MEASUREMENT RESULTS OF A SPATIALLY-RESOLVED DIAGNOSTIC METHOD AND INFLUENCING FACTORS IN FIELD ENVIRONMENT OF MV POWER CABLES

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ABSTRACT
Diagnostic methods with spatial resolution offer the great opportunity to detect local degradations before a cable failure occurs with the major advantage of a specific replacement of these degraded sections. In this paper, measurement results of a spatially-resolved diagnostic method, published for the first time at Jicable’15, will be presented. This method uses travelling waves and their interference characteristics to generate local energy losses inside the test object (i.e. power cable). The measurement principle itself and the fundamental approach for laboratory tests will be briefly introduced. In the case of application in field environment, several optimizations and first measurements had to be performed with the goal of receiving influencing factors in real-field application, which will be specified in this article. Especially external influences such as multiple reflections caused by cable joints or measurement noise require a further in-depth analysis. The main goal will be the development of a prototype system to transfer the functional laboratory setup into field and to verify the expected results for different types of cable lines. The combination of this new approach with other diagnostic methods could lead to a non-destructive and powerful diagnostic tool.

INTRODUCTION
Condition monitoring and remaining lifetime estimation of power cables and related equipment are of greatest interest in modern power grids to maintain supply reliability, to improve investment planning and for maintenance strategy. Therefore, diagnostic methods with spatial resolution offer the major advantage to detect local degradations before a cable failure occurs and allow a specific replacement of segments of power cables with the prognosis of a short remaining lifetime. As a result, cost efficiency will increase due to the discontinuation of a replacement of complete cable routes and related civil engineering. Fig. 1 shows an exemplary measurement of a power cable condition to illustrate what spatial resolution means. The abscissa divides the test object (power cable) into cable segments of a defined length (100 m) and the ordinate categorizes the test cable between healthy and critically-aged. The z-axis can be split up to all dielectric parameters of the test object (e.g. capacitance (C), conductance (G), dissipation factor (tanδ) or permittivity) [5]. The main goal will be the development of a diagnostic tool to determine all these mentioned parameters of every cable segment with the aid of combining different methods.

Fig. 1: Exemplary measurement of a cable condition with spatial resolution

In the following, the spatially-resolved measurement principle itself and the fundamental approach for experimental measurements will be briefly introduced. This diagnostic measurement method has been tested in simulations, laboratory and field environment, which will be presented afterwards.

DIAGNOSTIC MEASUREMENT METHOD
This new spatially-resolved diagnostic technique uses travelling waves and their interference characteristics to generate local detectable electrical energy losses inside the test object. The measurement is intended to be performed offline and is definitely non-destructive by using low-voltage signals. As a result, the generated energy losses can be measured and provide a qualitative indication about the local physical condition of cable insulation using a mathematical correlation with additional model calculations.

The measurement principle is based on injecting defined pulse patterns into the test object and measuring the voltage response. Thereby, the generated travelling waves propagate with a characteristic velocity and are attenuated and distorted caused by losses inside the transmission line. Assuming the simplification of travelling waves according to [1], the propagation velocity \( v_p \) is calculated as:

\[
v_p = \frac{\delta x}{\delta t} = \frac{1}{\sqrt{L/C}} = \frac{c_p}{\sqrt{\varepsilon_r}}
\]

This velocity depends on the type of insulation material of the test object, the relative permittivity. Generally, you have to differentiate between phase and group velocity for coaxial cables, whereby the phase velocity is
frequency-dependent (dispersion). The wave impedance can be directly calculated by the discrete elements of the common transmission line model or by the ratio of voltage and current curves of the incident and reflected waves:

$$Z_w = \frac{R + j\omega L}{G + j\omega C} = \frac{u(x,t)}{i(x,t)}$$

Applying the travelling wave theory proposed in [1], the wave impedance $Z_w$ can be described for distortion-free transmission lines as follows [4]:

$$Z_w = \sqrt{\frac{L}{C}}$$

Every impedance discontinuity $k$ causes a reflection of the incident or reflected waves. In common reflectometry setups the test cable terminates with open end, so load impedance is set to infinity and the reflection factor $r_k$ is defined as [2,4]:

$$r_k = \frac{Z_{k+1} - Z_k}{Z_{k+1} + Z_k} = \frac{1}{Z_{k+1} + Z_k}$$

After the injection of predefined pulse patterns their propagation and interference characteristics are used for the detection of local electrical energy losses. In simple terms, these pulse patterns consist of uniform rectangular pulses with predetermined amplitudes and time delays between them. These temporal distances and the propagation velocity of the test object define one or more interference points (points of impact) assuming a cable termination with an open end. Fig. 2 shows an illustration of these simplified pulse patterns consisting of two rectangular pulses. On the basis of a lossless transmission line without distortion, the first pulse will be totally reflected at the open end and propagates in backward direction. At the interference point the second pulse is superimposed by the first reflected pulse. At this point of impact the electrical energy losses are increased during the interference time of both pulses.

$$E_k = \Delta t \cdot P_{V,k} = \Delta t \cdot \left( \frac{u_k^2 \cdot N}{l \cdot \left( R' + \frac{1}{Z_{w}^2} + G' \right)} \right)$$

The quadratic dependency of the voltage shows that interference characteristics of this diagnostic method lead to a significant improvement for the visibility and resolution of degraded cable segments. Furthermore, increased energy losses can be generated at one discrete point, which are maximized directly there. As a result, the time duration of overlapping reaches its maximum there, is decreasing towards both sides of the impact point and leads to a triangular function of energy loss over time. By varying the interference point systematically over different sections of the test object, the complete line can be scanned and finally analysed with spatially-resolved measurement data. According to the size of spatial resolution, the number of impact points must increase or decrease, which is synonymous to the number of measurements to be performed [5]. In comparison to common reflectometry methods or LIRA (line resonance analysis), this method can detect a wide-band signal input (frequency sweep or noise) to the test object and measures the complex input impedance over the frequency. As a result, only changes of impedance and not losses inside of the insulation material can be spatially-resolved detected [3].
The fundamental approach for laboratory measurements is comparable to the classical time domain reflectometry (TDR). The basic experimental setup (Fig. 11) consists of an AWG (arbitrary waveform generator) and a digitizer, connected to the test object for injection of the incident signal and acquisition of the response of the test object.

**SIMULATION RESULTS**

As a first step, the new method has been tested in several computer simulations with realistic parameters to verify the main functionality of its spatial resolution. To set up a functional simulation environment, discretized cable models have been implemented in MATLAB-Simulink. The resulting partial differential equations are solved with Runge-Kutta method or by numerical iteration (FDTD technique). Different types of power cables and signal cables with defined degraded sections have been analysed. In the following, the most significant results of simulation tests of mixed cable lines will be presented. In the following, the most significant results of simulation tests of mixed cable lines will be presented. 

Fig. 3 shows the simulation results of a medium voltage (MV) mixed cable line. The simulated cable has been built up of two cable types (XLPE and PILC). The first type (NA2XS2Y 12/20 kV 150 mm² RM) has a length of 500 m and the second cable part extends from 500-1000 m (NAEKEBA 12/20 kV 150 mm² RM) with a degraded section of 100 m length, which is located at 600-700 m. The degradation consists of a modification of the conductance (G) and is set to double. The y-axis represents the energy loss $E_k'$, which is normalized to a reference energy loss of an arbitrary propagation medium. This is plotted over the cable length (in meters). Initially, a homogeneous reference model is used (1 km healthy XLPE-insulated cable), which results in Fig. 3. At the beginning of the PILC section (500 m) the graph shows a peak of energy loss, which is caused by an impedance change respectively a change of permittivity.

At the end of the curve progression the energy loss increases as well, explained by the fact that $t_{data}$ is getting shorter than the pulse width itself, what is amplified by the effect of distortion. To eliminate this blind zone at the final cable part, a second measurement site at the opposite cable end is necessary.

**Fig. 4:** Simulation results of a 1 km mixed power cable (XLPE and PILC) with wave impedance correction

Fig. 4 illustrates the equivalent simulated measurement results referenced to a different propagation medium with wave impedance correction. In this case, the reference medium consists of two sections, a 500 m healthy XLPE section and a 500 m XLPE-insulated cable with a changed $Z_W$ adapted to the PILC value. The graph of Fig. 4 shows also a peak at 500 m and in contrast to the results before the section from 500-1000 m has definitely a higher level of energy loss as the first section. According to the change of $Z_W$, the reference medium can be adapted for getting better results. This change can be measured by TDR or FDR. With the aid of this reference method, the degraded PILC section from 600-700 m can also be detected and localized.

**Fig. 5:** Simulation results of a 1 km mixed power cable (XLPE and PILC) with cable type correction

The next graph (Fig. 5) shows simulation results with the same preconditions and an again changed reference medium with cable type correction. This medium now consists of a mixed line with two different cable types, the first section is XLPE-insulated (0-500 m) and the
second section consists of a PILC cable (500-1000 m). By using this further modification, the degraded part between 600 m and 700 m can be definitely identified and highlighted.

EXPERIMENTAL RESULTS

As a second step, a laboratory test site with real cable samples with a total length up to one kilometer has been set up. The power cables were replaced by coaxial signal cables (e.g. RG213). These cables have a similar construction principle (coaxial) and insulation material (PE), similar electrical characteristics and the advantage of a wave impedance of 50 Ω. The overall length of the test object, the locations, length and kind of degraded sections (RG174, RG58, non-reflective test object, etc.) have been modified. In the case of the following experimental measurement results, the degraded part consists of a non-reflective test object, which can be seen in Fig. 6.

Fig. 6: Photograph of a non-reflective test object

This object is composed of an aluminium profile (outer conductor) and a coaxial arranged brass tubing (inner conductor). The degradation characteristics can be varied by soldering discrete components (e.g. resistors) on top of the aluminium profile. The brass tubing has the same resistance per unit length as the signal cable (RG213) before and after the degraded section and is exactly arranged for a $Z_w$ of 50 Ω.

As a result, this non-reflective test object allows a variation only of the dielectric characteristics without any undesirable side effects. Fig. 6 shows three elements, which are each 1 m long and connected to a test object with a total length of 3 m. The results of two laboratory measurements are illustrated in the graph of Fig. 7. The blue curve represents the measurement of a 801 m long RG213 cable with a degraded section from 355-358 m and the red curve of a 740 m long RG213 cable, whose degraded section extends from 400-403 m and consists of the non-reflective test object (Fig. 6) in both cases. The test object can be definitely identified and localized at both installation points. The next graph (Fig. 8) shows two additional measurements with a total cable length of approx. 740 m, but with different degraded sections. The measurement setup of the blue curve is degraded at 400-402 m with the shortened non-reflective test object (length of 2 m). Concerning the red curve, the degraded part consists of a 1 m long RG58 cable. In both cases, the shorter degraded sections can be detected and localized. Due to the shortening of the degradation, the peak of the blue curve decreased in comparison to the measurement of Fig. 7 (red curve). The variation of the dielectric characteristics between RG58 and RG213 is very small, but there is a significant change of the resistance per unit length. This explains the negative maximum of energy loss in the red curve of Fig. 8, which represents primarily the influence of increased conductor losses.

Fig. 8: Measurement results of coaxial signal cables (RG213) with different degraded sections

INFLUENCING FACTORS IN FIELD

For field measurements, connection conditions and complexity of the measurement setup are changed in contrast to the laboratory environment. During first measurements in field environment several influencing factors have been determined. By contacting the test object, which can be exemplary seen in Fig. 9, there is an as short as possible direct contacting necessary. In addition to that, an impedance matching between 50 Ω (measuring equipment) and the wave impedance of the test object must be implemented to avoid distortion of the
incident signal and to reduce reflections at impedance discontinuities because they have a strong impact on the measurement results.

**Fig. 9:** Photograph of contacting a new XLPE cable

Fig. 10 shows a measurement of a 2020 m long XLPE-insulated cable (NA2XS2Y 12/20 kV 150 mm² RE) with a very flat curve as is to be expected. This result represents a good reference for further field measurements and for the investigation of expected influencing factors.

**Fig. 10:** Field measurement result of a new XLPE cable

Before each field test, the velocity, \(Z_0\), length and type of the test object have to be measured or determined. Further influencing factors are the cable termination, type of substation or parallel cables. The influence of noise during the measurement e.g. caused by external interference can be strong, which could lead to useless results. To minimize that influence, the signal-to-noise ratio (SNR) must be increased and additional methods of noise cancelling and signal processing must be used.

**Fig. 11:** Schematic prototype system

Fig. 11 describes a schematic of a prototype system for field measurements with an amplifier, impedance matching and a hybrid circuit for signal separation. This setup will be the favorite measurement system for future field tests.

**CONCLUSION AND OUTLOOK**

In this paper, a new approach for spatially-resolved diagnosis of power cables has been briefly introduced and the theoretical background explained. This method has been verified by the results of model-based computer simulations and laboratory measurements, which show a good correlation. The simulation results of mixed cable lines with an adaptable reference medium point out that line setups close to reality can be further analysed with this method by using the corresponding reference model. In contrast to well-established diagnostic methods, small dielectric changes inside of power cables with a length of some meters within an overall cable length of several hundreds of meters (e.g. 800 m RG213) can be diagnosed and localized in laboratory environment. This possibility would result in a reliable condition diagnosis with spatial resolution. On the basis of first measurements in field environment, several influencing factors have been determined and form the basis for future work. Important steps in the future will consist in a further development of the diagnostic method by continuing laboratory measurements. External influences such as multiple reflections caused by cable joints or measurement noise will have to be further investigated. The main goal will be the development of a functional prototype system to transfer the experimental setup into field and to verify the expected results in consideration of the determined influencing factors.

**REFERENCES**


