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.

Reflectometry-based hard fault diagnosis

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

Geometrical deformation simulating a soft fault
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 \(\rightarrow\) diagnosis
From time domain to frequency domain

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

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

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

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

Characteristic impedance: \[ Z_0(z) = \sqrt{\frac{L(z)}{C(z)}} \]
The reflection coefficient $r(\omega)$ is given by:

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

\[
\begin{align*}
\frac{dv_1(\omega, x)}{dx} + i\omega v_1(\omega, x) &= q(x)v_2(\omega, x) \\
-\frac{dv_2(\omega, x)}{dx} - i\omega v_2(\omega, x) &= q(x)v_1(\omega, x)
\end{align*}
\]

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.