow density 350 kg/m³ at -5C

Table Data Last Update: 2010-03-25

1) March 2009, 9L960 (Suspected Galloping)
2) May 2009, 945L (Suspected Galloping)
3) May 2009, 7L760 (Suspected Galloping)
4) January 2011, 600L (Confirmed Galloping)
5) December 2011, 24.83 (Suspected Galloping)
6) January 2012, 5L92, Located in British Columbia (Confirmed Galloping, tripped 1201L west of Fort Macleod)
7 & 8) November 2013, 924L and 937L (Confirmed Galloping)
9) December 2013, 9L59 (Suspected Galloping)
10) January 2014, 935L (Suspected Galloping)

SKETCH 6: POTENTIAL GALLOPING CASES BETWEEN OCTOBER AND MAY, 2006-2014



Weather Loading Summary - AESO Tower Development

Wet Snow & Wind Loadings

100 Year Return Values

	Radial Wet Snow Accretion (mm)	Wind Speed (km/hr) at 10m Height	Wind Pressure (Pa) at 20 m Height	Wind Pressure (Pa) at 30 m Height	Wind Pressure (Pa) at 40 m Height
Zone A	70	77	295	320	340
Zone B	70	71	240	260	280
Zone C	50	67	210	230	245
Zone D	50	64	190	205	220

75 Year Return Values

	Radial Wet Snow Accretion (mm)	Wind Speed (km/hr) at 10m Height	Wind Pressure (Pa) at 20 m Height	Wind Pressure (Pa) at 30 m Height	Wind Pressure (Pa) at 40 m Height
Zone A	65	75	270	290	310
Zone B	65	70	235	255	270
Zone C	45	65	200	215	230
Zone D	45	62	180	195	210

50 Year Return Values

	Radial Wet Snow Accretion (mm)	Wind Speed (km/hr) at 10m Height	Wind Pressure (Pa) at 10 m Height	Wind Pressure (Pa) at 20 m Height	Wind Pressure (Pa) at 30 m Height
Zone A	60	74	220	255	280
Zone B	60	69	190	220	240
Zone C	40	63	160	185	200
Zone D	40	60	145	170	185

Wet snow density 350 kg/m³ at -5C

Table Data Last Update: 2010-03-25

Each point plotted represents one line outage that could have potentially been caused by galloping (listed as unknown cause: October - May) or that could have potentially experienced galloping (outage caused by icing or weather).

- Ice/Snow/Weather
- Wind
- Unknown Cause

Appendix C

Air Gap Computation Summary

Revision Date August 28, 2014

1. Study Details

1.1 Air Gap Parameters

Analysis Method	IEEE 1313.2
Nominal Line-to-Line Voltage	260.0 kV
Maximum Line-to-Ground Crest Voltage	233.5 kV
Temporary Overvoltage	10.0%
Switching Surge Factor	2.75 (phase-to-ground) 4.26 (phase-to-phase)
Normalized Standard Deviation for Switching Surges	0.05 (phase-to-ground)
Withstand Level	90.0% (switching surge) 99.7% (temporary overvoltage)
Elevation	1000 m
Gap Factor	1.35

Table 1: Summary of Parameters in Study

1.2 Methodology

The procedure outlined in section 6 of IEEE 1313.2 was used to find the required air gaps for the parameters summarized in Table 1.

The nominal line-to-line voltage used in the analysis was 260 kV with a 10% overvoltage corresponding to a maximum crest voltage of 233.5 kV line-to-ground. Switching surge factors and normalized standard deviations were obtained from CSA C22.3. A switching surge factor of 2.75 with a standard deviation of 5.0% was used in line-to-ground air gaps. IEEE 1313.2 recommends a ratio of 1.55 for phase-to-phase to phase-to-ground switching surges with the standard deviation being equal. The IEEE recommendations resulted in a 4.26 switching surge factor with a standard deviation of 5.0% was used in line-to-line air gaps.

The switching surge values obtained from CSA C22.3 are maximum expected switching surges. In some cases it may be appropriate to convert these values to a 50% expected switching surge factor (50% of switching surges would be at or below this level). Maximum switching surge values were used in the following calculations as opposed to 50% values to provide adequate protection against flashovers during temporary conditions that may for a sustained period, e.g. ice shedding events as opposed to short term events such as wind gusts.

The withstand level was set to 90.0% for switching surges and 99.7% for temporary overvoltages. A gap factor of 1.35 was used for horizontal rods. An elevation of 1000 m was used to account for most sections of Alberta.

2. Results

2.1 Calculated Air Gaps

The phase-to-ground air gaps calculated from the parameters in Table 1 are 1.559 m during a switching surge and 0.587 m for temporary overvoltages. The required phase-to-phase air gap during a switching surge is 2.647 m and 1.063 m for temporary overvoltages. The results are summarized in Table 2.

	Switching Surge Air Gap (m)	Temporary Overvoltage Air Gap (m)
Phase-to-Ground	1.559	0.587
Phase-to-Phase	2.647	1.063

Table 2: Summary of 260 kV Air Gaps

2.2 Sample Calculation

Provided below is a sample calculation for the phase-to-ground switching surge air gap.

For a nominal line-to-line voltage of 260 kV, including a 10% overvoltage, the maximum crest voltage is

$$V_{crest} = 1.1\sqrt{\frac{2}{3}}\,V_{line-to-line} = 233.5\ kV$$

During a switching surge, the voltage may increase to

$$V_{surge} = V_{crest}\ x\ F_{surge} = 642.2\ kV$$

For a 90% withstand, the critical flashover voltage is

$$CFO = \frac{V_{surge}}{\left(1 - 1.28\left(\frac{\sigma}{CFO}\right)\right)} = 686.1\ kV$$

Using the formulas below, calculations are iteratively completed until they converge on a stable value.

$$G_0 = \frac{CFO_S}{500S} \qquad\qquad m = 1.25\,G_0(G_0 - 0.2)$$

$$\delta^m = e^{-\frac{A}{8.6}}$$

$$S = \frac{8}{\left(\frac{3400\delta^m k_g}{CFO_S}\right) - 1}$$

Iteration #:	S	G_0	m	δ^m	S_{new}
1	1.000	1.372	2.011	0.792	1.862
2	1.862	0.737	0.494	0.944	1.505
3	1.505	0.912	0.811	0.910	1.572
4	1.572	0.873	0.734	0.918	1.556
5	1.556	0.882	0.752	0.916	1.559
6	1.559	0.880	0.748	0.917	1.559

3. Conclusion

Using the process described in IEEE 1313.2, CHV has completed an analysis of required air gaps for 260 kV transmission lines. The study found:

- The minimum phase-to-phase spacing to prevent 90% of flashovers between phases during switching surges is 2.647 m.
- The minimum phase-to-phase spacing to prevent 99% of flashovers between phases during temporary overvoltages is 1.063 m.
- The minimum phase-to-ground spacing to prevent 90% of flashovers to ground during switching surges is 1.559 m.
- The minimum phase-to-ground spacing to prevent 99% of flashovers to ground during temporary overvoltages is 0.587 m.