CSCanada
Advances in Natural Science
Vol. 5, No. 4, 2012, pp. 1-6
DOI:10.3968/j.ans.1715787020120504.1854

ISSN 1715-7862 [PRINT]
ISSN 1715-7870 [ONLINE]
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Protection of High Voltage Transmission Lines of Canada from the Ice by High-Frequency Electromagnetic Waves

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Received 3 October 2012; accepted 14 December 2012

Abstract
The way of heating the air electricity transmission line by spreading it on a running high-frequency electromagnetic waves, which is to protect the electric power system from ice storm. At the heart of the heating are two physical phenomena: the skin effect and the transformation of radiated energy into heat. Calculated impedance wire line for optimal matching of the generator to the line. The results of the experiment and block diagram of an industrial plant are provided.

Key words: Power line; Ice; Electromagnetic waves; Skin effect; Thermal heating; Input impedance; Industrial plants

Kaganov William (2012). Protection of High Voltage Transmission Lines of Canada from the Ice by High-Frequency Electromagnetic Waves. *Advances in Natural Science*, *5*(4), 1-6. Available from: http://www.cscanada.net/index.php/ans/article/view/j.ans.1715787020120504.1854
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THE ESSENCE OF THE PROBLEM

One of the major causes of accidents in power systems more powerful is the formation of a dense cake of ice when freezing of supercooled droplets of rain, drizzle or fog at temperatures from 0 to -5°C on the wires of high voltage power lines.

Let's briefly examine the physical mechanism of nucleation of ice. Each cubic meter of air-Soviet can contain some moisture, but not exceeding a given temperature T (0°C), the determination of maximum r (g/m^3). Graph of r(T), shown in Figure 1, can be approximated using:

$$\rho(T) = 32\exp(0.06295(T\text{-}30)) \quad (1)$$

Where T (°C) – temperature, called the dew point temperature corresponding to the maximum of quantity of moisture.

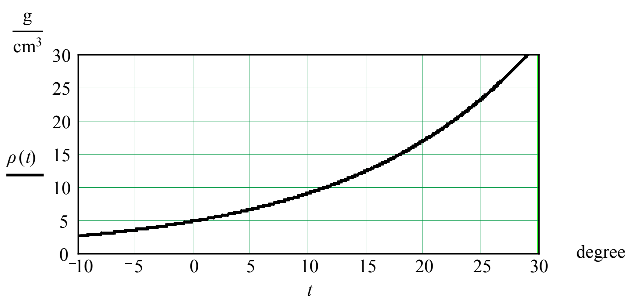

Figure 1
Schedule of Maximum Saturation Moisture in the Air

From the above graph shows that the temperature decreases relative to the dew point, the maximum amount of moisture contained in the air decreases and the process of condensation of water vapor (figuratively speaking, "extrusion" of excess water from the air), deposited on various subjects and forming a sub-zero temperatures icy crust, including on the wires.

As a result of significant increases of ice stuck to the wire (Figure 2), which results, especially in high winds, to hazards: cliff conductive wire and ground wire is unacceptable close together and strong rocking, deterioration of protective properties of insulators and the destruction of the supports.

Figure 2
Wires with Accrued Ice

We describe one possible physical mechanisms of ice that take place in Canada in the Montreal area, due to the emerging accompanied contact the narrow boundary between two air masses – the cold that comes from the east and north, and a warm humidity, moving from the south[1].

Warm air mass pushes a thin layer of cold air to the ground. As a result, the upper level is formed of snow, which melts in the warm layer and becomes rain when the temperature of crystallization. Drops of rain, falling into a layer of cold air near the ground, freeze on contact with the cool surface of various items, including wires and transmission towers, and the process of avalanche formation of ice dams.

Such an "icy" rain, lasting up to several hours, falling to 15 times a year, leaving a layer of ice on the ground and frost thickness of 30-60 mm on the wires of the lines power.

Particularly intensive ice storm formation occurred in Canada 5-10 in January 1998, when for more than 80 hours over an area of thousands of square kilometers of continuous walking cooled fine rain. Due to the heavy weight of ice, accrued interest on the wires were broken off many power lines and destroyed about 1000 transmission towers. As a result, more than 4 million people in Canada for many days without electricity. In areas covered in icing killing twenty-five people, and total economic losses exceeded 5 million dollars[1].

There are other examples of large-scale power failure due to ice large areas in different countries of Northern Europe, Russia, and China.

Thus, De-icing wire power lines is a truly global problem relevant to many countries in the world, with regions with high humidity and low temperatures.

Total weight of stranded aluminum wire length of 1 km from the ice clinging to it in accordance with Figure 4 can be determined by the formula:

$$M(S, h) = 0{,}0037S + \pi 10^{-3} h(\sqrt{4S/\pi} + h)\, m_k \quad (t/km) \quad (2)$$

Where the first term is the mass of the stranded wire, the second term – mass of the ice adhering to the wire, S – cross-section (mm^2), h – thickness of the ice on the wire (mm), m_k = 0.6-0.9 ton/m^3 – specific mass of ice.

For example, according to (2) m_k = 0.9 ton/m^3 and ice thickness h = 50 mm mass of wire grade AS-500 increased by 7 times, and 12 t/km, while the three-phase network- up to 36 t/km. Because of this significant increase in the mass of wires are their gap and the destruction of the legs (Figure 3).

Figure 3
Reliance, Collapsed Under the Weight of Ice

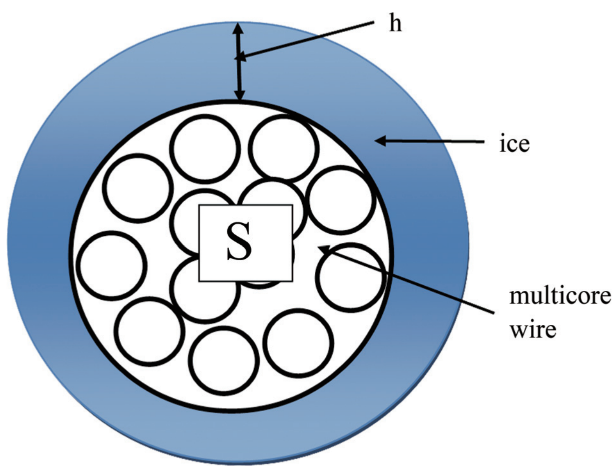

Figure 4
Stranded Wire with Frazil

The traditional way to deal with ice, carried out by the so-called melting short-circuits transmission lines and switching off from it all the consumers, sometimes ineffective, inconvenient, expensive and dangerous.

Therefore there is an urgent need to develop new, modern technology is not anti-icing after the build-up of ice on the wires, and prevent its formation at the approach of icing conditions. To solve this problem can by heating to a temperature of wires + (10-20)°C until the ice. This heating of the can be performed by running a high-frequency electromagnetic wave propagating along the transmission line together with the main voltage of industrial frequency. No fault in the network, as in melting, produce is not necessary, and no consumer disconnect from the network is not required. The consumer in this method combat icing should not feel anything, because the two waves – power frequency of 50 Hz and an electromagnetic frequency of about 100 MHz – can be simultaneously distributed power line, so to speak, without interfering with each other. One wave (50 Hz) sends electrical energy on the wires, and the other (a frequency of about 100 MHz) – heats the wires.

TRAVELING ELECTROMAGNETIC WAVES AND CONVERTING IT INTO HEAT ENERGY

Falling component traveling electromagnetic wave propagating along the two-wire line of infinite length is[2, 3]:

$$u_i(t, x) = U_0 e^{-\alpha x}\cos(2\pi f t - \beta x) \qquad (3)$$

Where U_0 – the amplitude of the voltage at the input of the line to which the oscillator frequency f; x – coordinate measured from the place of connecting the generator to the line; $\alpha = R_f/\rho$(1/m) – the decay constant; R_f – linear resistance of one of the two identical wires; $\beta = 2\pi/\lambda$ – the phase constant; ρ^- – wave impedance line; λ^- – wave length corresponding to the frequency f.

With regard to (3) the power of the incident wave varies in accordance with

$$P_I(x) = \frac{U_0^2 e^{-2\alpha x}}{2\rho} = P_G e^{-2\alpha x} \qquad (4)$$

Where $P_G = (U_0)^2/2\rho$ – wave power in the beginning of the line, which is equal to the optimal matching of lines with its high-frequency generator output power.

The equation of power balance in the system: high-frequency generator-line electric transmission line is given by:

$$P_G = P_S(x) + P_E(x) + P_L(x), \qquad (5)$$

$P_S(x)$ – the power loss of electromagnetic energy, which is determined by the active resistance of the line and turns into heat, $P_E(x)$ – emission power lines, $P_L(x)$ – power transmitted to the load or reflected from the end of the line.

With increasing frequency of the electromagnetic wave propagating along of the line, due to the phenomenon of the skin effect the displacement current to the surface of the conductor-ka[2, 4]. The thickness of the skin layer in the round conductor (Figure 5) at a frequency of more than 1 MHz:

$$\delta(F) = 0{,}5\sqrt{\frac{\sigma}{\mu F}}\ (\text{mm}), \qquad (6)$$

Where σ (Ω·mm²/m) – the electrical resistance at direct current; μ – relative permeability, F – frequency in MHz.

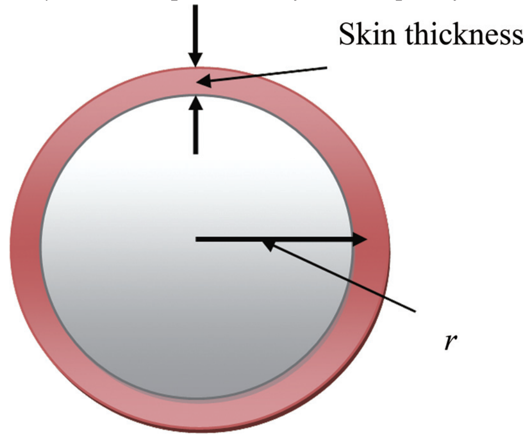

Figure 5
Picture of Current Displacement Due to the Skin Effect

Thinning of the layer to the current flow (Figure 5) leads to an increase in resistivity of the conductor, whose value at (r/2δ) > 10:

$$R_f = \frac{R_0\, r}{2\,\delta(F)}\ (\Omega/\text{m}). \qquad (7)$$

Where r – the radius of the wire (mm), $R_0 = \sigma/\pi r^2$ (Ω/m) – specific resistivity of the same wire DC.

By (7) at a frequency of more than 1 MHz for aluminum wire have:

$$R_{fal}(F)/R_0 = 6.047 r\sqrt{F}\ (\Omega/\text{m}), \qquad (8)$$

By (8) at the wire radius r = 10 mm its resistance per unit length to the ratio of the resistance at DC increases 190 times at a frequency of 10 MHz and 600 times at a frequency of 100 MHz.

According to (4) the power of the traveling wave to be converted into heat because of the loss of active line of length x with the skin effect will be:

$$\Delta P(x) = P_G - P_I(x) == P_G\left(1 - e^{-2\alpha x}\right). \qquad (9)$$

Where $\alpha = R_f/\rho$ – damping constant.

Located along the line in steps of 5-10 m special emitters graphite ceramic type with high resistance value of 1-2 kΩ, we can significantly increase the power delivery of the incident wave on the radiation, and then converted into heat, heated line. As a result, the line can be long enough to completely transform the energy of high-frequency electromagnetic waves into heat.

MATCHING HIGH-FREQUENCY GENERATOR TO THE LINE

To transfer maximum power from the RF generator to the line, which is a type of distributed load, it is necessary to know the input impedance of the line, which will optimally align the output resistance of the generator with the input impedance[3].

According to[2, 3], the input resistance wire line with losses in length x:

$$Z_{\text{in}}(x) = \rho \frac{Z_L \text{ch}(\gamma x) + \rho \text{sh}(\gamma x)}{\rho \text{ch}(\gamma x) + Z_L \text{sh}(\gamma x)} \quad (10)$$

Where $\gamma = \alpha + j\beta$ – propagation constant, α – decay constant, $\beta = 2\pi / \lambda$ – phase constant, x – length of the line, λ – wave length, $\rho = 276\lg(a/r)$ – two-wire impedance, Z_L – resistance to the end.

Example graphs of active RB = Re (Z_{in}) and reactive XB = Im (Z_{in}) component of the input impedance open at the end of long lines at $\rho = 600\ \Omega$ and $\gamma = 0.1 + 6.28i$ shown in Figure 6. They imply that $\beta x >> 1$ the value of the active component of the characteristic impedance tends to ρ, and the reactive component - to 0.

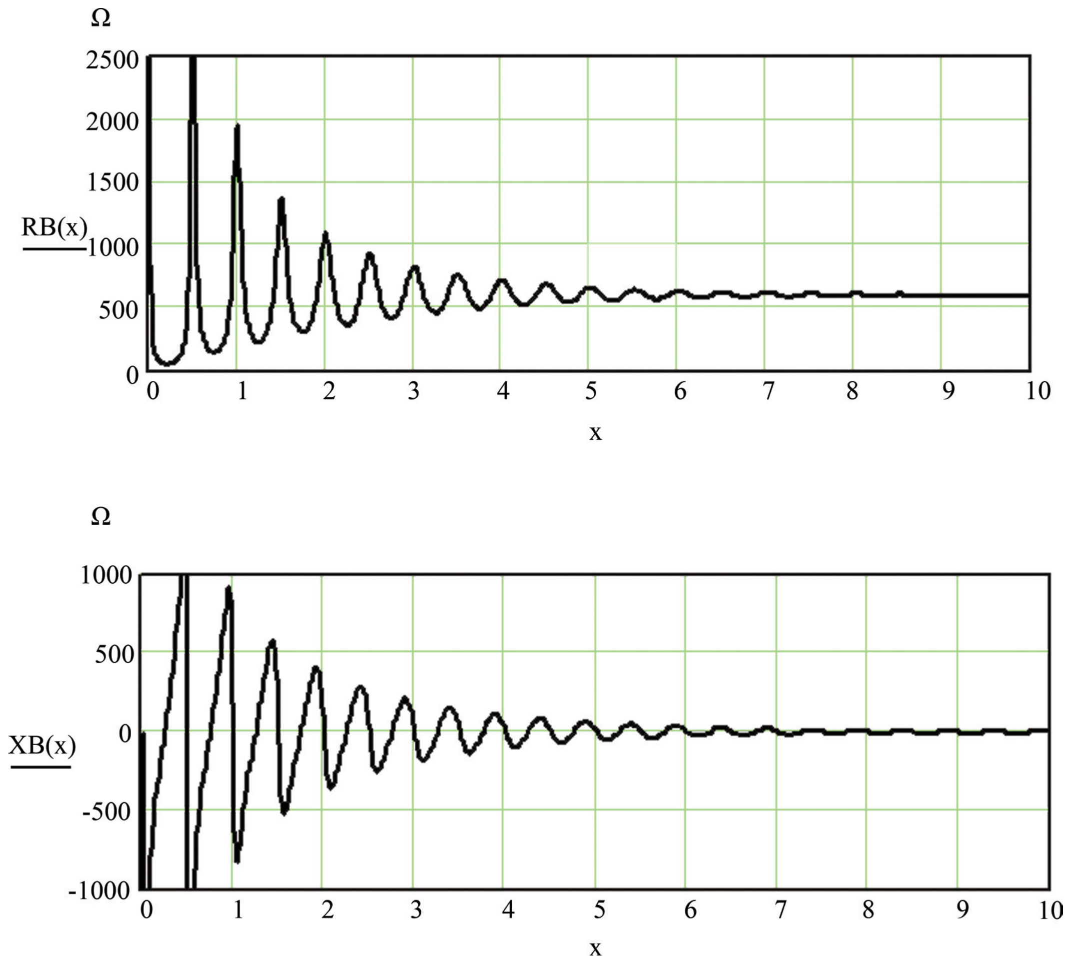

Figure 6
Graphics for the Active (RB) and Reactive (XB) Input Impedance of the Two-Wire Line

Knowing Z input optimally align the output impedance of the RF generator to the two-wire line. For this purpose between the generator output cable, usually with impedance of 50 Ω, and a two-or three-wire line to the radiation resistance 300-700 Ω should include a matching device that acts as a transformer of RF resistance.

EXPERIMENTAL VERIFICATION OF THE METHOD OF HEATING THE WIRES WITH HIGH-FREQUENCY ELECTROMAGNETIC WAVES

The general scheme of the experiment is shown in Figure

7. As an energy source produced high-frequency generator used 500 watt frequency 81.36 MHz, for use in industrial and scientific purposes under the "Radio Regulations". During the experiment, two-wire heats the spectral line with stranded aluminum conductors such as AS-16 radius r = 2.5 mm and a length of 200 m. Tests were conducted in Podolsk, Moscow region, at the Podolsk chemical and metallurgical plant. The temperature was measured with the help of alcohol thermometers attached to the wire, and an infrared pyrometer.

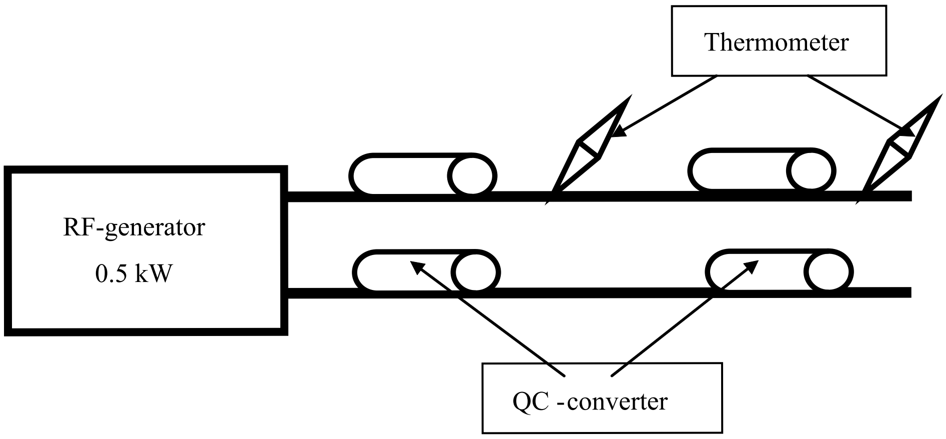

Figure 7
Block Diagram of the Experimental Setup

When the RF generator heating temperature ceramic transducers, which are mainly used MLT resistance was equal to 50°C to 80°C at an ambient temperature of 20°C, and the surface of the wire is heated by an average of *ΔT*= 15…20°C relative to the ambient air at a specific power cost RF power of about 2 to 3 W/m.

Thus, our experimental studies have confirmed the principle of heating stranded wire with high-frequency electromagnetic waves using two physical phenomena: the skin effect and discrete transformation of the radiated energy into heat.

ON CREATION OF AN INDUSTRIAL PLANT TO COMBAT ICE

For the practical implementation of a new method for dealing with icing on overhead power lines, including in Canada, you need to make industrial unit – oscillator frequency range of 100 MHz, power 8-10kW, and conduct field tests. The tests will:

- to confirm the idea of a method that on the wires, pre-heated to a temperature of +10…15°C, frost dots not form;
- to specify the desired power density per meter three-phase line-by-wire transmission of different sections;
- in full make up an action plan to mass production have developed devices and commercialization of a new method for protecting power lines from ice.

General block diagram of an industrial unit, which includes three main real parts: two generators with a capacity of 4 kW, unmanned matching device used to connect generators to the transmission lines and transmission line maximum power, and graphite-ceramic converter are arranged at a certain step at wires is shown in Figure 8, where MD – matching device, MPU – microprocessor unit, Th – high throttle, QC converter – graphite-ceramic converter.

This industrial unit can be made one of Russian firms under the author of the article.

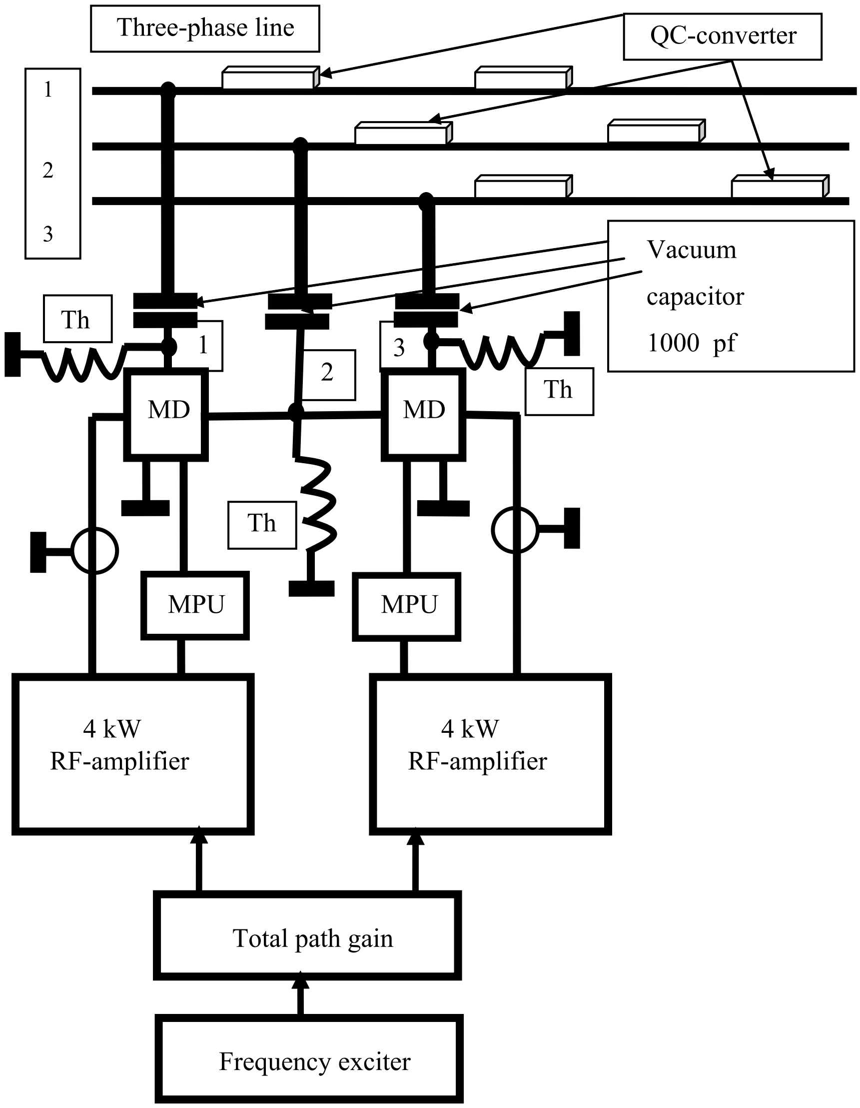

Figure 8
The Block Diagram of an Industrial Plant

FINDINGS

1. Developed a method of heating stranded wire electrical networks with the aid of high-frequency electromagnetic waves, which should prevent the formation of ice on wires. At the heart of the heating are two physical phenomena: the skin effect and the method of direct, discrete conversion of radiated electromagnetic energy into heat.

2. The proposed method prevents the formation of ice on the wires are heated by approaching gust of education, and does not melt the ice build-up after it was on the wires. The method allows not to disconnect users from the network during the heating and saves the amount of energy consumed.

3. Experimental evidence method of heating wires with propagating thereon RF electromagnetic waves.

4. After manufacturing the RF generator power 8-10kW and conduct relevant field tests can definitively establish a rule of RF energy required to heat one meter track three-phase power transmission line, and recommend this method to combat icing in high voltage overhead transmission lines of electricity, including power grids in Canada.

5. Opens the possibility of full automation to prevent ice in electrical networks.

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