Diagnostic de Défauts de Câbles Electriques par l'Estimation de l'Impédance Caractéristique Distribuée

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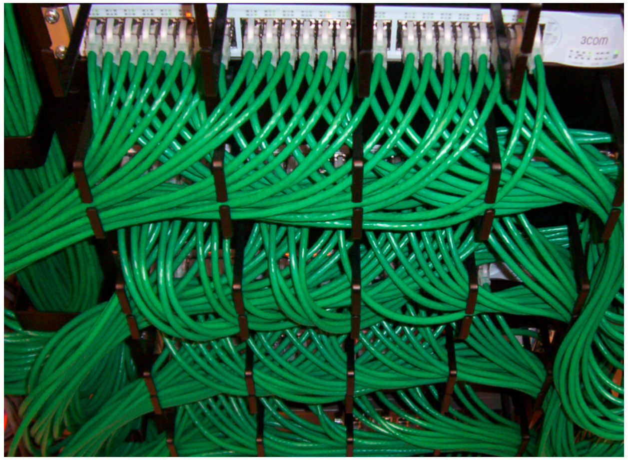
Electrical cables are everywhere

Power lines

Data lines



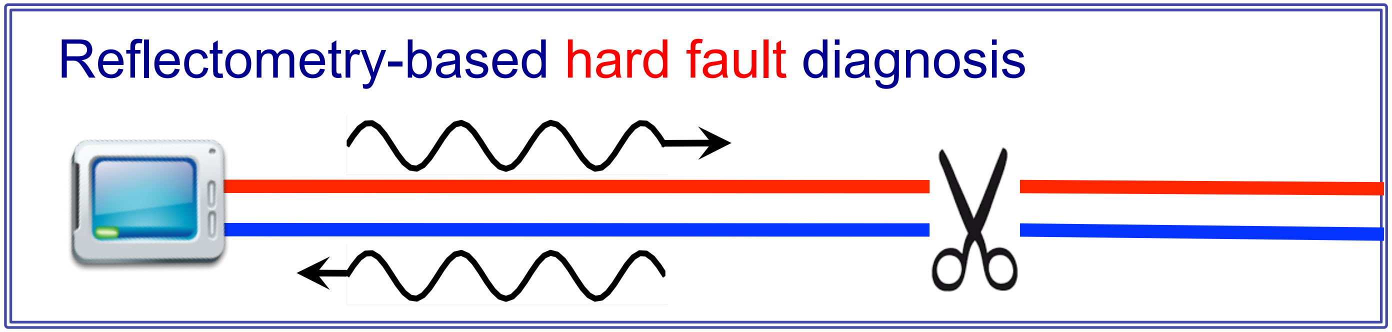
Cables are usually solid, but…

they are often installed
for decades,

and there are more
and more cables.

It is easy to notice that a cable is cut off

Reflectometry-based methods can also tell the distance of the cutoff point.



It remains relatively easy to deal with such hard faults, but how about soft faults (défauts non francs) ?

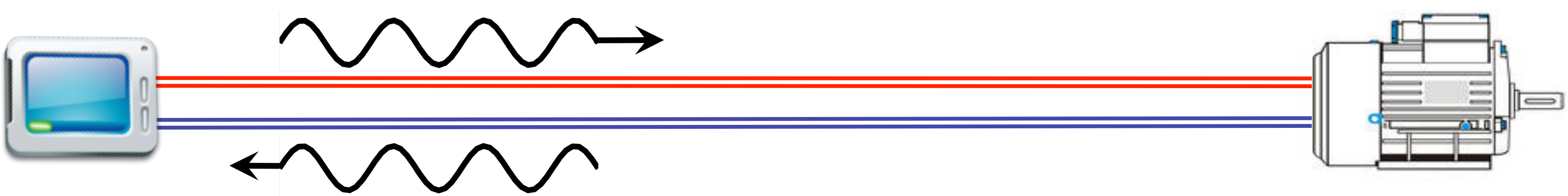
Reflectometry for **soft** faults?

Mechanical accidents

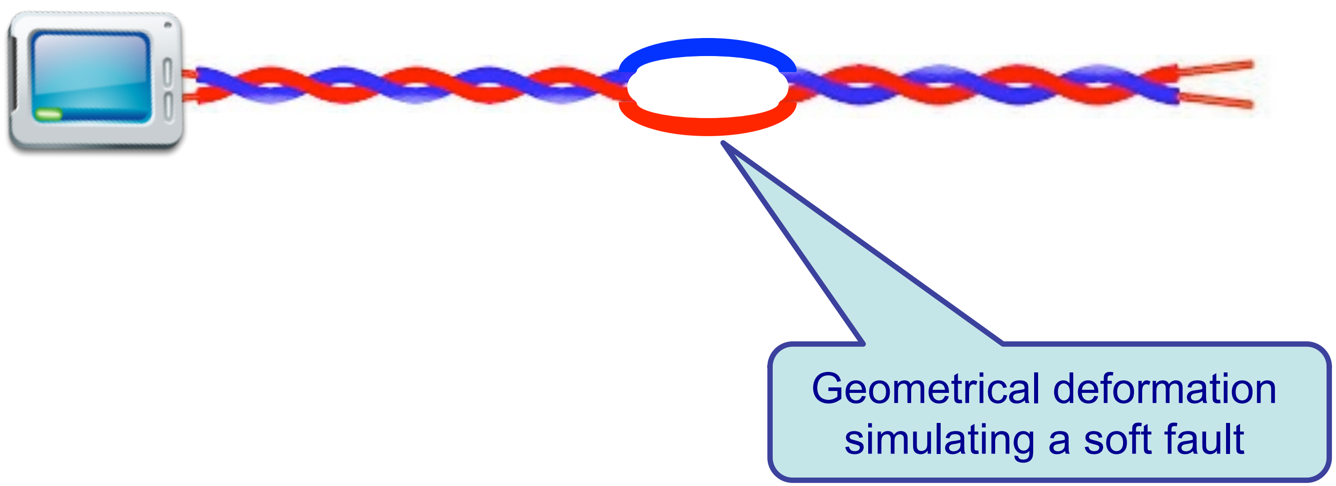
Chemical attack

Over heating

Difficulty: single point observation for fault detection-location-characterization.



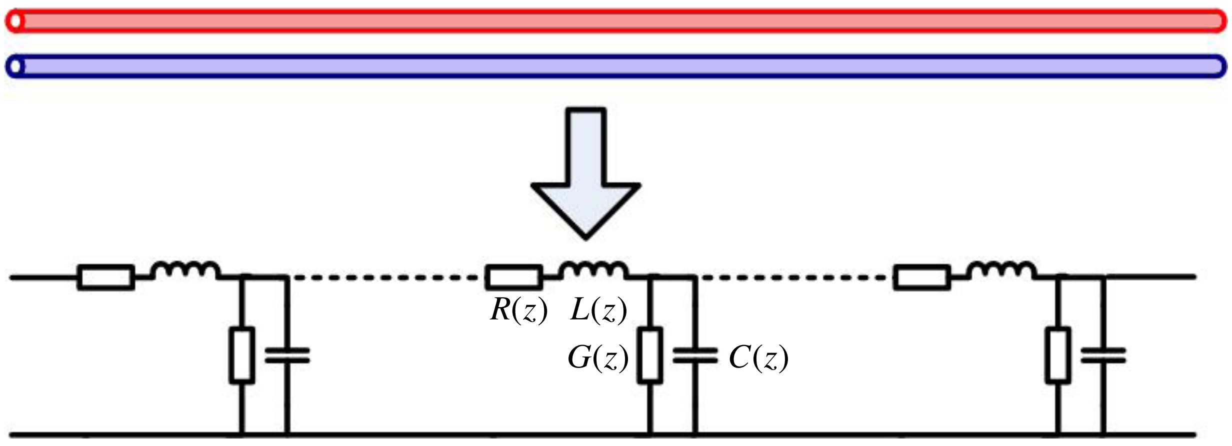
Demo: real time soft fault diagnosis



Difficulty: multiple reflections

(video illustration)

Advanced reflectometry: model-based analysis

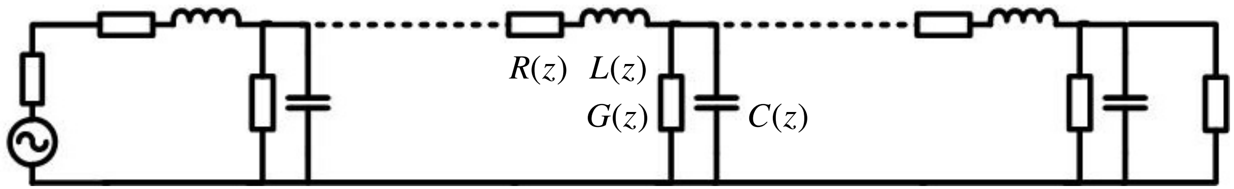


$$\frac{\partial V(t,z)}{\partial z} + L(z)\frac{\partial I(t,z)}{\partial t} + R(z)I(k,z) = 0$$

$$\frac{\partial I(t,z)}{\partial z} + C(z)\frac{\partial V(t,z)}{\partial t} + G(z)V(k,z) = 0$$

Telegrapher's equations + inverse algorithm ⇒ diagnosis

From time domain to frequency domain



$$\frac{\partial V(t,z)}{\partial z} + L(z)\frac{\partial I(t,z)}{\partial t} + R(z)I(k,z) = 0$$

$$\frac{\partial I(t,z)}{\partial z} + C(z)\frac{\partial V(t,z)}{\partial t} + G(z)V(k,z) = 0$$

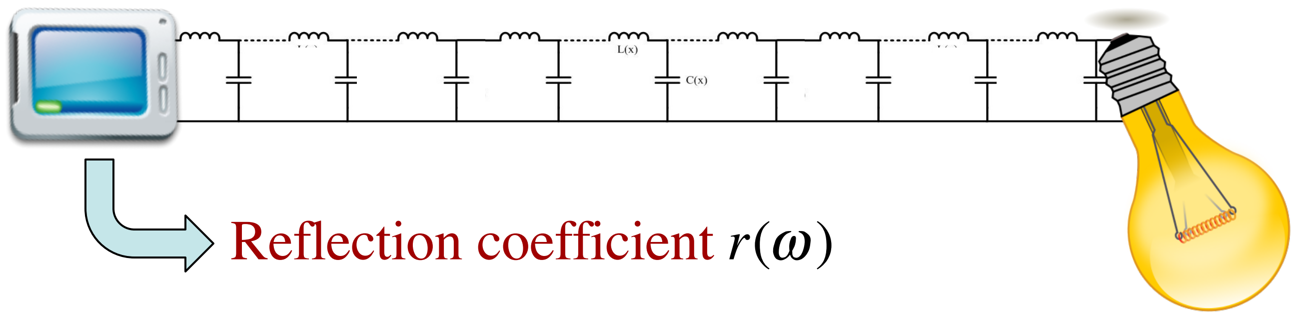
Fourier transform

$$\frac{dV(\omega,z)}{dz} + R(z)I(\omega,z) + i\omega L(z)I(\omega,z) = 0$$

$$\frac{dI(\omega,z)}{dz} + G(z)V(\omega,z) + i\omega C(z)V(\omega,z) = 0$$

Characteristic impedance: $Z_0(z) = \sqrt{\frac{L(z)}{C(z)}}$

The reflection coefficient

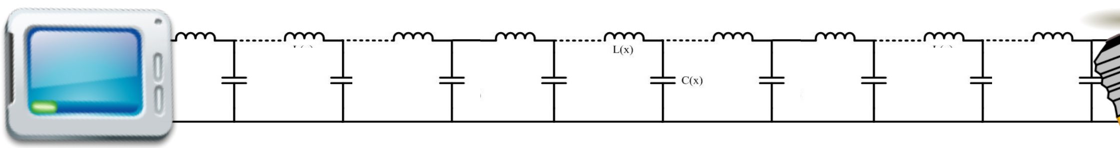


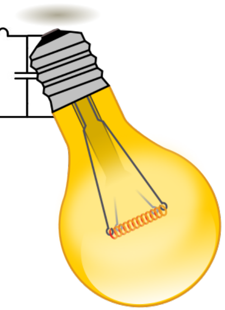
Reflected wave

$$r(\omega) = \frac{V(\omega, x_S) - Z_S I(\omega, x_S)}{V(\omega, x_S) + Z_S I(\omega, x_S)} = \frac{Z(\omega, x_S) - Z_S}{Z(\omega, x_S) + Z_S}$$

Incident wave

The transmission line inverse problem





Reflection coefficient $r(\omega)$

$$Z_0(x) = \sqrt{\frac{L(x)}{C(x)}}$$

The inverse algorithm based on the **inverse scattering** theory

The inverse scattering theory about Zakharov–Shabat equations

$$\frac{dv_1(\omega,x)}{dx} + i\omega v_1(\omega,x) = q(x) v_2(\omega,x)$$
$$\frac{dv_2(\omega,x)}{dx} - i\omega v_2(\omega,x) = q(x) v_1(\omega,x)$$

was studied during the 1970s-1980s for the analysis of nonlinear wave equations. It turns out to be useful for the cable inverse problem!

References:
[Lamb 1980], [Eckhaus and Harten 1981], [Jaulent 1982].

The inverse scattering algorithm

Fourier transform: $$\rho(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} r(\omega)\exp(-i\omega x)\,dk$$

Solution of Gel'fand-Levitan-Marchenko (GLM) integral equations:

$$A_1(x,y) + \int_{-y}^{x} A_2(x,s)\rho(y+s)\,ds = 0$$

$$A_2(x,y) + \rho(x+y) + \int_{-y}^{x} A_1(x,s)\rho(y+s)\,ds = 0$$

$$q(x) = 2A_2(x,x)$$

$$Z_0(x) = Z_0(x_S)\exp\left(-2\int_{x_S}^{x} q(\tau)\,d\tau\right)$$

Particularities of the numerical algorithm

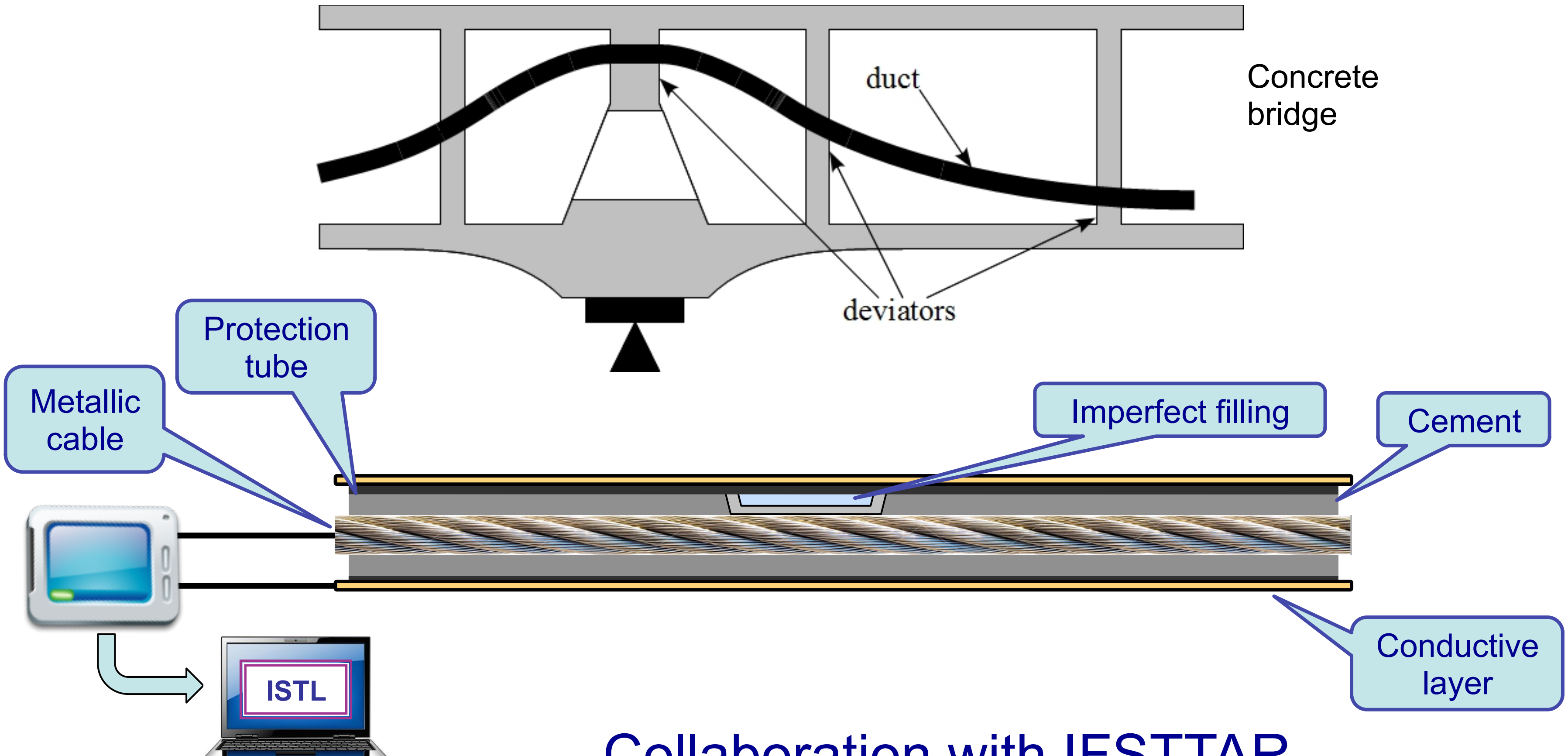
- The theory is continuous in space, time and frequency, but discretization is necessary for numerical algorithms.

- For a cable spatially discretized at 1000 points, each of the kernels $A_1(i,j), A_2(i,j)$ of the integral equations has 1000^2 unknowns. Fast algorithms exist.

- The inverse scattering algorithm does not make any assumption about the particular form of impedance profile $Z_0(x)$, but only some regularity assumptions.

- Multiple faults are naturally covered.

Application in civil engineering: non destructive post-tensioned cable monitoring



Collaboration with IFSTTAR

Conclusion

Inverse scattering applied to reflectometry is a powerful tool for soft fault diagnosis of electrical cables.

Fast algorithm for real time applications.

Applications in electrical engineering and in civil engineering.

Ongoing research: electrical network monitoring.