HIGHVOLT KOLLOQUIUM '23
Cable diagnostic
Diagnose von Kabeln
4.2

Analysis of cable systems by modelling their transfer functions

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Abstract

An extended method for on-line transfer function measurement of cable systems with discontinuities was validated under conditions close to practice. The method allowed to precisely synthesize measured impulse responses of a test cable system. It furthermore allowed to estimate the spectral characteristics of single components, such as the transfer function of one specific cable or the reflection coefficient of one specific joint. Due to these and other advantages, which are of particular interest for a convenient and cost-effective application in the field, the proposed method could be a powerful tool for global and local condition monitoring of cable systems.

1 Introduction

Many studies aim to measure the transfer function of cable systems [1-3] to assess its global condition. Furthermore, the transfer function can help to localize partial discharges in a relatively simple and cost-effective way [4], and thereby enable *local* condition monitoring of a cable system. Such condition monitoring can be realized on-line, i.e., without requiring the cable system to go out of service, and without prior knowledge about geometries and materials of the cable system [4]. Overall, transfer function measurement has the potential to provide versatile condition monitoring in the context of ageing state recognition and predictive maintenance of cable systems.

Recently, we have further elaborated the method and studied its practical applicability [5-7]. It became clear that discontinuities in the cable system like joints and terminations, which have their own spectral characteristics, are problematic. They limit not only the meaningfulness of the measured (overall) transfer function of the cable system, but also the accuracy of partial discharge localization. The question arises how to deal with such discontinuities. In a broader sense, other fields such as geophysics and acoustics already suggested answers here. They exploited discontinuities in the ground [8] and in the airways [9], respectively, to determine the structure of each medium. Inspired by these, the present study suggests an extended method for on-line transfer function measurement of cable systems with discontinuities.

2 Materials and methods

2.1 Test cable system

To assess the method under conditions close to practice, the test cable system shown in *Figure 1* was used. It includes three medium-voltage cables of lengths 800 m, 600 m, and 800 m. The cables were connected to each other by two straight joints

J1 and J2. Two terminations T1 and T2 were placed at both ends of the resulting cable system. High frequency current transformers [10] were used for the capacitive injection and measurement of signals.

Figure 1: Test cable setup with three cables in the background, and two straight joints with connected high frequency current transformers in the foreground.

2.2 Modelling

A calibration signal $X(\omega)$ was injected into the test cable system at T1 and the responses were measured at T1 and T2. As shown in *Figure 2*, an impulse is assumed as calibration signal here for explanatory purposes. *Figure 2* illustrates that the measured impulse responses are superpositions of signals with different propagation paths through the cable system for example, the impulse response at T1 is the superposition of an incident signal and reflected signals. The incident signal is the injected and directly measured impulse. It can be written as:

$$I(\omega) = X(\omega) \cdot H_{\text{in}}(\omega) \cdot H_{\text{out}}(\omega), \qquad (1)$$

where $H_{\text{in}}(\omega)$ and $H_{\text{out}}(\omega)$ are the coupling and decoupling transfer functions, respectively. The first reflected signal, following its propagation path (green path in *Figure 2*), can be written as:

$$\begin{aligned} R(\omega) = I(\omega) \ \cdot [H_{\text{cable}}(\omega)]^{l} \cdot r_{\text{J1}}(\omega) \cdot \\ [H_{\text{cable}}(\omega)]^{l} \cdot [1 + r_{\text{T1}}(\omega)], \end{aligned} \qquad (2)$$

where $H_{\text{cable}}(\omega)$ is the cable transfer function over a cable length of 1 m, l is the length of the first cable segment, and $r_{\text{J1}}(\omega)$ and $r_{\text{T1}}(\omega)$ are the reflection coefficients of J1 and T1, respectively. Eq. (2) makes clear that $R(\omega)$ can be synthesized from $I(\omega)$ by making assumptions about the characteristics of the cable system. All other reflected and transmitted signals in the impulse responses at T1 and T2, respectively, can be synthesized from $I(\omega)$ in a similar way. The minimization of the error between measured and synthesized signals leads to the best estimates for the characteristics of the cable system.

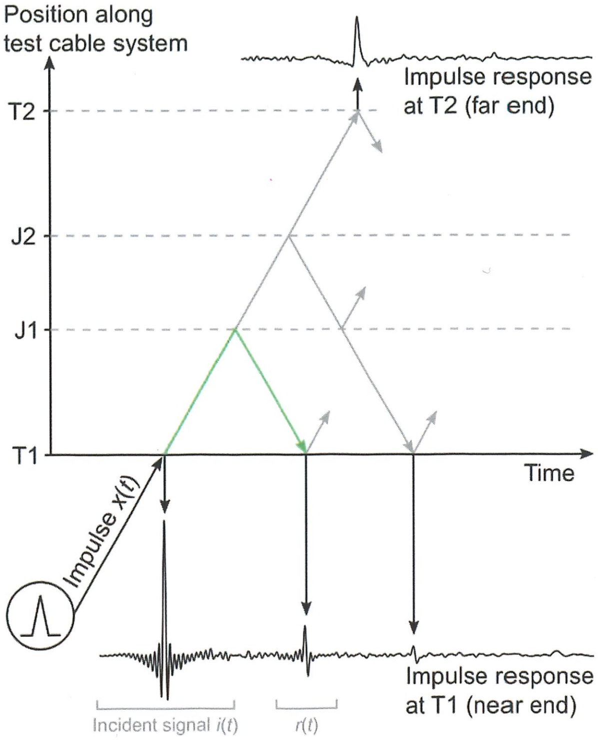

Figure 2: A calibration impulse injected at T1 propagates through the test cable system along different paths. Each path deforms the impulse. The deformations carry information about the spectral characteristics of the cable system along each path. The measured impulse responses at T1 and T2 are superpositions of deformed impulses.

2.3 Implementation

In the custom Matlab R2021a GUI shown in *Figure 3*, the structure of the test cable system (left window) and the measured signals (middle window) were specified. The measured signals included the incident signal (blue curve), the reflected signals (gray curve at bottom), and the transmitted signals (gray curve at top). The transfer functions of the cables (right top window) and the reflection coefficients of the joints and terminations (right bottom window) were specified as piecewise linear functions between a user-defined number of points in a given frequency range. The user can manipulate all parameters of the cable system by draggable markers (black filled circles). This leads to an immediate change in the synthesized signals (black curves in middle window). Furthermore, the parameters can be estimated automatically (button "Optimize" below windows) using the particle swarm optimization implemented in the Matlab R2021a function `particleswarm`.

3 Results and discussion

The automatic estimation of the 22 parameters of the test cable system took around 5 minutes using eight CPUs. *Figure 3* shows the estimated parameters that lead to a minimum squared error

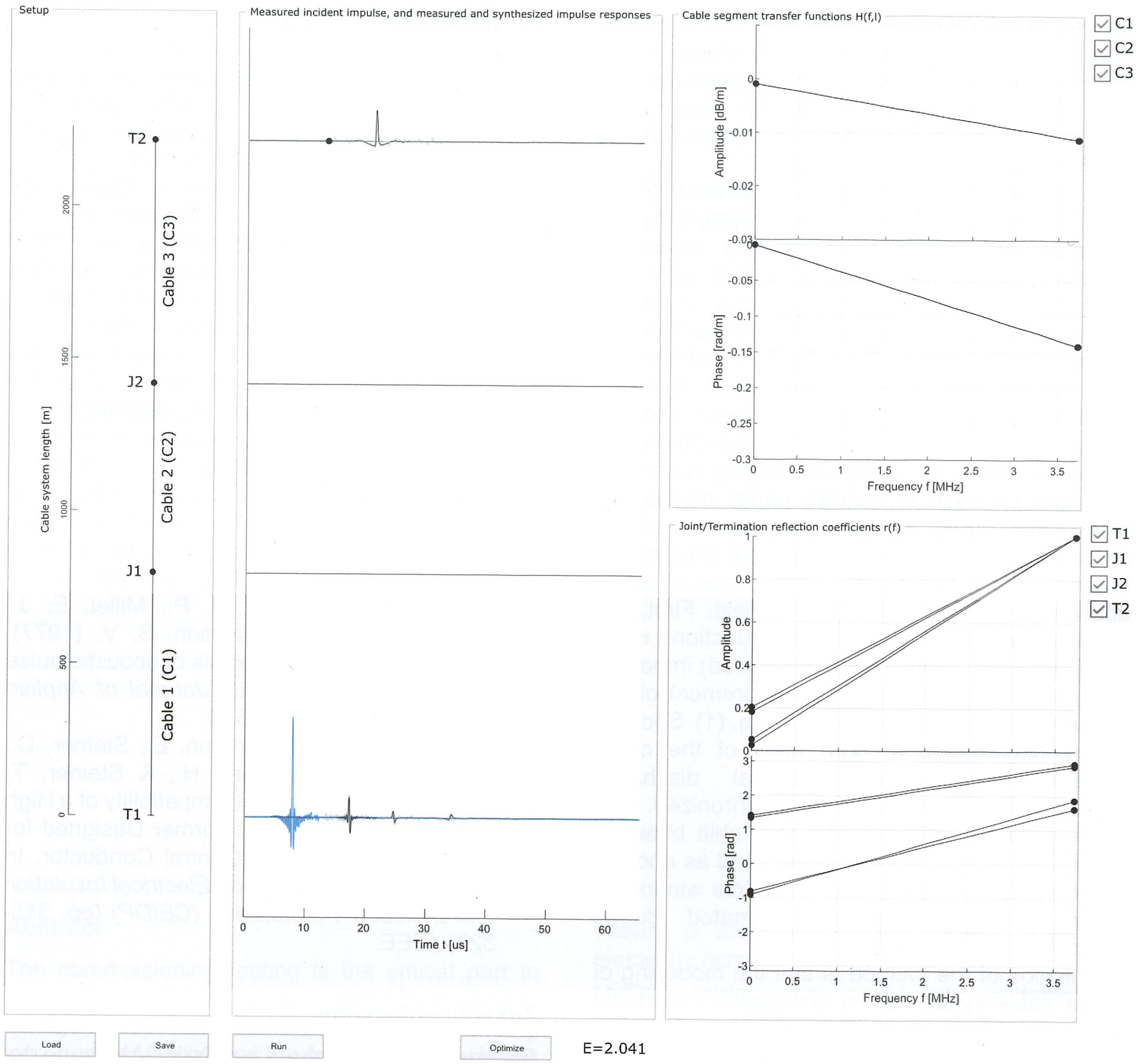

Figure 3: Matlab GUI for interactive manipulation of cable system parameters (black filled circles). Left window: User-defined cable system structure. Middle window: Measured impulse responses, where the blue curve is the incident signal, and the gray curves are the reflected and transmitted signals. The black curves are the synthesized signals corresponding to the current parameters. Right top window: Transfer functions of cables. Right bottom window: Reflection coefficients of joints and terminations.

between measured and synthesized signals. These signals are shown in *Figure 3* (middle window) and in more detail in *Figure 4*. The very good agreement between the measured signals (gray curves) and the synthesized signals (black curves) proves the functionality of the suggested method. The estimated parameters identify the cable characteristics, especially the transfer functions of the cables (upper right window in *Figure 3*) and the reflection coefficients of the joints and terminations (lower right window of *Figure 3*). In this example, the transfer functions of the cables were assumed to be identical, which is why the three estimates exactly overlay each other. No such assumption was made about the reflection coefficients, i.e., they were estimated completely independently from each other. They cluster in two groups, which is plausible since they represent two groups of physical elements, namely joints and terminations. Among the magnitude

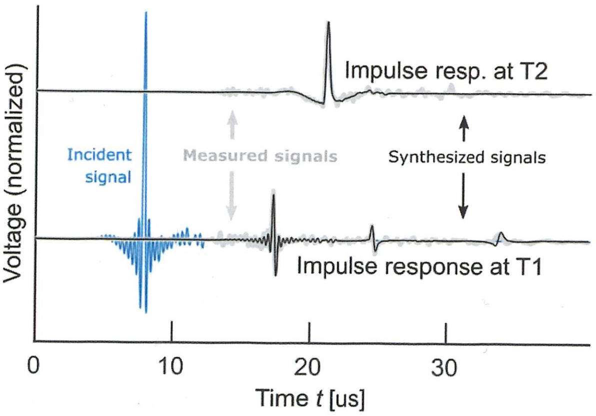

Figure 4: Measured and synthesized impulse responses with optimal parameters (see *Figure 3*).

spectra of the reflection coefficients (upper plot in lower right window), the upper lines represent the terminations, and the lower lines the joints. Among the phase spectra (lower plot in lower right window), the lower lines represent the terminations and the upper lines the joints.

One advantage of the presented method is that it is directly applicable to any cable system by the definition of another structure and measured signals. Another advantage is that it allows to estimate the spectral characteristics of single cable system components like the transfer function of one specific cable or the reflection coefficient of one specific joint without physically isolating or directly accessing them. The spectral characteristics can be estimated repeatedly for global condition monitoring of the cable system, or they can be used to localize partial discharges along the cable system for local condition monitoring. Two more advantages are of particular interest for convenient and cost-effective application of the method in the field. First, the coupling and decoupling transfer functions need not to be known, since their (combined) impact is considered internally by the measurement of the incident signal, as emphasized by Eq. (1). Second, the measurements at both ends of the cable system, and especially partial discharge measurements, need not to be synchronized. This is because the unknown temporal shift between the signals at both ends is considered as another parameter (black filled circle in middle window of *Figure 3*), which can be estimated during optimization.

A limitation of the method is that the modelling of larger cable system could considerably increase the number of parameters and therefore the computational effort. This is not only because more components are involved, but also because they may require more linear segments to model their spectral characteristics.

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Zusammenfassung

Ein erweitertes Verfahren zur Online-Messung der Übertragungsfunktionen von Kabelsystemen mit Unstetigkeiten wurde unter möglichst realistischen Bedingungen validiert. Die Methode ermöglichte eine präzise Synthese der gemessenen Impulsantworten eines Test-Kabelsystems. Darüber hinaus konnten die spektralen Eigenschaften einzelner Komponenten des Kabelsystems geschätzt werden, z. B. die Übertragungsfunktion eines einzelnen Kabels oder der Reflexionskoeffizient einer einzelnen Garnitur. Aufgrund dieser und weiterer Vorteile, die für eine einfache und kostengünstige Anwendung in der Praxis von besonderem Interesse sind, könnte die vorgeschlagene Methode ein leistungsfähiges Werkzeug für die globale und lokale Zustandsüberwachung von Kabelsystemen sein.

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