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Countermeasures for high and extreme ice loads typical for Norwegian environment based on the concept of heating of shield wires and phase conductors

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SUMMARY

Severe ice events in Norway can lead to such a high ice accretion that it causes the collapse of overhead lines (OHL), leading to outages that may last for days. Norway's specific OHL service conditions are characterized by a highly non-uniform distribution of the ice loads along the OHL due to varying topography, very high local ice loads (over hundred kilograms per meter of the conductor in certain areas), and remoteness of affected areas. At present, Statnett’s primary countermeasure against icing is a mechanical ice removal using a helicopter with a suspended pole to strike the ice-covered conductors. This paper presents the results of feasibility studies of countermeasures using current for heating of both phase conductors and shield wires. The applicability and expected gain were evaluated through a case study comprising two of Statnett’s OHL with recorded ice-related issues. This case study used actual historical weather parameters and operational data to make the evaluation as representative as possible. The main conclusion is that the countermeasures against ice formation in Norwegian conditions by current heating methods are promising for both phase conductors and shield wires. The next step could be a detailed economic analysis of practically possible installations for comparison with other possible countermeasures, i.e., removal of the shield wires from sections of the OHL (by keeping them aside of the OHL) or re-routing of the most critical sections.

These methods might be even more promising for countries experiencing lower ice loads than Norway. Applicability at other voltage levels is possible but depends on the design of the conductor bundle and the specific environment.

KEYWORDS

Ice Load – Ice Removal – Shield Wire – Phase Conductor – Conductor Bundle – Heating

BACKGROUND AND GOALS

Operational experience shows that icing events in Norway can cause failures of overhead lines (OHL), which may result in outages that last days. The specific conditions for OHLs in Norway are defined as follows: very non-uniform distribution of the ice loads along the OHL route due to varying topography (mountains and valleys), very high local ice loads (in certain areas even over hundred kilograms per meter) typically covering only a few spans. In addition, affected areas are not easy to reach in a short time, especially during snow/ice storms [1]. At present, Statnett primarily uses mechanical methods for ice removal using helicopters with a "striking" pole; see example in Figure 1 [1]. Most Nordic countries use similar mechanical methods for ice removal, e.g., insulated ropes or composite insulators.

Figure 1 Example of "typical" ice removal procedure deployed by Statnett [1].

One of the goals of the ongoing "Icebox" project, supported by Statnett and the Norwegian Research Council, is the development of concepts for the most promising modern technologies to reduce and remove ice from OHLs. The countermeasures should be simultaneously applicable for both phase conductors and shield wires; otherwise, the clearance between the bare phase conductor and the ice-covered shield wires may be reduced leading to a flashover. Many different countermeasures, such as coatings, counterweights, ferromagnetic spirals, special conductor types, and robot-based systems, were evaluated in the frame of the "Icebox" project [1]. Theoretically, coating of conductors might be very promising for both conductors and shield wires. Unfortunately, their service trials are limited and related to mostly snow or light ice stress conditions, which is supported by [1] and recently published CIGRE Technical Brochures (TB 631 and TB 838) [2], [3]. Thus, this countermeasure is not discussed further.
Removal of the shield wires is also a simple countermeasure applied in several countries. However, Statnett has specific requirements on safety and communications, requiring a continuous ground wire or shield wire with optical fiber; thus, the removal of shield wires is difficult to realize in practice [1].
Thus, the goal of this paper is to present a feasibility study of countermeasures for ice removal using current heating of both phase conductors and shield wires. To make the study as representative as possible and thereby applicable for Statnett, historical weather and operational data were used for the selected case studies.

CIGRE AND OTHER DATA AVAILABLE vs. PRACTICAL CONSIDERATIONS

At present, only one CIGRE TB (issued in 2010) relates to the issues of ice reduction and removal by heating methods [4]. For phase conductors, three different approaches are mentioned in the TB and further considered in this paper, based on practical considerations:

- <u>Load shifting between different overhead lines.</u> Applying this method might theoretically be the best option, requiring no additional equipment. However, normal operating conditions must be modified, which may affect system reliability. The challenges and practical difficulties listed by

Statnett operating personnel showed that it is not always possible to find a network topology and relevant production units to achieve the required increase in current. Also, system configurations where several parallel lines are disconnected may reduce system reliability. Therefore, this method was not considered promising for Statnett and was not further investigated.

- Re-distribution of current between bundled sub-conductors. The idea of this method is that a special device (i.e., a small circuit breaker) forces the current, which normally flows in all the sub-conductors, into fewer sub-conductors. The increased current density increases the temperature and melts the ice. The process is repeated for the remaining sub-conductors until complete de-icing is obtained. The concept is presented in a paper from the USA [5] and was tested in China [6]. This approach was considered promising to investigate further.
- Conversion of load current into high-frequency current. This is another method intending to increase the heating of the conductor. The concept was published in the USA [7] and was also investigated in Russia [8]. The most developed concept [7] utilizes the skin effect appearing at high frequency, increasing the electrical resistance of the conductors by one order of magnitude or more. Further, ice is a lossy dielectric at high frequencies, causing heating directly in the ice [7]. A potential implementation of this approach is similar to the re-distribution of current between the sub-conductors. However, the complexity of this approach is a disadvantage with respect to reliability in a harsh environment. Thus, this method was not considered promising for further investigation.

For the shield wires, the heating can be achieved by current injection (utilizing the joule effect) and applications using both AC and DC are known [4], however the rectifying equipment for high power DC supply is quite costly and thus was not considered further. Two options are available: heating of directly earthed or insulated shield wires. Possibilities for directly earthed shield wires are limited to short sections, e.g., two spans (one on each side of a tower), as the heating section is short-circuited at the adjacent towers. Thus, this alternative is not a promising option.

To achieve heating of shield wires in several spans, they must be insulated or at least sectionalized, and this is considered a promising option for further investigation. Considering the insulation level of a single cap and pin insulator, the operating voltage for the heating system of can be up to 20 kV. Further, by the estimated impedance of the shield wire circuit and the required heating power (160 kW/km), the maximum length of a heating section is estimated as 20 km. This is considered acceptable for practical applications, taking into account that shorter sections would be most probably of interest. However, the cost for the modification of the sections of existing OHL of interest might be high and the insulation could require long time. This should be compared with other options, e.g. the option to re-locate severe ice-affected sections from the mountains/hills into the valleys. Implementation at new OHL might require modified tower design.

Finally, two options, i.e., re-distribution of current between the sub-conductors in the same bundle for phase conductors, and heating of insulated shield wires by AC current, were selected for further case studies based on practical considerations. The feasibility study utilized time series of historical weather data for representing the conditions along the line routes, and corresponding time series of current loading. This allowed for making the feasibility study as representative as possible.

SELECTION OF OHL AND DATA FOR FEASIBILITY STUDY

Data on selected OHLs

The study comprised two of Statnett's 400 kV lines in the western part of Norway which are routed through areas prone to icing and with recorded severe ice loads. The lines are designated as OHL-1 and OHL-2. OHL-1 is 29 km long and is directed from North to South, while OHL-2 is 93 km long and is directed from East to West. The routes of the two lines are schematically illustrated in Figure 2. Black dots indicate locations for which detailed weather data have been obtained.

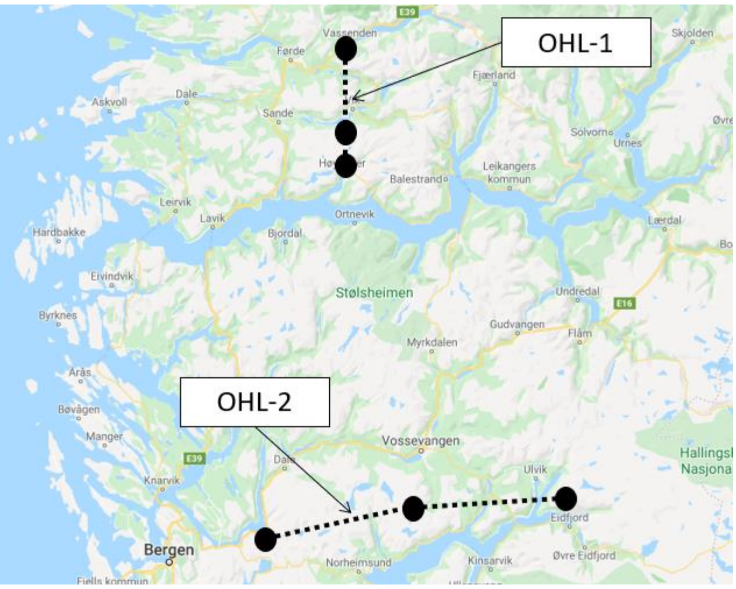

Figure 2 Approximate routes of OHL-1 and OHL-2. Black dots indicate locations for which detailed weather data have been obtained.

Data on conductors and shield wires

Both lines are equipped with twin ACSR Parrot special phase conductors (further called Parrot). Major characteristics of these conductors are presented in Table 1. A potential option for improvement of ice-melting capacity could be to replace the existing Parrot conductors by the ASCR Condor type (further called Condor), which has almost twice as high resistance, thus, major parameters for Condor are also given in Table 1. However, such high losses will create significant limitations on thermal ratings of conventional conductor types during summer months and the increase in resistance will double the energy losses. To evaluate the possibilities for further improvement, a conductor with even higher resistance is needed. The potential gain from application of a high-temperature low-sag (HTLS) conductor was therefore explored. Since conductors are usually designed to minimize the power losses, the study was based on a fictive conductor design based on Nexans ACPR LO-SAG 850/87, with a carbon fibre composite core and a maximum operating temperature of 150°C using data available from Nexans website. By utilizing the largest standard core diameter (12.5 mm), in combination with only one layer of aluminium strands, one would obtain a conductor with characteristics according to Table 1. The parameters of the two types of shield wires used on these OHLs are presented in Table 2.

Table 1. Characteristics of phase conductors investigated in the feasibility study

Parameter	Parrot	Condor	HTLS conductor
Diameter (mm)	38.3	27.8	20.7
Area of aluminium (mm^2)	766	402	192
Area of steel core (mm^2)	97	52	
Total area (mm^2)	863	454	
DC resistance (Ω/km)	0.038	0.072	0.148

Table 2. Characteristics of shield wires investigated in the feasibility study

Parameter	Sveid (StAl310), OHL-1	Trima, OHL-2
AC resistance (Ω/km)	0.26	0.17
Reactance (Ω/km)	0.45	0.44

First weather data set

Two sets of weather data were used for the feasibility study. The first comprised historical weather data representing the conditions along the line routes for a 4-6 years period, as obtained from the openly available UERRA dataset [9] with a spatial resolution of 5.5 x 5.5 km. Extracted weather parameters are available four times per day representing: ambient temperature at 2 m height above the surface, wind speed and direction at 10 m height above the surface, and the daily precipitation. Three locations along each line were selected for the study, i.e., the two line ends and one location at high altitude (designated in Table 3 as "Ice area"), i.e. typically characterized by higher wind speeds and lower temperatures. Selected locations are illustrated in Figure 2 by black dots. The weather parameters are summarised in Table 3.

Table 3. Weather parameters along the selected OHLs for a 4-6 years period

Name of parameter	OHL-1			OHL-2		
	End-1	Ice area	End-2	End-1	Ice area	End-2
Average ambient temperature (°C)	4.9	4.6	6.5	4.5	2.5	7.2
Min. temperature (°C)	-15.9	-11.5	-10.4	-15.9	-23.7	-14.5
Max. temperature (°C)	26.8	26.4	26.6	29.0	25.8	30.3
Average wind speed (m/s)	2.9	6.2	2.6	2.7	6.0	2.7
Max. wind speed (m/s)	12.8	24.5	11.4	11.1	25.1	11.6
Average wind direction, >1m/s (deg.)	166	187	169	181	194	171
Average yearly precipitation (mm)	2522	2473	2180	1206	2902	3069
Time with temp. <0 °C (h)	8022	7998	4002	14496	20094	5784
Part of time with temp. <0 °C (%)	23	23	11	28	38	11

Second weather data set

The second weather data set comprised more detailed weather data, including theoretical estimates for expected icing intensity. Time series of weather parameters at two locations, corresponding approximately to the ice areas in Table 3, were retrieved from the hindcast data provided by Kjeller Vindteknikk (KVT), a partner of the "Icebox" project. This data corresponded to hourly values of wind speed, wind direction, and air temperature during a period of 40 years (1980-2020). Together with weather data, KVT provided estimates of icing intensity (kg/m/h) on a standard vertical measuring cylinder at a temporal resolution of 1 hour. The icing intensity data is presented in Table 4. From the estimate of ice accretion on the vertical cylinder, it is possible to derive the weather parameters that are typical for ice accretion on the lines of interest, as illustrated in Figure 3:

- Icing can be expected at ambient temperatures above -10 °C, and more typically at temperatures above -5 °C.
- Icing can be expected at any wind speed, but the majority of icing events occurs below 20-25 m/s.

It is clearly seen from Figure 3 that a major part of the ice can be prevented if the conductor temperature can be maintained above freezing temperature during such conditions, i.e., ambient temperature > -5 °C and wind speed < 20 m/s. Keeping the conductor above 0 °C became the main criterion for the evaluation of effectiveness of ice prevention. The estimation of ice accretion on the conductors is conservative since possible ice shedding is not considered.

Table 4. Estimated icing on vertical cylinder for 40-year period (1980-2020)

Parameter	Ice area OHL-1	Ice area OHL-2
Number of icing hours (h)	20064	26800
Average icing intensity (kg/m/h)	0.016	0.031
Maximum icing intensity (kg/m/h)	0.226	0.215
Total icing during 40-year period (kg/m)	323	819
Average total yearly icing (kg/m)	8.1	20.5

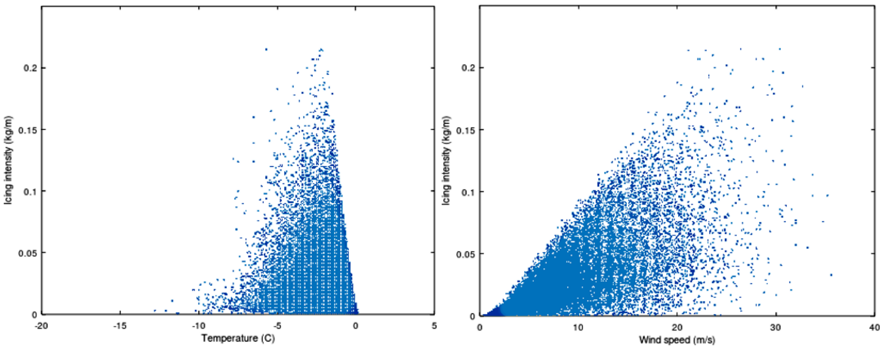

Figure 3. Icing intensity at ice area of OHL-1 as a function of temperature and wind speed. Data correspond to a period of 40 years (1980-2020).

Historical current loading

Historical data representing the power transferred on the selected OHLs were provided by Statnett. Data were obtained in the form of time series corresponding to hourly readings of active and reactive power covering periods of 4-6 years. Corresponding time series of current loading were calculated assuming a service voltage of 415 kV, see an example for OHL-2 in Figure 4. Average and maximum currents are summarised in Table 5. Considering all periods when the lines were in operation, the average values of load current are 210-220 A for both lines. The average load current during freezing ambient temperature is 210-270 A.

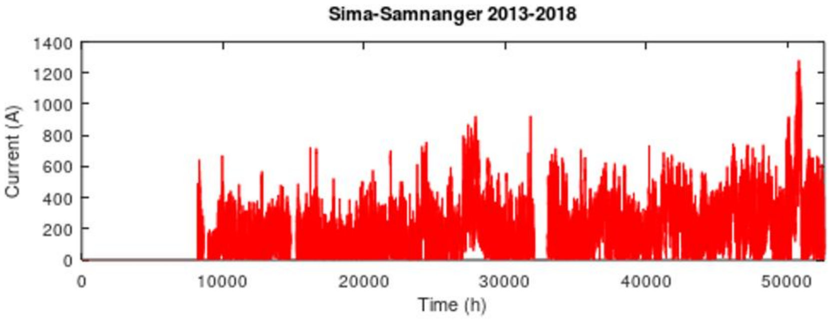

Figure 4 Historical current levels of OHL-2 for a 6 years period.

Table 5. Historical current loading during selected time periods

Parameters	OHL-1	OHL-2
Period of data collection	2015-2018	2013-2018
Average load current (A) with the line in or out of operation	157	165
Average load current, line in operation (A)	217	208
Maximum current (A)	1120	1282
Average current in operation and ambient temp. <0 °C *	242/250/272	213/213/236

* Values corresponded to temperatures at the three positions along the line route shown in Table 3

FEASIBILITY STUDY FOR PHASE CONDUCTORS

Conductor temperatures were estimated by the I-line software [10], [11] developed for the estimation of thermal current rating of OHLs according to CIGRE TB [12], using a set of weather parameters and the permitted maximum conductor temperature. The program was utilized to calculate the level of current required to maintain the conductor temperature at 0 °C, i.e., the minimum temperature to prevent ice accretion under freezing ambient temperature conditions. For such estimations, the wind direction was conservatively assumed to be perpendicular to the conductor, and heating by solar irradiation was neglected. Estimations were carried out for both the phase conductors and the shield wires.

Step 1: Using first weather UERRA-based dataset

The average percentage of time with the conductor temperature above 0 °C is summarized in Table 6 for different phase conductor configurations. Calculated values are based on time periods when the studied OHLs have been in operation. It is considered that due to low loading of the OHLs (see Table 5), the efficiency of heating by load current is relatively low (20-30 %). Only for the single HTLS conductor, with maximized utilization of current heating, this method shows promising results (50 % efficiency).

Table 6. Summary of effect of load current on conductor temperature

Type of conductor	Average percentage of time with conductor temperature ≥0 °C (%)
Twin Parrot	7
Single Parrot	19
Twin Condor	12
Single Condor	33
Triple HTLS	13
Single HTLS	49

Step 2: Using second detailed weather dataset

Detailed weather data for the iced areas of the two OHLs were utilized to estimate the power needed to prevent ice accretion on the HTLS conductor for a given percentage of the time in icing conditions, i.e., the heating power required to melt the mass of ice expected to accrete every hour. By integrating the icing intensity, the amount of ice expected to be prevented by a certain available power could be estimated, and the results are summarized in Table 7. As seen, a power loss of approximately 30 kW/km is required to prevent 90% of the ice accreted on a single HTLS conductor. This power loss corresponds to a load current in the order of 500 A, i.e., more than twice the average load current of any of two lines. The thermal capacity of the OHL allows for such currents, but the actual load currents are too low to heat the conductors sufficiently. Considering actual average load currents of 200-250 A, it is estimated that 21-35% and 15-26% of expected ice accretion may be prevented for OHL-1 and OHL-2, respectively.

Table 7. Power and current required to prevent ice accretion on a single HLTS conductor. Estimated from expected icing events in the period 1980-2020.

Percentage of prevented ice accretion	Required power for iced areas (kW/km)		Required current for iced areas (A)	
	OHL-1	OHL-2	OHL-1	OHL-2
10%	3	4	146	174
30%	7	9	232	267
50%	12	15	301	332
70%	16	21	350	400
90%	27	32	452	495
99%	42	51	562	619

Step 3: Combination with additional countermeasure

The result presented in Step 1 and Step 2 showed that the current is too low to provide the desired ice removal in practical cases, which requires consideration of additional measures for increasing the heating current. It is well known internationally [4] that higher current levels may be obtained by applying an intentional three-phase short circuit to the line, the so called SC technology. The SC currents will depend on the voltage level and the impedance of the feeding network, the OHL characteristics, and the distance from the substations supplying the power. The feasibility of Statnett using this methodology was first evaluated for an actual 400 kV line equipped with twin Parrot conductors in three different networks. The current resulting from an intentional short circuit at the remote end, 4000 A, would be comparable to maximum load currents, i.e., levels that could be maintained for periods of time long enough to remove the ice. However, in practice, the allowed maximum current is limited by equipment ratings and permissible impact on the voltage level at the feeding substation. Thus, conductor heating by short-circuiting at nominal voltage level is expected to be limited to rather long lines, (not necessarily providing sufficient power for de-icing of bundled conductors). Therefore, a combination of re-distribution of current between sub-conductors, and intentional SC at a lower voltage than nominal, was evaluated for a Condor twin conductor bundle. Calculations were performed for OHL-1 and OHL-2 assuming that the lines being energized at a reduced voltage level via a typical 420/132 kV transformer connected to a 400 kV substation (see example in Figure 5 left) with a short circuit current of 15 kA as shown in Figure 5. The acceptable voltage drop (10%) at the supplying 400 kV substation allows for line lengths down to approximately 30 km.

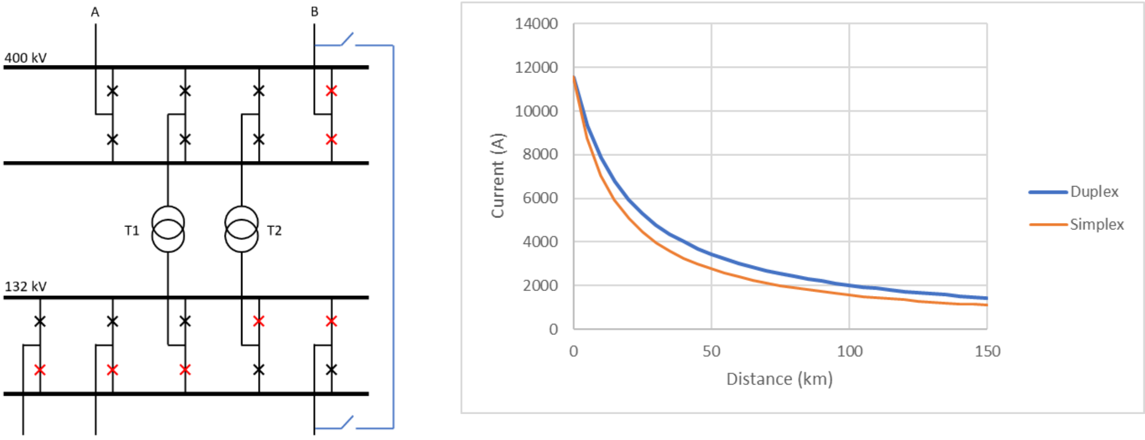

Figure 5 Left: Scheme for de-icing by feeding line B with a short circuit at the remote end at reduced voltage; breakers required to be open are marked by red colour. Right: Short circuit current levels at energization with 132 kV (phase-to-phase voltage).

For the shortest line, OHL-1 with a length of 29 km, resulting currents at reduced voltage are estimated as 4900 A, which is considered too high with respect to typical current ratings of equipment. A further reduction would require supply by an even lower voltage level, or introduction of additional impedance, e.g.by connecting a short-circuited transformer (420/132 kV) at the remote end of the line. This would result in currents of 1600 A (short circuit on 132 kV side) compared with 3700 A (short circuit on 420 kV side). Another option could be to arrange for an extension of the line length by connection of a second line in series with the one to be heated. For OHL-2 (93 km), the current resulting from short circuit at the remote end would be 2100 A when energized from 132 kV. Higher currents can be achieved by placing the short circuit closer to the sending end.

From the above it is clear that relevant current levels can be provided by application of short circuits to lines energized at a reduced voltage level. However, the equipment's current rating is crucial. Typical ratings are in the range of 2000-4000 A and will therefore not allow for sufficient heating of bundled conductors. A potential solution to the problem could be to combine short-circuiting with load transfer within the bundle, allowing for de-icing of one sub-conductor at the time.

FEASIBILITY STUDY FOR SHIELD WIRES

Step 1: Two strategies for ice prevention

Two strategies for ice prevention by current heating of shield wires were proposed: The heating could be applied temporarily to melt already accreted ice, this strategy is defined in this paper as de-icing. Another approach, defined as anti-icing, is to maintain the conductor temperature above 0 °C, thus avoiding any ice accretion. The power requirements for the different strategies depend mainly on ambient temperature, wind velocity, heat exchange involving wind and water droplets, and ice thickness (in the case of de-icing).

Step 2: Using first weather UERRA-based dataset

A) Anti-icing strategy

The power and corresponding energy required to maintain the temperature of the shield wires above 0 °C, i.e. in anti-icing mode, were estimated from available weather data [9] using the I-Line program. The typical ice accretion climatic conditions were the same as for for the phase conductors, i.e., ambient temperature > -5 °C and wind speed < 20 m/s. The results are presented in Table 8. Precipitation will also affect the power balance at the shield wires. During freezing conditions, ice and snow particles colliding with the shield wire may stick to it, and the accumulated mass need to be melted by the power losses. The associated energy may be conservatively estimated by assuming that all precipitation received by the shield wire during freezing conditions should be melted. Using actual precipitation data for OHL-1 and OHL-2, the annual energy was estimated as between 2.1 and 2.6 MWh/km, respectively.

Table 8. Power and energy required for anti-icing of the insulated shield wires on OHL-1 and OHL-2 during 2015-2018.

Parameters	OHL-1 (Trima)	OHL-2 (Sveid)
Average power (kW/km)	2.6	2.9
Maximum power (kW/km)	101	54
Energy (MWh/km/year)	23	25

B) De-icing strategy

To evaluate the feasibility of de-icing, a criterium is needed for starting the heating. A simple strategy can be driven by the maximum icing intensity and a critical ice load. The idea is to assume conservatively that high icing intensity occurs every day. Using this assumption, it is possible to calculate the number of days until a critical ice load is reached, i.e., the load which the OHL was dimensioned for. De-icing of the shield wires is then performed regularly to keep the ice load below the design load. The maximum icing intensity was derived from Table 4, i.e., roughly 0,22 kg/m/h for both OHLs, which were originally dimensioned for ice loads of 25 kg/m. From these data, de-icing shall be made every 5th day during the winter season. The required heating power and energy were estimated by assuming that de-icing is made every 5th day and that the average ambient temperature during the last five days was below 0 °C. At each de-icing event, lasting 3 hours and intended to melt 25 kg/m of accreted ice, a required de-icing current is calculated for ambient temperatures and wind conditions obtained from the UERRA weather dataset. The power and energy required for de-icing during the years 2013-2018 are presented in Table 9.

Table 9. Power and energy required for de-icing of the insulated shield wires on OHL-1 and OHL-2 during 2013-2018 every 5th day during the winter season

Parameters	OHL-1 (Trima)	OHL-2 (Sveid)
Average power (kW/km)	104	117
Maximum power (kW/km)	268	348
Energy (MWh/km/year)	3.4	8

Comparing the two strategies illustrated in Table 8 and Table 9, anti-icing will lead to higher energy consumption and costs for the heating, while the required power is significantly less compared with de-icing.

An additional benefit of using insulated shield wires is the reduction of OHL losses in normal operation. Using historical current loadings (see example in Figure 4) and actual conductor data provided by Statnett, calculations were performed using the Tower/Pole Earthing (TPE) software [11]. This is a specialized tool for calculating currents and voltages in OHLs and external structures during normal operation or during fault events, as well as the potential distribution in the soil during a fault. The average annual reduction of losses by insulating the shield wires on OHL-1 and OHL-2 was estimated as 660 kWh/km and 1540 kWh/km, respectively, for the period 2015-2018.

CONCLUSIONS

This feasibility study, intended to find the most promising anti-icing and de-icing technologies for Statnett, was for phase conductors focused on re-distribution of the current between the sub-conductors in the bundle. Unfortunately, this concept requires that the line has a sufficiently high loading current to be effective. Using historical current loading levels, the re-distribution of load current between sub-conductors is not a promising solution on its own, as shown by the detailed case study. However, a potentially promising solution would be to combine this concept with an increased phase conductor current obtained by intentional short circuiting of the line at the remote end, possibly via a transformer.

For shield wires, heating by AC current is considered a practical proposal, although requiring insulation of the shield wires. Using insulated shield wires, both de-icing and anti-icing methodologies are possible alternatives. Anti-icing will lead to higher energy consumption and costs for heating, while the required power is significantly less compared to de-icing. Based on preliminary economic estimations, both heating strategies are economically competitive, but de-icing is more promising, especially if the cost for equipment and material can be optimized.

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