Using Dielectric Losses to De-Ice Power Transmission Lines with 100 kHz High-Voltage Excitation

J. D. McCurdy
C. R. Sullivan
V. F. Petrenko

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Joshua D. McCurdy, Charles R. Sullivan and Victor F. Petrenko

Thayer School of Engineering

Dartmouth College

Hanover NH 03755

Abstract—**Icing of power transmission lines during winter storms is a persistent problem, causing outages and costing millions of dollars in repair expenses. Excitation at approximately 33 kV 100 kHz can be used melt ice off of power transmission lines through dielectric losses in the ice itself. Standing wave effects result in non-uniform heating if dielectric losses are used alone, but the combined effect of dielectric loss and skin-effect resistive loss can be tuned to provide uniform heating. A single high-voltage source may be used to de-ice sections of line up to 100 km long before attenuation impacts efficiency excessively. A prototype system capable of exciting a 1 m test line to 30 kV has been tested and show to be capable of removing a 7 mm ice layer from the line.**

I. Introduction

Icing of power transmission lines during winter storms is a persistent problem, causing outages and costing millions of dollars in repair expenses. High-frequency excitation at approximately 60 kHz to 100 kHz has been proposed as a method to melt ice. The method works by a combination of two mechanisms: At these frequencies, ice is a lossy dielectric, causing heating directly in the ice. In addition, skin effect causes current to flow only in a thin layer on the surface of the line, causing resistive losses and consequent heating.

We have developed a prototype system for applying 33 kV 100 kHz power to a 1 m line (an aluminum bar). In this paper we describe the design of this system, experimental tests of de-icing using it, and also discuss higher-power systems that would be deployed for deicing lines up to 100 km long.
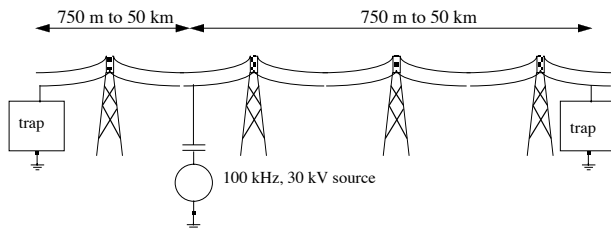
The overall system is illustrated in Fig. 1 It could be deployed in two different ways. For lines with chronic icing problems, or where icing is likely and high reliability is desired, the system could be permanently installed connected to a section of line, with traps at either end of the section to confine the excitation to a controlled region. Alternatively, it could be mounted in trucks that could be dispatched in an emergency to "rescue" a section of line from icing. A set of three trucks could carry a source and two traps.

II. Principle of Ice dielectric heating

With ice modeled as a lossy dielectric, the equivalent circuit for a short section of transmission line coated with ice is as shown in Fig. 2. The component values for R_{ice} and C_{ice} may be calculated from models of the electrical properties of ice given in [1]. For frequencies as low as 8 kHz, the dielectric properties become sufficiently lossy to generate significant heating. As frequency increases, the voltage needed to produce adequate loss drops. A preferred range of operation is around 100 kHz, as is detailed in the next section.
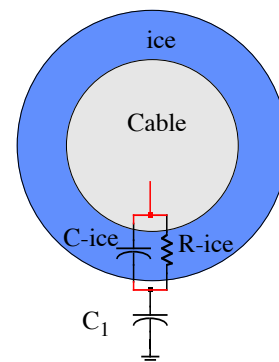

Fig. 1. Deicing of power lines by applying high-frequency high-voltage.

Fig. 2. Equivalent circuit for ice-coated transmission line.

III. ACHIEVING UNIFORM HEATING

Exciting a transmission line with high frequency power will produce standing waves, unless the line is terminated with a matched impedance at the far end. With standing waves, either ice dielectric heating, or skin effect resistive heating would, acting alone, result in uneven heating.

A possible solution to this problem is to terminate the line, producing running waves rather than standing waves. However, the running waves entail energy flow that is typically much larger than the energy dissipation in the ice. This energy must be processed by the power source at one end and absorbed by the termination at the other end. Thus, the power capability of the power source must be increased well beyond the power required for heating. The termination must be capable of dissipating or recycling this power as well. Thus, this is an expensive solution, both in terms of the cost of the equipment and, if it is not recycled, the cost of the energy dissipated in the termination.

A better solution is to use standing waves which apply the two heating effects in a complementary fashion. The ice dielectric heating occurs most strongly at the voltage antinodes in the standing wave pattern, whereas the the skin-effect heating occurs most strongly at the current antinodes. Thus, the two are complementary, and, if the magnitudes are in the proper ratio, the total heating can be made uniform over the length of the line. At 60-100 kHz, we estimate that 33 kV is sufficient to produce 50 W/m of heating in a 1 cm layer of ice. Because of the skin effect (skin depth in aluminum at 100 kHz is about 0.3 mm), moderate currents (on the order of 200 A) can achieve sufficient heating of about 50 W/m in a 25 mm diameter aluminum cable, so it is possible to have similar magnitudes for both effects.

Fig. 3 shows the combined heating effect of a standing wave in a one-wavelength-long section of transmission line. The complementary nature of the two heating effects can be seen– the peaks in dielectric heating correspond to valleys in resistive heating. For this example, based on estimated parameters at 60 kHz, the total heating still has significant ripple. Although this may be acceptable, it requires a higher total input power for a given minimum heating power density along the line. Adjusting the frequency affects both the dielectric loss in ice and the skin-effect loss in the conductor, and so it is typically possible to tune the frequency for uniform heating along the line. Fig. 4 shows the heating power along a one-wavelength-long section of line, assuming these effects are approximately equal at 100 kHz.

Fig. 5 shows the heating power along a 50 km line. Here one may see the cancellation of ripple discussed above, and attenuation along the length of the line. It is possible to drive a 100 km line from the center in the same manner. Over a dis-
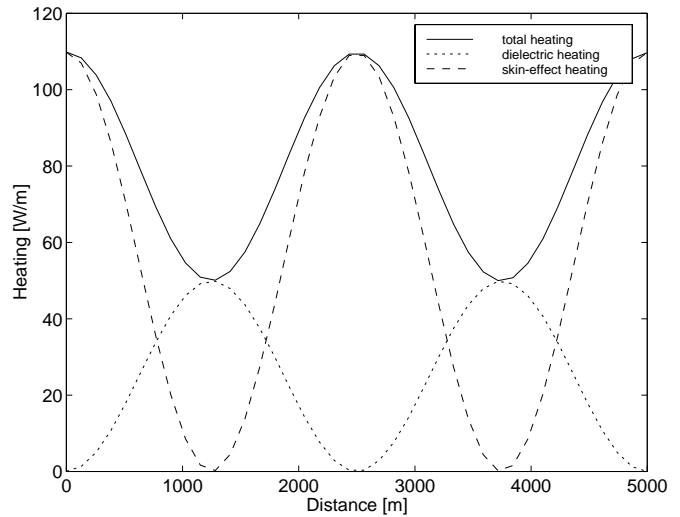

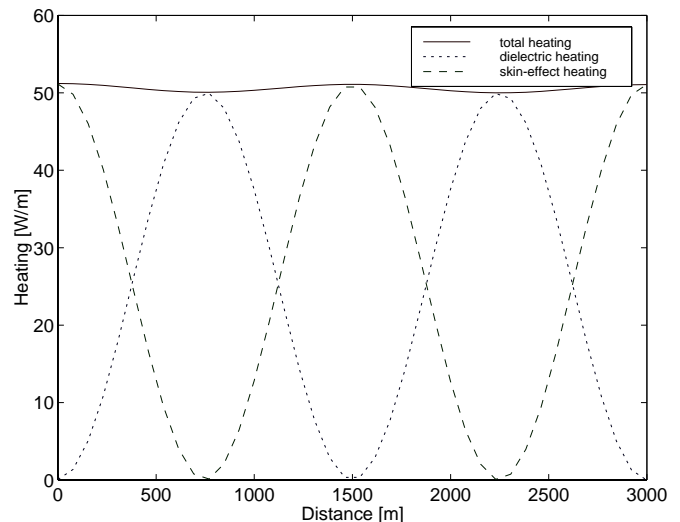Fig. 3. Combined ice dielectric and skin-effect heating at 60 kHz.

Fig. 4. Combined ice dielectric and skin-effect heating at 100 kHz, where we estimate the two effects are optimally balanced.

tance of 50 km, the attenuation results in about half the heating power at the far end. This requires that the input voltage be augmented, but the total input power is only increased by about 30% compared to the power required to heat the entire line to the same minimum level everywhere. Longer lengths are possible with lower efficiency. For example, driving a 200 km line from the center results in about half the efficiency, and so requires a power source four times the size of one to drive a 100 km line. Where it is necessary, a smaller high-frequency power source can be used to protect a shorter length, such as a short segment through a mountain pass, or even a single cable span between two towers.
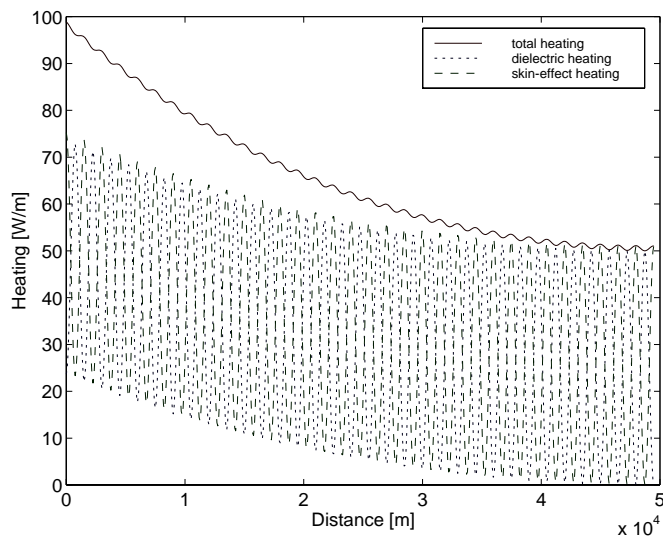
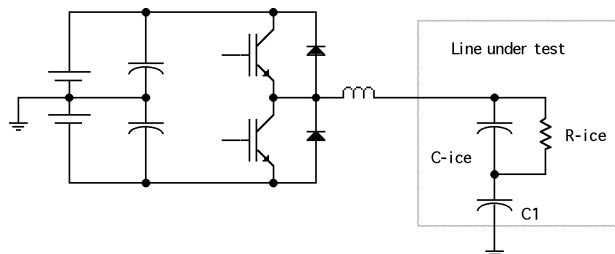Fig. 5.   Combined ice dielectric and skin-effect over a 50 km line.
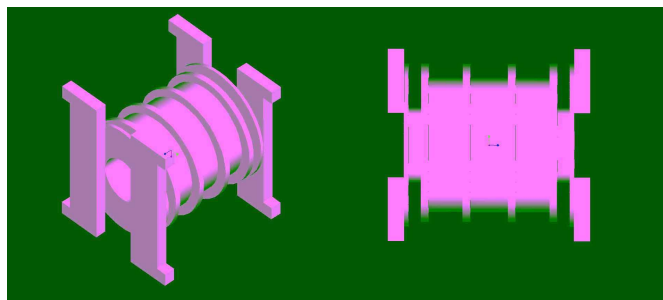

Fig. 6.   Schematic diagram of prototype inverter.

Fig. 7.   Two views of a bobbin for optimized-shape winding, for an EC70 ferrite core. Overall length is about 70 mm.

IV. POWER SOURCE DESIGN

Both the small-scale prototype and the full-scale system use soft-switching resonant inverters in which the most significant challenges and innovations are in the resonant inductors. Because the dielectric loss in the ice is small compared to the overall capacitive VA, the power source sees a very low power factor capacitive load. For the prototype system, which must supply only about 50 W of real power to melt the ice on a one-meter line, the reactive power is 16.5 kVA. Thus, the power factor is only 0.3%. A very high Q resonant inductor is needed if the system is to have even moderate efficiency. Litz wire windings with optimized shapes [2], [3] are used to construct this critical component.

A. Prototype inverter

The prototype inverter is designed to excite a one-meter length of 25 mm diameter line to 33 kV with 50 W of dielectric loss in the ice. The line, suspended in the test configuration in a refrigerated room, has a measured capacitance of 27 pF, and thus requires approximately 0.5 A at 33 kV, 100 kHz. A series resonant inverter for this application is shown in Fig. 6. The circuit has several important advantages for this application. Zero voltage switching allows the use of IGBTs at 100 kHz. MOSFETs could be used for the prototype, but for the full scale inverter, they would be prohibitively expensive. Also, most of the circuit operates at low voltage—under 1000 volts. The only high voltage node is the node between the inductor and the line; thus the only circuit component that sees the high voltage is the inductor, and most of the circuit can be constructed without special attention to high-voltage

insulation.

The inductor required is 93.8 mH. We originally targeted loss in it equal to the 50 W loss in the ice. Achieving this low loss in an inductor with large high-frequency ac current requires careful attention to the ac resistance of the winding, which can be negatively impacted by the gap fringing field. A distributed or quasi-distributed gap is one possible solution to these problems [4], [5], [6], [7]. However, in [2] it is shown that an optimized winding shape can lead to even lower losses than would be obtained with an ideal distributed gap, without the added expense of multiple gaps. We applied the method in [2] and derived an optimized design that could meet the specification, using five inductors in series, each wound with litz wire with AWG 48 strands. Multiple inductors in series were used because of the availability of appropriate core sizes, and because it allows reducing the voltage across each inductor in order to simplify insulation issues and avoid problems with parasitic capacitance. To construct the optimized-shape winding, custom bobbins (Fig. 7) were fabricated with a fusion-deposition-molding rapid-prototyping machine. The inductors are submerged in dielectric oil to avoid corona problems in high voltage operation.

The design actually built (Fig. 8), however, was modified to use 75-strand litz wire with AWG 46 strands that was available from stock, in order to avoid a longer wait for the lower-loss AWG 48 litz wire. The design built is summarized in Table I.
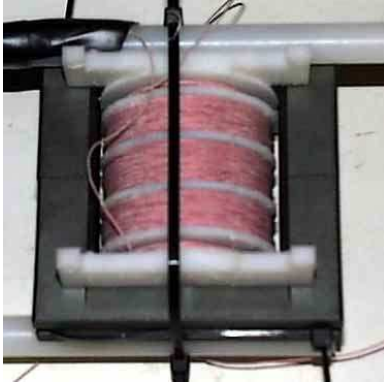
Fig. 8. One of five inductors used in series for the prototype system.

The losses in the inductor are small enough to be difficult to measure; the most precise measurement of this is testing in the actual resonant circuit configuration with no ice so that dielectric losses are negligible. With the inductors connected to the 1 m test line to form a resonant circuit with the capacitance of the line, the input impedance of the network is real at resonance, corresponding the to ESR of the inductors. This resistance was 194 Ω in a small-signal measurement, which corresponds to loss very near the original loss target, although in full-power operation losses will be higher because of the nonlinear nature of the core loss.

TABLE I

INDUCTOR DESIGN

Inductor construction	
Core	EC70 geometry, Philips 3C85 ferrite, center gap
Turns	375
Wire	75 strand litz, AWG 46 strands
Bobbin	Custom optimized shape
Inductance	18.76 mH each $\times$ 5 = 93.8 mH total

B. Full-Scale Inverter

With a 50 km (30 mile) line, transmission line calculations indicate that, if the line is driven in resonance, it would present a purely real input impedance of about 55 or 180 ohms, depending upon whether a "series" or "parallel" resonance is chosen. The input power, for heating at 50 W/m at the far end (more at the near end), would be 3.25 MW. For a three-phase transmission line, a single power source could be used by switching it successively to different phases to remove ice from each.

An inverter for this power level could be largely a scaled up version of the prototype inverter. One important design issue would again be the resonant inductor design. However, because of the resonance of the line, the power factor can be much lower. If we design the inverter's resonant tank for a

Fig. 9. Experimental test of de-icing a 1 m line. The suspended bar, 1 m long and 25.4 mm in diameter, was coated with 7 mm of ice for the test. The large-diameter white cylinder on the right contains the resonant inductors submerged in oil.

loaded Q of five, the per-unit reactive power handled by the inductor is a factor of 50 lower than it is in our prototype system, making the inductor requirements much less severe. Thermal considerations will still require a careful design that minimizes loss.

V. EXPERIMENTAL TESTING OF DEICING

The deicing capability of the prototype system was tested with 7 mm of ice on the bar a 1 m bar. The setup is shown in Fig. 9. The input impedance of the system with ice applied was 850 Ω. About 550 Ω of this represents loss in the ice, while about 200 Ω of it corresponds to the loss in the inductors. The input power was gradually increased by adjusting the drive frequency closer to the resonant frequency. About 25 minutes after the ice power dissipation was increased to about 5 W, with 5 kV rms on the line, the ice started to melt and drip. The power was continually increased, with the melting rate also increasing. Two hours later, with about 17 W in the ice, and about 11.6 kV rms on the line, chunks of ice started to fall off of the line.

Faster melting would be possible at higher power levels, that were not reached in this initial test. However, problems with voltage breakdown in the inductors have delayed testing at these higher power levels. The voltage breakdown is attributed to poor wire routing in the windings, and we expect new, better-constructed windings to solve this problem.

VI. ADDITIONAL CONSIDERATIONS

A. *EMI*

The electromagnetic radiation from a long line excited at 100 kHz has the potential to cause interference with radio communications systems, and emissions in this frequency range are regulated in many countries. In an emergency situation where loss of power to a large area was a possible consequence, deicing operations may be more important than possible interference. If EMI remains a concern, it is possible to effect deicing at lower frequencies. For example, 8 kHz is below the range of regulated frequencies in the US. Unfortunately, this is far from the frequency range where skin-effect and ice-dielectric heating can be easily balanced for uniform heating. But skin effect heating alone can be effective. The non-uniform heating produced by standing waves could be mitigated by changing the standing waves by shifting the excitation pattern by one-quarter wavelength, or by sweeping frequencies.

In any case, very careful filtering is necessary to prevent harmonics from exciting the line and radiating interference at higher frequencies.

B. *Deicing Shield Wires*

Shield (ground) wires are also a concern for icing. Although direct high-voltage excitation of these wires is not possible, excitation of the phase conductors will result in current in the ground wires and electric field on their surface. Although this indirect excitation is not as strong as direct excitation would be, the smaller diameter of the wire increases both heating effects. The electric field strength is higher near a surface with a smaller raidus of curvature, and the high-frequency resistance is inversely proportional to the wire's circumference. It is not possible to make a general conclusion about the relative magnitude of deicing on shield wires, as it depends on the particular transmission line geometry.

C. *Corona*

Adding high-frequency high-voltage to a line will increase corona effects. To first order, this is not a problem, because the corona would increase the heating effect and melt the ice faster. However, the larger diameter where icing is most severe would decrease the amount of corona. It is possible that the corona in regions of little icing would attenuate the high-frequency waves propagating on the transmission line and inhibit power from reaching and effectively deicing where there is thicker ice.

VII. CONCLUSION

The application of 100 kHz electric fields to melting ice on power transmission lines appears promising. Combined dielectric heating and skin-effect heating can be used to achieve uniform heating despite standing-wave patterns. For both small-scale prototypes and for full scale systems, the critical component is the resonant inductor. Winding shape optimization techniques allow achieving low loss in this component despite the high ac current in it. Tests on a 1 m line demonstrated effective deicing, even with relatively low power applied.

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