Comparison of ice accumulation on simplex and duplex conductors in parallel overhead transmission lines in Iceland.

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Abstract: **This paper presents results from icing measurements which have been operated for more than 8 years in two parallel OHTLs. The two OHTLs are built for 400 kV but are currently operated on 220 kV. The measurements are made in suspension towers with load cells in one phase conductor attachment points.**

The ice accumulation at the measuring site from November 2006 to May 2015 is analysed. The lines were energised January 2007. A diagram of icing on simplex and duplex conductors is published. Icing periods are recorded and the icing accumulation calculated for each period. Timing of the beginning of ice shedding is evaluated. Icing accumulation on simplex and duplex conductors is investigated with regards to estimated torsional stiffness of the conductors.

Keywords: **Icing measurements, icing on duplex conductor, icing on simplex conductor, torsional stiffness, ice shedding, energised OHTL.**

I. INTRODUCTION

Since autumn 2006 load measuring cells have been in operation in side-by-side towers in two parallel transmission lines at Hallormsstaðaháls in the eastern part of Iceland (Fig. 1, Fig. 2 and Fig. 6). Test measuring spans have been operated at the same site since 1983 [1].

The measuring site Hallormsstaðaháls is a mountain ridge, located 575 m a. s. l. between two narrow valleys. Most icing events at the site occur when wind is blowing from north to northeast. The distance from the site to the east coast of Iceland is approximately 65 km in this direction. One of the OHTLs has simplex conductors (49.9 mm in diameter). The other OHTL has duplex conductors (2x39.2 mm in diameter).

Icing is frequent every year at the site which in most cases is due to in-cloud icing events, although wet snow icing events also occur. 300 m away from the location of the measuring towers there is a test span where icing has been measured continuously for more than 30 years. Also there is a long experience of
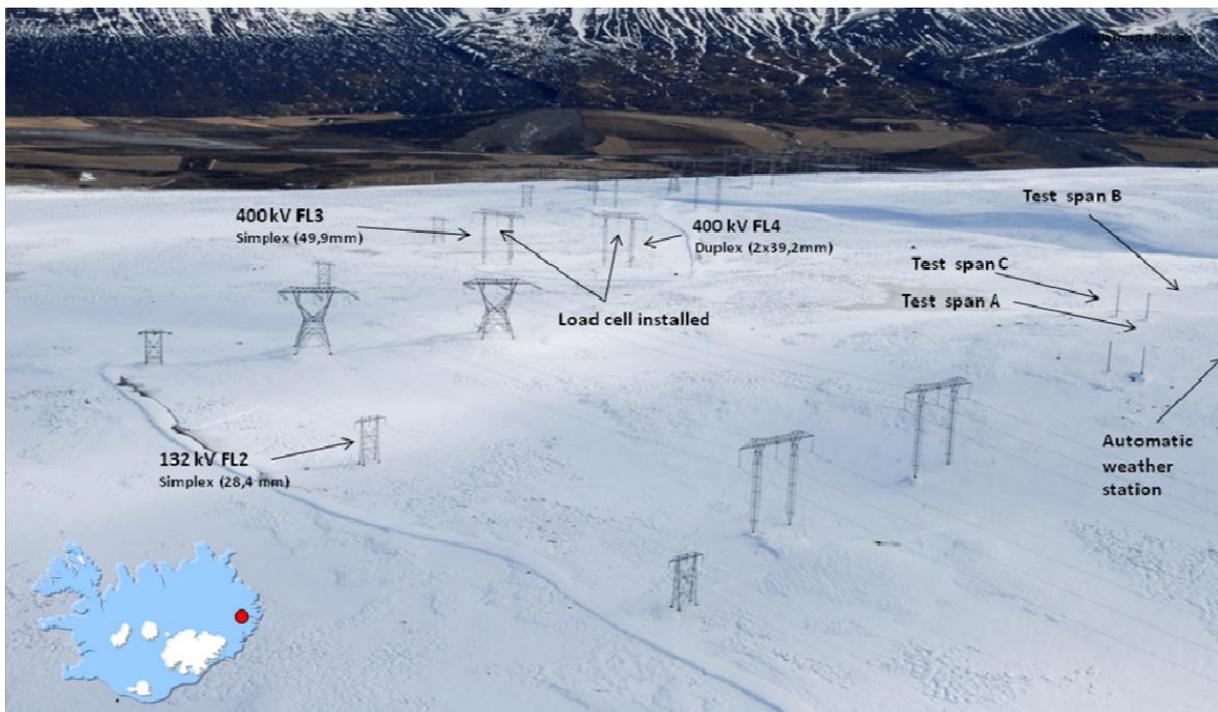
Fig. 1. Hallormsstaðaháls measuring site.

Fig. 2 The towers with measuring cells. The test spans and the automatic weather station can be seen in the background.

operating a 132 kV transmission line parallel to the two 400/220 kV lines. An automatic weather station has been in operation close to the test span for 19 years.

II. SETUP AND MEASUREMENTS

Detailed information on the measurement site is given in [1].

The parallel OHTLs Fljótsdalslína 3 and Fljótsdalslína 4 have centre spacing of 60 m and direction of the lines at the measuring site is 117° (True).

Fljótsdalslína 3 is fitted with a simplex conductor, Austria, d=49.9 mm (Table 1). Height is 540 m a. s. l. with conductor attachment 19 m above ground. Adjacent spans are 205 m and 192 m and weight of the suspension chain is 435 kg. The OHTL was energized in January 2007.

Fljótsdalslína 4 is fitted with a duplex conductor, AACSR, d=39.16 mm (Table 1) with 0.45 m conductor spacing. Height is 545 m a. s. l. with conductor attachment 19 m above ground. Adjacent spans are 175 m and 192 m and weight of the suspension chain is 525 kg. The 175 m span has the following sub spans between spacers: 30, 36, 42, 37 and 30 m. The 192 m span has the following sub spans between spacers: 33, 40, 46, 40 and 33 m.

Table 1

Parameter	Unit	Austria 49.9 mm	AACSR 39.16 mm
Diameter, d	[mm]	49.9	39.16
Cross section area, A	[mm^2]	1470.9	905.8
Modulus of elasticity, E	[N/mm^2]	70533	81099
Weight, g	[kg/m]	5.24	3.7
Tensile strength, Pu	[kN]	613	453
Temperature expansion coefficient, α_T	[°C^{-1}]	1.9 E-5	1.8 E-5
No wind and ice reading, $P_{LOAD\ CELL,0}$	[kg]	1452	1768

An on-line monitoring system was installed in one suspension tower in each line. It consists of load cells with data loggers and video cameras (Fig. 3). The load cells are fitted between the tower bridge and the insulator string in the middle phases. A reading is taken and recorded every 5 minutes.
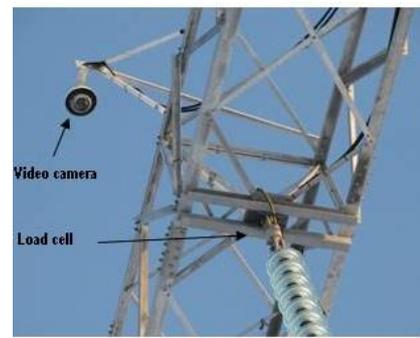
Fig 3. Measurement equipment in one of the OTHLs.

The ice accumulation at Hallormsstaðaháls measuring site on simplex and duplex conductors from November 2006 to May 2015 is analysed. Due to some instrumental or communication failures during this period some of the data acquired could not be used. Thus, data from mid-January 2007 to spring 2008 and from March 2012 to spring 2013 could not be included in the analysis.

III. OBSERVED ICING EVENTS

During the recording periods 61 icing events were observed. Fig. 4 shows the plot of the maximum ice load in the events. The figure shows the general tendency of the duplex line to have lower maximum unit ice load on each sub conductor than the simplex line. However the larger load cases have a greater scattering.

Considering two extreme points, marked with 1 and 2 respectively (Fig. 4), the first was observed during an icing event from 13-28 November 2006 (Fig. 5), before the OHPL's were energized. The temperature at the beginning of this event was just

below 0°C and became gradually lower during the first three days to a minimum of –14 °C. It then raised a little and then remained low, mostly between –4 °C and –9 °C, during the remainder of the event. Ice shedding occurred first after about one day on the duplex and occurred again a few times during the period. Ice shedding did not occur on the simplex until the end of the event.
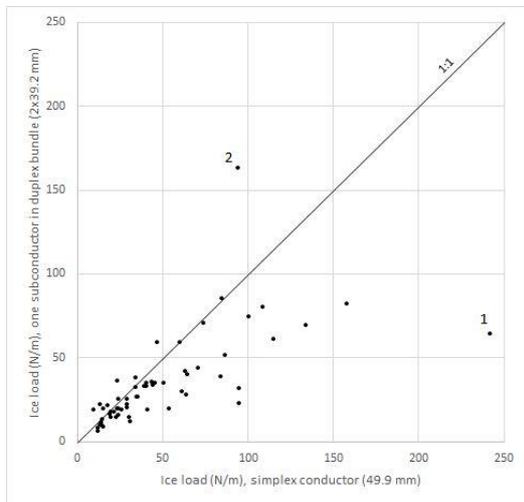
Fig. 4.   Comparison of maximum ice load during each icing event on simplex conductor (49.9 mm) and one sub-conductor in duplex conductor (2x39.2 mm).
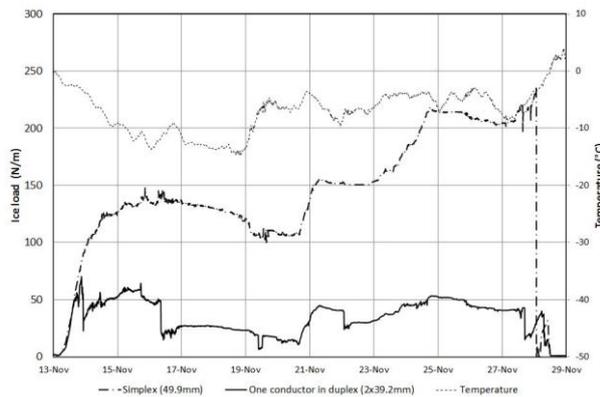
Fig. 5.   Ice load on simplex conductor (49.9 mm) and one sub-conductor in a duplex conductor (2x39.2 mm) during the period 13-28 Nov.2006.

Point 2 (Fig. 4) was observed during an icing event from 18-21 March 2010 (Fig. 7). The temperature at the beginning is just below 0°C becoming gradually lower and remains at -2 °C for a day, then lowering down to -6 °C during the day after. Ice shedding starts on the simplex after approximately half a day. The icing falls off the duplex after a little less than two days, but no shedding until that time.

Fig. 6. Fljótsdalslína 3 and Fljótsdalslína 4 parallel at Hallormsstaðaháls, view to the east.
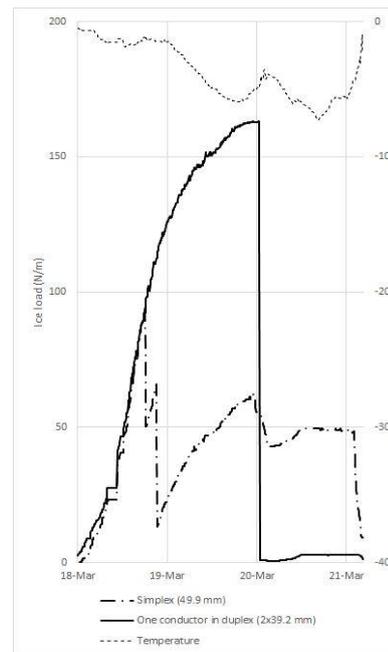
Fig. 7. Ice load on simplex conductor (49.9 mm) and one sub-conductor in a duplex conductor (2x39.2 mm) during the period 18-21 March 2010.

IV. EFFECT OF TORSIONAL STIFFNESS

While studying the load diagrams of the ice load events it became evident that ice shedding has a great effect on the resulting maximum ice load values. However, the effect of differences in the torsional stiffness of the two systems could only be investigated by selecting loads up to the occurrence of the first shedding in cases where no evident disturbances (such as wind fluctuations) occur during the ice accumulation period. 26 such cases were observed. The relation between the two power lines is shown in Fig. 8.

It can be seen from Fig. 8 that by applying a linear trend line, on average the unit ice load on one sub-conductor of the duplex is about 93% that of the simplex conductor.
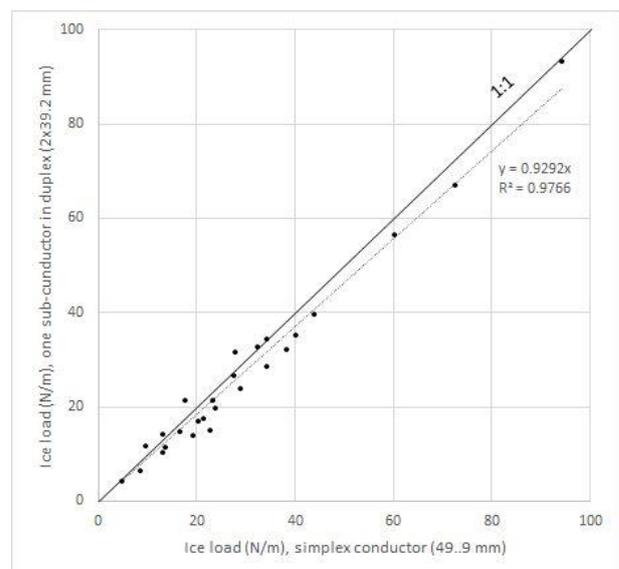
Fig. 8. Comparison of undisturbed ice load on simplex conductor (49.9 mm) and one sub-conductor in duplex conductor (2x39.2 mm).

In [2] a model for the theoretical assessment of ice loading depending on torsional stiffness is presented. A precipitation

direction of 45° is assumed. Figure 6 in [2] shows relation between precipitation and accumulated ice volume for cylinders with different torsional stiffness. In order to compare the results in Fig. 8 to the model presented in [2] the following assumptions and calculations were made:

The torsional stiffness can be approximately calculated as 20% of the stiffness of an equivalent solid bar [2]. The stiffness ratio of the duplex conductor system to simplex conductor, k_{bundle}/k_{single}, $= He^2/GJ +2$, is half of that given in [2] for a quad bundled conductor. Further assuming that the higher shear modulus of the relatively narrow steel core may be omitted, with a load of 50 N/m resulting in horizontal tension of H = 103860 N and with e = 0.45 m:

The shear modulus of aluminium is G = 27 GPa. Therefore, for the simplex $GJ_{simplex}$ = 1860 Nm^2/rad and for one conductor in duplex $GJ_{1-in-duplex}$ =705 Nm^2/rad and k_{bundle}/k_{single} = 31.8, $k_{eq,simplex}$ = 112 Nm/rad, $k_{eq,duplex}$ = 1468 Nm/rad and then for the duplex line $k*_{eq,duplex}$ = 182, and for the simplex line $k*_{eq,simplex}$ = 15.

Moment about C from ice load
$\mathcal{M}$ = q e

Moment about C from ice load
$\mathcal{M}$ = q (d/2 +e) - q (d/2 - e)
$\mathcal{M}$ = 2 q e
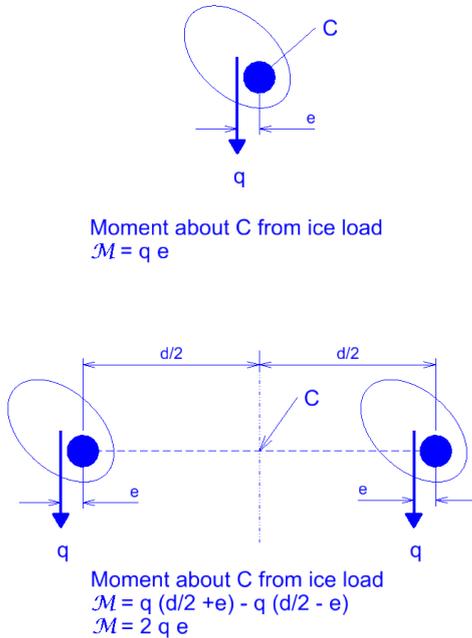
Fig 9. Eccentric ice load on a simplex conductor (upper figure) and on a duplex conductor (lower figure).

Looking closer at how the duplex system rotates (Fig. 10), the bundle system rotates ϕ_1 about its axis due to $2\mathcal{M}$ moment (Fig. 9), but the sub spans between spacers will rotate additionally ϕ_2 due to the $\mathcal{M}$ moment.
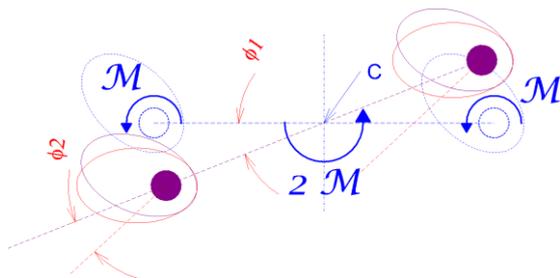
Fig 10. Rotation of the duplex system due to eccentric ice load.

Sum of the rotations gives with local stiffness of the sub spans (on average L_{sub} = 36.7 m, and $k_{eq,sub}$ = 12*705/36.7 = 231 Nm^2/rad).

$\mathcal{M}/k_{eq,duplex,mod} = \phi = \phi_1 + \phi_2 = 2\mathcal{M}/k_{eq,duplex} + \mathcal{M}/ k_{eq,sub}$

$k_{eq,duplex,mod}$ $= k_{eq,duplex} k_{eq,sub} /(2 k_{eq,sub} + k_{eq,duplex})$

$= 1468 \cdot 231/(2 \cdot 231 + 1468) = 176$ Nm/rad

and $k*_{eq,duplex}$ = 2, which is considerably lower that calculating the torsional stiffness of just the bundle system.

Reading and calculating through the rather small Figure 6 in [2] applying the k* = 16 curve for $k*_{eq,simplex}$ = 15 simplex, and between k* = 16 and k* = 32 curves for the $k*_{eq,duplex}$ = 24 for the duplex assuming that the same precipitation applies for both conductors, then Figure 6 in [2] gives that the duplex line should have about 87% of the load on the simplex line compared with 93% obtained from the observations.

This is a considerable difference. One or more of the following reasons could explain this:

(a) The precipitation direction may vary from the assumed 45° in [2] and could in fact vary throughout the icing event.

(b) The ice might accumulate on the conductors differently from just setting on the face it hits directly and may set on the leeward side as well, similar to snow that blows over a mountain edge (see Fig. 11 with downward pointing ice tail on the leeward side). Thus the eccentricity of the ice will be less or even zero.

(c) The estimated stiffness of the system with respect to ice accumulation may be inaccurate (too high). It is a little unclear how the torsional stiffness of the bundled system is to be calculated. In [3] it is clear that the sub span configuration, i.e. distance between spacers, does not have an effect on the torsional stiffness of the bundle as such. In the calculations above the torsional stiffness calculated for the bundle has been lowered in order to compensate for additional rotation of the sub spans caused by the eccentric ice load.

Fig. 11. In-cloud icing on duplex conductor in FL4 (400 kV OHTL) in Dec. 2006.

V. EFFECT OF ICE SHEDDING

It is evident that ice shedding has great effect on the resulting load on the conductors in the two power lines.

In the study here it was assumed that an ice shedding event started with a 2 N/m over 10 minutes load decrement and stopped when load decrement became lower than 2 N/m again. For the simplex conductor the lowest load decrement during a shedding event was 4.6 N/m and the highest observed was 236.7 N/m. For one conductor in duplex the lowest load decrement during a shedding event was 5.6 N/m and the highest observed was 161.9 N/m.

It was observed that on average ice started to fall off the duplex line at lower unit load (35.5 N/m) than observed for the simplex conductor (54.9 N/m), as shown in Fig. 12. It was also noted that the period of ice shedding from the simplex conductor

often lasted a little longer than observed for the duplex conductor. Thus 53% of ice shedding events for the duplex were over in less than 10 minutes, but 33% in case of the simplex conductor.
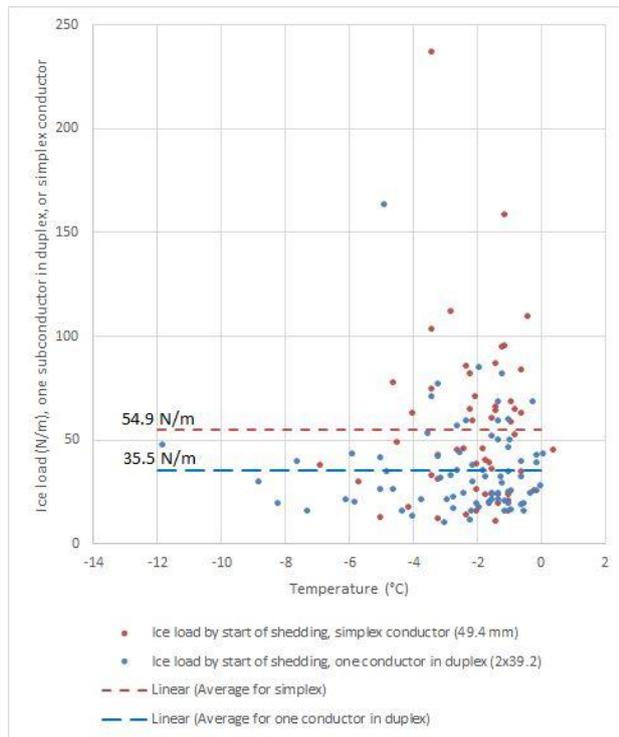
Fig 12. Ice load by the start of a shedding episode.

More ice shedding events were observed for the duplex conductor (75) than for the simplex conductor (55).
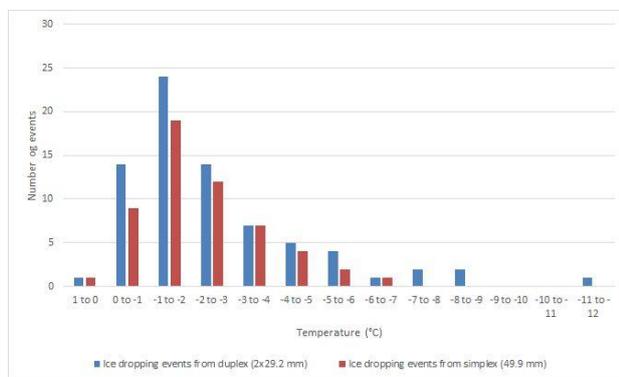
Fig 13. Temperature at the start of ice shedding events.

It is difficult to pinpoint any specific rule for the ice shedding process. The ice shedding events start at different temperatures and at different, very scattered ice load intensities.

Weaknesses in the ice formations are probably more in the case of the duplex conductors, i.e. larger leeward area due to difference in torsional stiffness and weaker ice (thinner ice or less compact) on the leeward side. Weaknesses by the spacers as can be seen on Fig. 11 where the ice has begun to fall off by the spacer.

The measurements showed that wind excitement was more frequent in case of the duplex conductor and dynamic forces due to that excitement could lead to an earlier ice shedding.

The effect of temperature is important when considering causes of ice shedding. Ambient temperature, solar radiation and energy transfer in the power lines can all have an effect to raise

the temperature of the conductors and thereby weaken the bond between ice and conductor. It can be seen in Fig 14 that when ambient temperature rises close to or above -2°C, ice begins to fall of the duplex line. Ice falls off the simplex line more seldom, but at similar time points. The energy transport on the lines during the period shown in Fig. 14 was rather steady and generated heat energy of 6 W/m for each conductor in the duplex and 13.7 W/m in the simplex.
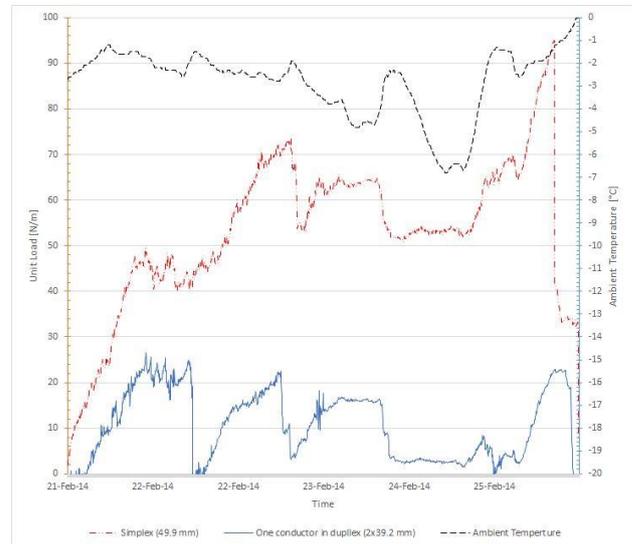
Fig. 14. Unit Ice Loads and Temperature for Fljótsdalslína 3 and Fljótsdalslína 4 OHPL: February 21 5:10 – February 26 11:10 2014.

VI. CONCLUSION

The case studied showed that ice load accumulated on one conductor in duplex was about 7% less than ice load accumulated on the simplex conductor. It could not be verified if this was due to variations on torsional stiffness alone.

It was observed for both the simplex and duplex OHTLs that ice shedding had considerable lowering effect on the ice load. The ice shedding had more effect on the duplex OHTL where the ice shedding began on average at lower load intensities and was more frequent.

VII. REFERENCES

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