Breaking the ice: de-icing power transmission lines with high-frequency, high-voltage excitation

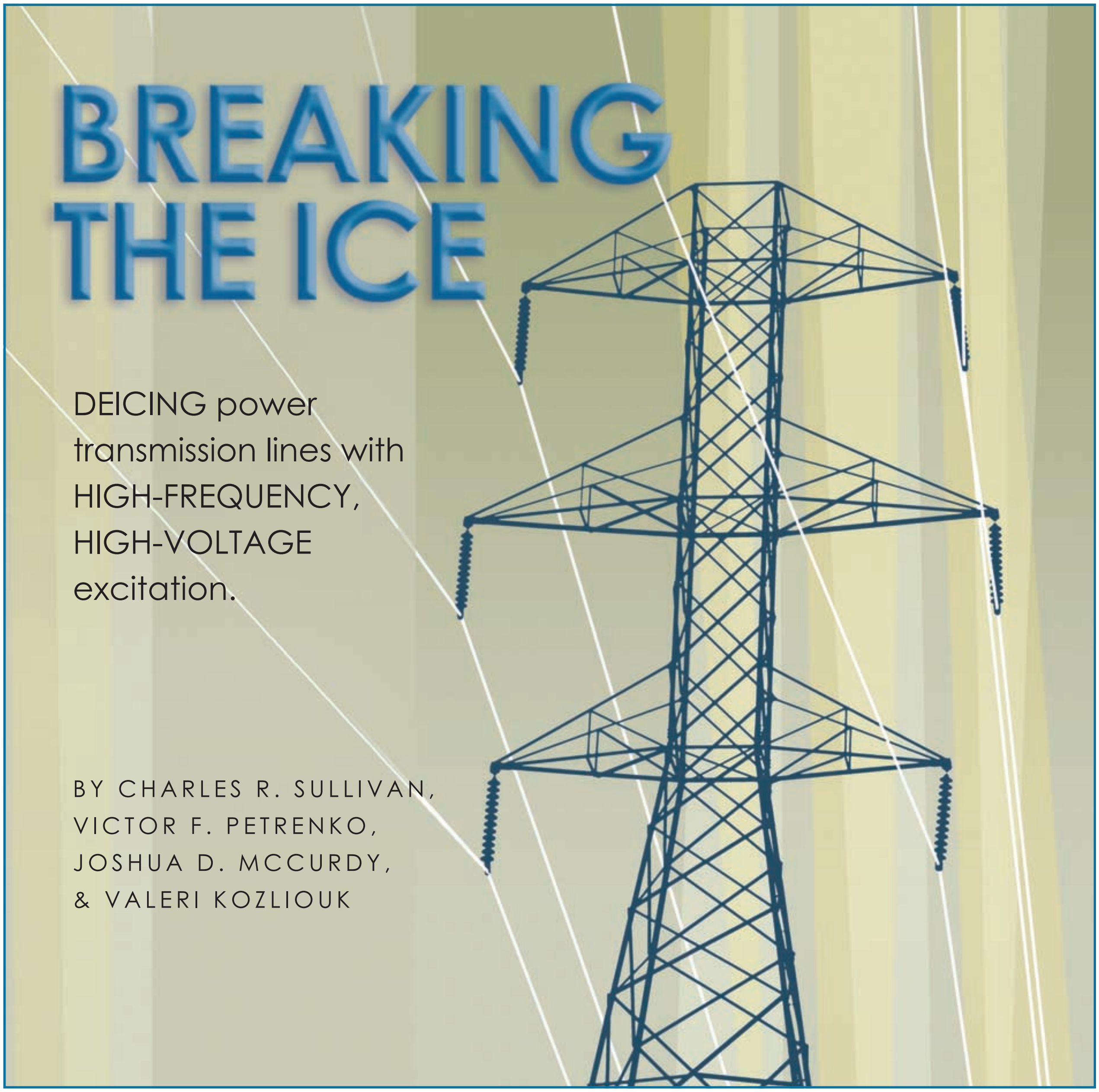
Sullivan, C. R.
Petrenko, V. F.
McCurdy, J. D.
V. Kozliouk

From *IEEE Industry Applications Magazine,* vol. 9, no. 5, pp. 49–54.

BREAKING THE ICE

DEICING power transmission lines with HIGH-FREQUENCY, HIGH-VOLTAGE excitation.

BY CHARLES R. SULLIVAN,
VICTOR F. PETRENKO,
JOSHUA D. MCCURDY,
& VALERI KOZLIOUK



© ARTVILLE

ICING OF POWER TRANSMISSION lines during winter storms is a persistent problem that causes outages and costs millions of dollars in repair expenses. High-frequency excitation at approximately 8-200 kHz has been proposed as a method to melt ice [1], [2]. 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.

In this article, we describe the design of systems to implement this method on lines up to 1,000 km long. We also report experimental tests of deicing of a 1-m simulated line using dielectric losses in ice using a prototype system that applies 33-kV, 100-kHz power.

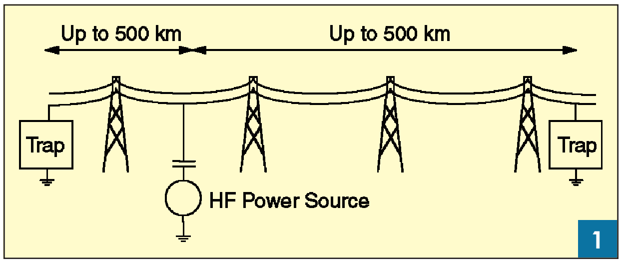
The overall system is illustrated in Figure 1. It could be deployed in two different ways. For lines with chronic icing problems, or where icing is likely, and high reliability is desired, the system could be permanently installed connected to a section of line, with traps at either end of the section to confine the excitation to a controlled region. Alternatively, it

1077-2618/03/$17.00©2003 IEEE

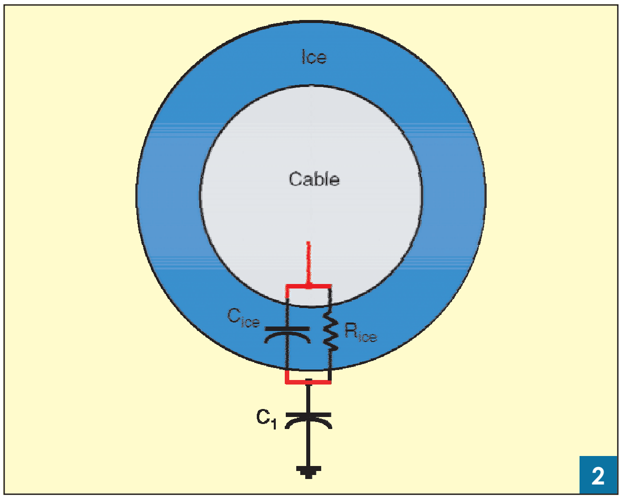
could be mounted in trucks that could be dispatched in an emergency to "rescue" a section of line from icing. A set of three trucks could carry a source and two traps.

Principle of Ice Dielectric Heating

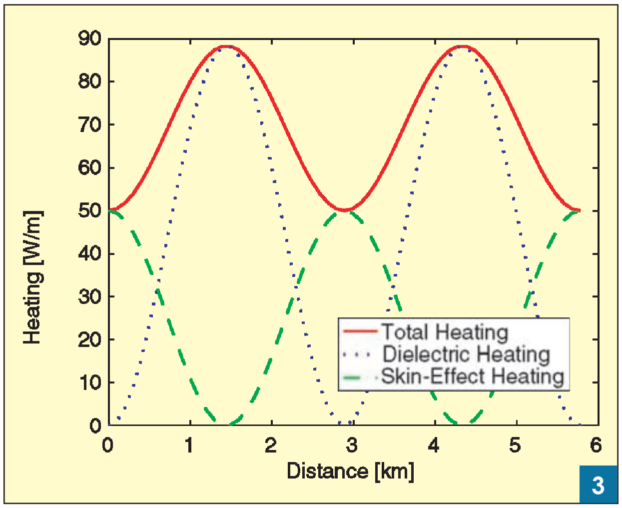
With ice modeled as a lossy dielectric material, the equivalent circuit for a short section of transmission line coated with ice is as shown in Figure 2. The component values for R_{ice} and C_{ice} may be calculated from models of the electrical properties of ice given in [3]. For frequencies as low as 12 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 often around 20-150 kHz, as is detailed in the next section, although lower frequencies can also be used in order to avoid regulated frequency ranges.



The deicing of power lines by applying high-frequency high voltage.



An equivalent circuit for an ice-coated transmission line.



Combined ice dielectric and skin-effect heating with 15-mm thick ice at 50 kHz. The rms voltage at the anitnodes is about 100-kV rms.

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, rather than standing, waves. However, 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 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 that apply the two heating effects in a complementary fashion. Ice-dielectric heating occurs most strongly at the voltage antinodes in the standing wave pattern, whereas 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.

The ratio of the two heating effects depends on many factors, including the type of conductors, their geometrical configuration, and the thickness of the ice. The examples below are based on a 230-kV, two-circuit transmission line configuration in which the conductor-to-conductor distance in one circuit is 6.3 m. The conductors are 35-mm diameter aluminum conductor steel reinforced (ACSR).

To obtain the necessary parameters to model this line, we performed two-dimensional, finite-element simulations. With one phase excited with high frequency and with other phase conductors, as well as the ground wires and the earth, acting as high-frequency ground, the capacitance is 8.06 pF/m, and the external inductance is 1.38 mH/m. The resistance can be easily calculated if the stranding is ignored and the conductor is modeled as an aluminum cylinder. To check this assumption, we measured the resistance of a 3-m section of conductor at 8 kHz. Tests with full-power excitation were included in order to detect any nonlinear losses in the steel core. However, the results did not reveal any significant nonlinearity. The measured 8-kHz resistance was about 10% higher than the calculated resistance for an ideal aluminum cylinder. For modeling loss at other frequencies, we use the calculated resistance of an aluminum cylinder, increased by the 10% experimental factor.

Figure 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 50-kHz excitation and a 15-mm thick ice layer, 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, so it is typically possible to tune the frequency for uniform heating along the line. Figure 4 shows the heating power at 33 kHz, where we calculate that the heating would be uniform with 15-mm ice. For 50 W of heating power per meter of line, the required 33-kHz voltage at the antinodes would be about 110-kV rms.

Figure 5 shows the heating power along a 300-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 600-km line from the center in the same manner. Over a distance of 300 km, the attenuation results in significantly lower heating power at the far end. This requires that the input voltage be augmented, but the total input power is only increased by about 18% 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 1,000-km line from the center results in about 55% higher power compared to what would be required if the heating was uniform. 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.

Power Source Design

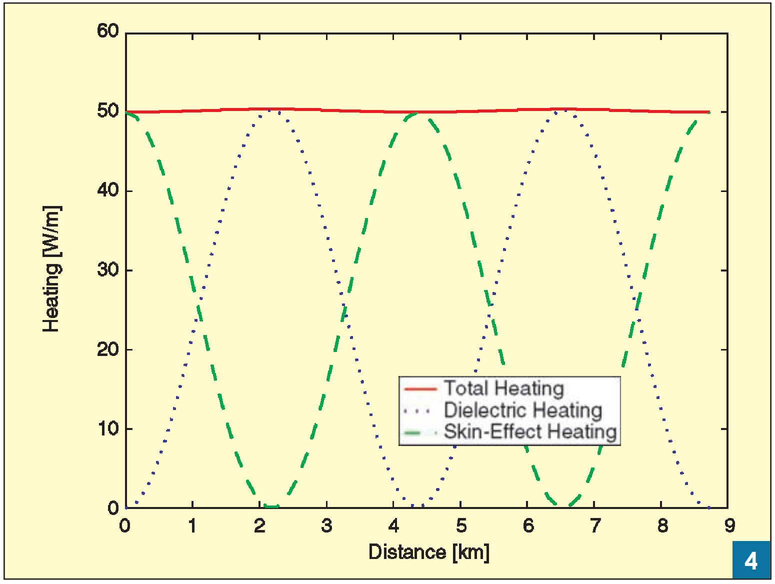
Both the small-scale prototype and the full-scale system use soft-switching resonant inverters in which the most significant challenges and innovations are in the resonant inductors. For the prototype system, the dielectric loss in the ice is small compared to the overall capacitive voltamperes such that the power source sees a very low power factor capacitive load. To melt ice on a 1-m line, the system must supply only about 50 W of real power, whereas 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 [4]-[7] are used to construct this critical component.

Prototype Inverter

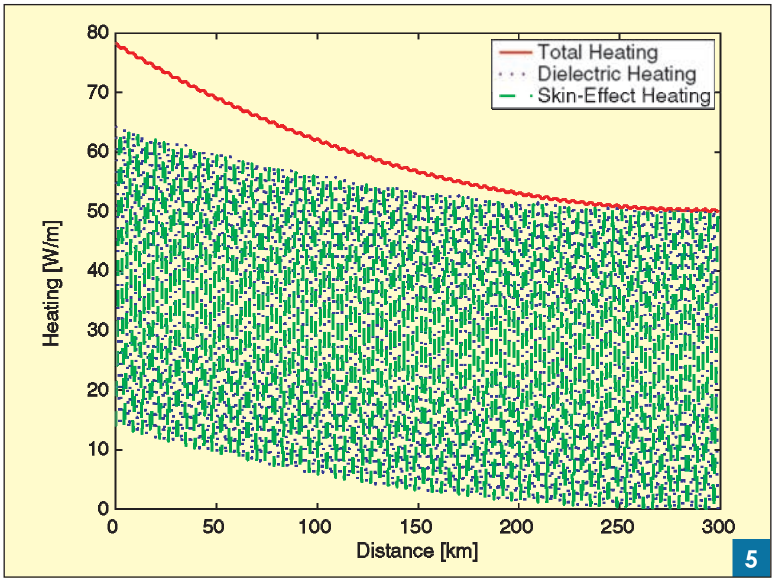
The prototype inverter is designed to excite a 1-m length of 25-mm diameter line to 33 kV with 50 W of dielectric loss in the ice. The line, suspended in the test configuration in a refrigerated room, has a measured capacitance of 27 pF, and, thus, requires approximately 0.5 A at 33 kV, 100 kHz. A series-resonant inverter for this application is shown in Figure 6. The circuit has several important advantages for this application. Zero-voltage switching allows the use of isulated gate bipolar transistors (IGBTs) at 100 kHz.

Metal-oxide-semiconductor field-effect transistors (MOSFETs) were used for the prototype, but for the full scale inverter they would be prohibitively expensive. Also,



4

Combined ice dielectric and skin-effect heating in 15-mm ice at 33 kHz, where we calculate that the two effects are balanced. The rms voltage at the anitnodes is about 110-kV rms.



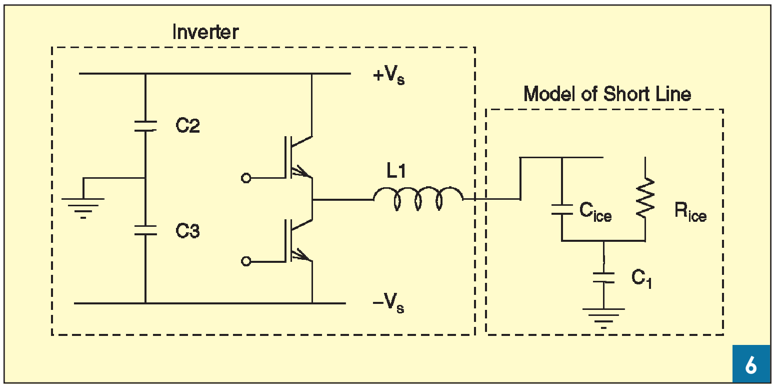
5

Combined ice dielectric and skin-effect over a 300-km line. Similar performance is possible, driving a 600-km line from the center.

most of the circuit operates at low voltage—under 1,000 V. 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.

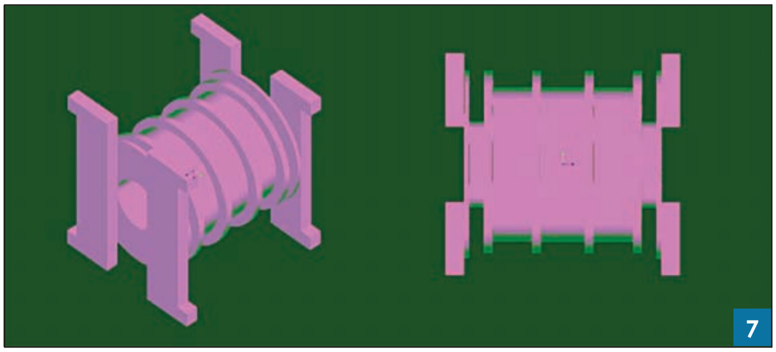
The inductance required is 93.8 mH. We originally targeted loss in it equal to the 50 W loss in the ice. Achieving this low loss in an inductor with large high-frequency ac current requires careful attention to the ac resistance of the winding, which can be negatively impacted by the gap fringing field. A distributed or quasidistributed gap is one possible solution to these problems [8]-[11]. However, in [4] 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 used inductors based on this approach to meet the specification with five inductors in series. 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 (Figure 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 (Figure 8 and Table 1) was modified to use litz wire that was available from stock rather than the optimal design. 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 the equivalent series resistance (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 loss in the inductor core.



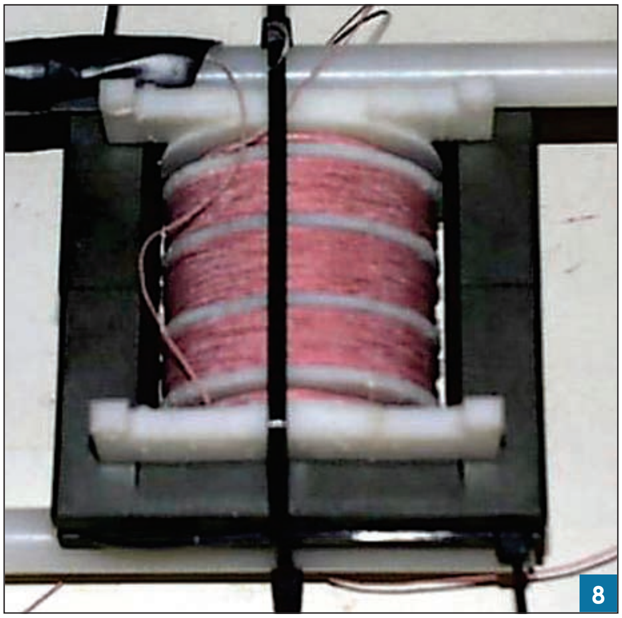
6

A schematic diagram of a prototype inverter.



7

Two views of a bobbin for optimized-shape winding and for an EC70 ferrite core. The overall length is about 70 mm.



8

One of five inductors used in series for the prototype system.

Full-Scale Inverter

With a 50-km line driven at 33 kHz with 15-mm ice, transmission line calculations indicate that, if the line is driven in resonance, it would present a purely real input impedance of about 34 Ω or 4.7 kΩ, depending upon whether a "series" or "parallel" resonance is chosen. The input power, for heating at 50 W/m at the far end of the

TABLE 1. INDUCTOR DESIGN.

Core	EC70 geometry, Phillips 3C85 ferrite, center gap
Turns	375
Wire	75 strand litz, AWG 46 strtands
Bobbin	Custom optimized shape
Inductance	18.76 mH each × 5 = 93.8 mH total

50-km line (slightly more at the near end), would be 2.53 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 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.

Experimental Testing of Deicing

The deicing capability of the prototype system was tested with 7 mm of ice on a 1-m bar. The setup is shown in Figure 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 min 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. Deicing through skin-effect heating has also been tested and confirmed to work as expected.

9

An experimental test of deicing a 1-m line. The suspended bar, 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.

Additional Considerations

Electromagnetic Inferferrence

The electromagnetic radiation from a long line excited at 30 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 electromagnetic interferrence (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 United States. Unfortunately, this is outside 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 nonuniform heating produced by standing waves could be mitigated by changing the standing waves by shifting the excitation pattern by one-quarter wavelength, by sweeping frequencies, or by exciting a length smaller than a quarter wavelength from the source (9 km at 8 kHz). Because the current needed for a given heating power is higher at 8 kHz, and because the characteristic impedance stays the same, the voltages in a standing wave pattern become higher at 8 kHz, and heating sections shorter than a quarter wavelength may be the best approach at 8 kHz. For example, a 5-km section, driven from the center with 72 kV, has 50 W/m of heating in the center, rising to 60 W/m at the ends.

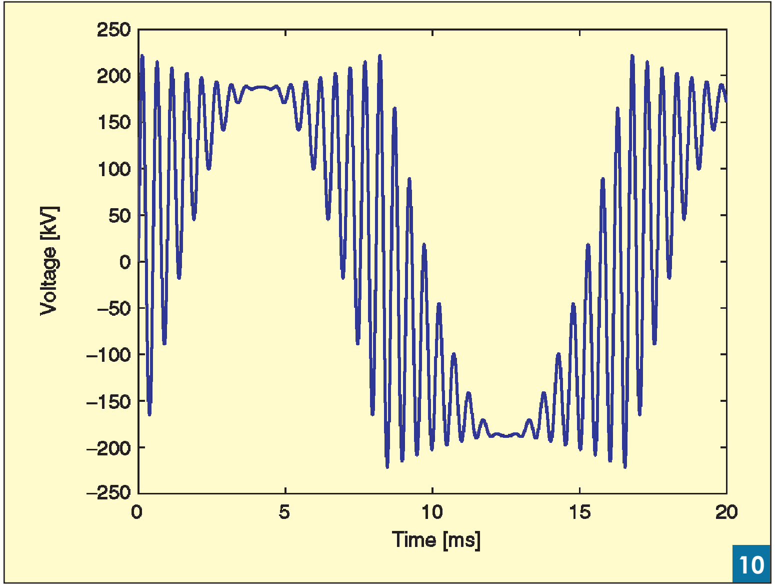
In any case, very careful filtering is necessary to prevent harmonics from exciting the line and radiating interference at higher frequencies.

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.

Corona

Adding high-frequency high voltage to a line will increase corona effects. In one respect, increased corona could be beneficial, because it would produce additional heating and melt the ice faster. However, where icing is most severe, the overall diameter, including the ice, is larger, which decreases 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.



10

The addition of a high-frequency waveform to a 133-kV rms, 60-Hz phase-to-ground voltage with no increase in peak voltage. The modulation of the high-frequency waveform keeps the peak field at the surface of the conductor from exceeding that present with only the low-frequency, three-phase excitation. The high-frequency peak can be slightly higher than the low-frequency peak because only a single phase is excited at high frequency. For clarity, the high-frequency waveform shown here is at 2 kHz, much lower than the 8 kHz to 150 kHz that would be used in practice.

To reduce corona, the waveform could be modulated, as shown in Figure 10, to reduce the high-frequency amplitude as the peaks in the low-frequency voltage are approached. Modulation could be used to achieve a waveform with constant peak voltage. In Figure 10, the high-frequency peaks are higher than the low-frequency peaks. This is because the low-freequency excitation is three-phase, whereas the high-freqeucny excitation is applied to only one conductor, which allows it to have a higher peak voltage for the same peak field strength.

Another strategy is to increase the frequency, which increases both skin-effect and dielectric losses for a given excitation voltage, thus allowing lower voltage for the same heating requirement. Dielectric loss tends to increase faster with frequency, leading to poorer matching between the two heating effects. However, this may not be a problem: the ice in the regions of high dielectric loss (voltage antinodes) will melt first, even with low excitation. Then, the excitation level can be increased to melt the remaining ice through skin-effect loss. For example, at 145 kHz, 50 kV is sufficient to heat 15 mm ice with 50 W/m at the voltage antinodes, but at the current antinodes, the heating is only about 22 W/m, which won't melt the ice as fast. However, increasing the voltage to 75 kV will produce 50 W/m at the current antinodes and higher heating at the voltage anitnodes, but only if ice remains on them.

Conclusion

The application of high-frequency 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 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.

Acknowledgment

This work was supported by the New York Power Authority, CEA Technologies Inc., and Ice Engineering LLC.

References

[1] V.F. Petrenko and C.R. Sullivan, "Methods and systems for removing ice from surfaces," U.S. Patent Application PCT/US99/28330, 1999.

[2] J.D. McCurdy, C.R. Sullivan, and V.F. Petrenko, "Using dielectric losses to de-ice power transmission lines with 100 khz high-voltage excitation," in *Conf. Rec. IEEE Industry Applications Society Annu. Meeting*, 2001, pp. 2515-2519.

[3] V.F. Petrenko and R.W. Whitworth, *Physics of Ice*. London, U.K.: Oxford Univ. Press, 1999.

[4] J. Hu and C.R. Sullivan, "Optimization of shapes for round-wire high-frequency gapped-inductor windings," in *Conf. Rec. IEEE Industry Applications Society Annu. Meeting*, 1998, pp. 900-906.

[5] J. Hu and C.R. Sullivan, "Analytical method for generalization of numerically optimized inductor winding shapes," in *IEEE Power Electronics Specialists Conf. Rec.*, 1999, vol. 1, pp. 568-573.

[6] C.R. Sullivan, J.D. McCurdy, and R.A. Jensen, "Analysis of minimum cost in shape-optimized litz-wire inductor windings," in *IEEE Power Electronics Specialists Conf. Rec.*, 2001, vol. 3, pp. 1473-1478.

[7] R. Jensen and C.R. Sullivan, "Optimal core dimensional ratios for minimizing winding loss in high-frequency gapped-inductor windings," in *Proc. IEEE Applied Power Electronics Conf.*, 2003, pp. 1164-1169.

[8] W.M. Chew and P.D. Evans, "High frequency inductor design concepts," in *IEEE Power Electronics Specialists Conf. Rec.*, 1991, vol. 22, pp. 673-678.

[9] K.D.T. Ngo and M.H. Kuo, "Effects of air gaps on winding loss in high-frequency planar magnetics," in *IEEE Power Electronics Specialists Conf. Rec.*, 1988, vol. 2, pp. 1112-1119.

[10] N.H. Kutkut and D.M. Divan, "Optimal air-gap design in high-frequency foil windings," *IEEE Trans. Power Electron.*, vol. 13, pp. 942-949, Sept. 1998.

[11] J. Hu and C.R. Sullivan, "The quasi-distributed gap technique for planar inductors: Design guidelines," in *Conf. Rec. IEEE Industry Applications Society Annu. Meeting*, 1997, pp. 1147-1152.

Charles R. Sullivan (Charles.R.Sullivan@Dartmouth.EDU), Victor F. Petrenko, Joshua D. McCurdy, and Valeri Kozliouk are with Dartmouth College in Hanover, New Hampshire, USA. This article first appeared in its original form at the 2001 IEEE IAS Annual Meeting.