Determining Wave Propagation Characteristics of MV XLPE Power Cable using Time Domain Reflectometry Technique

G. Murtaza Hashmi[1], Ruslan Papazyan[2], and Matti Lehtonen[1]

[1]Power Systems and High Voltage Engineering, Helsinki University of Technology (TKK), Finland
murtaza.hashmi@tkk.fi, matti.lehtonen@tkk.fi
[2]Department of Electrical Systems, The Royal Institute of Technology (KTH), Stockholm, Sweden
ruslan@kth.se

Abstract

In this paper, the wave propagation characteristics of single-phase medium voltage (MV) cross-linked polyethylene (XLPE) power cable are determined using Time Domain Reflectometry (TDR) measurement technique. TDR delivers the complex propagation constant (attenuation and phase constant) of lossy cable transmission line as a function of frequency. The frequency-dependent propagation velocity is also determined from the TDR measurements through the parameters extraction procedure. The measurement results can be used to localize the discontinuities as well as the design of communication through distribution power cables.

1. Introduction

THE use of solid dielectric power cables for underground transmission/distribution has been increasing over the past twenty years. This trend is likely to continue since the cable material, insulation, and manufacturing process are steadily improving. While the primary purpose of these transmission/distribution lines is to deliver power at 50 or 60 Hz, they are also capable of carrying high frequency signals reasonably well; i.e., their high frequency performance is comparable to some commercial rf coaxial cables. Consequently, this capability is likely to be utilized more and more in the future for applications such as diagnostics, system protection, and load management. While there is some data available on the wave propagation characteristics in these conductors, there seems to have been no systematic study to date in this area [1].

There is a growing interest in the study of high frequency properties of distribution lines. One major reason is the potential to use widely distributed cable networks for high capacity data communications [2]. The measurements of such studies are generally carried out at high frequencies, up to about 100 MHz, by sending pulses or signals from a point, which then travel through the conductor that essentially acts as a transmission medium. The incident and the reflected signals are analyzed. These signals are distorted or changed in one way or the other by the transmission medium, and the reconstruction techniques are applied to get the desired wave propagation characteristics (propagation constant; attenuation and phase constant, and propagation velocity) from the measurements. Frequency and time domain techniques are used, hence, the need for understanding basic electromagnetic theories and their practical applications is prerequisite [3, 4].

Any signal will loose some of its energy or signal strength as it propagates down the conductor. This loss is attenuation, which is frequency-dependent. Propagation velocity is a specification of the conductor indicating the speed at which a signal travels down through it. Different conductors have different propagation velocities. Typically, propagation velocity of a communication cable under test is listed in the cable manufacturer's catalogue. However, this figure for medium voltage (MV) power cables is not specified. In this case, a required procedure is to make time domain reflectometry (TDR) measurement on a known length of the conductor. An even more accurate way to estimate propagation velocity is to make measurements from both ends of the conductor. Propagation velocity depends upon the phase constant and the frequency of the impressed signal.

The paper is organized in the following pattern. Section 2 presents transmission line analysis and Section 3 gives a general theoretical background of TDR. Section 4 depicts the drawing of the TDR measuring set-up. Section 5 describes parameters extraction procedure from the measurements. Section 6 gives the wave propagation characteristics results of MV XLPE power cable and the concluding remarks are given in Section 7.

2. Transmission line analysis

In the following analysis, th power cable is considered as a transmission channel that can be represented by a coaxial transmission line and is approximated as a close form of the two-wire transmission line. According to [5], the two-wire transmission line must be a pair of parallel conducting wires separated by a uniform distance. Based on the above considerations, the single-phase power cable is regarded as a distributed parameter network, where voltages and currents can vary in magnitude and phase over its length. Therefore, it can be described by circuit parameters that are distributed over its length.

A differential length Δz of a transmission line is described by its distributed parameters *R, L, C,* and *G* as shown in Fig. 1. *R* defines the resistance per unit length for both conductors (in Ω/m), *L* defines the inductance per unit length for the both conductors (in H/m), *G* is the conductance per unit length (in S/m), and *C* is the capacitance per unit length (in F/m). The quantities $v(z, t)$ and $v(z+\Delta z, t)$ denote the instantaneous

Ruslan Papazyan received PhD degree from KTH in year 2005. Currently, he is affiliated with ABB Power Technologies in Sofia, Bulgaria.

voltages at locations z and $z+\Delta z$ respectively. Similarly, $i(z, t)$ and $i(z+\Delta z, t)$ denote the instantaneous currents at the respective locations. In the circuit of Fig. 1 (b), applying Kirchhoff's voltage and current laws respectively, the following two equations can be obtained as [6]:

$$v(z,t) - R\Delta z \cdot i(z,t) - L\Delta z \cdot \frac{\partial i(z,t)}{\partial t} - v(z+\Delta z,t) = 0 \qquad (1)$$

$$i(z,t) - G\Delta z \cdot v(z+\Delta z,t) - C\Delta z \cdot \frac{\partial v(z+\Delta z,t)}{\partial t} - i(z+\Delta z,t) = 0 \qquad (2)$$

If v and i are expressed in phasor form, i.e. $v(z,t)=\mathrm{Re}[V(z)\cdot e^{j\omega t}]$ and $i(z,t)=\mathrm{Re}[I(z)\cdot e^{j\omega t}]$ and when $\Delta z \to 0$, the time harmonic line equations can be derived from (1) and (2) as:

$$-\frac{dV(z)}{dz} = (R + j\omega L)I(z) \qquad (3)$$

$$-\frac{dI(z)}{dz} = (G + j\omega C)V(z) \qquad (4)$$

The coupled time harmonic transmission line equations can be combined to solve for $V(z)$ and $I(z)$ as:

$$\frac{d^2V(z)}{dz^2} = \gamma^2 V(z) \qquad (5)$$

$$\frac{d^2I(z)}{dz^2} = \gamma^2 I(z) \qquad (6)$$

where

$$\gamma(\omega) = \alpha(\omega) + j\beta(\omega) = \sqrt{(R + j\omega L)\cdot(G + j\omega C)} \qquad (7)$$

γ is the propagation constant whose real and imaginary parts, α and β, are the attenuation constant (Np/m) and phase constant (rad/m) of the line respectively. ω is the angular velocity (rad/sec), where $\omega=2\pi f$, and f is the frequency (Hz) of the propagated signal. The complex propagation constant is also given as:

$$\gamma(\omega) = \sqrt{Z \cdot Y} \qquad (8)$$

where $Z=R+j\omega L$ is the series impedance per unit length and $Y=G+j\omega C$ is the shunt admittance per unit length of the line. The characteristic impedance of the line is given as:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{Z}{Y}} \qquad (9)$$

It is clear from (7) and (9) that γ and Z_0 are the characteristic properties of a line whether or not the line is infinitely long. They depend on $R, L, G, C,$ and ω but not on the line length [6].

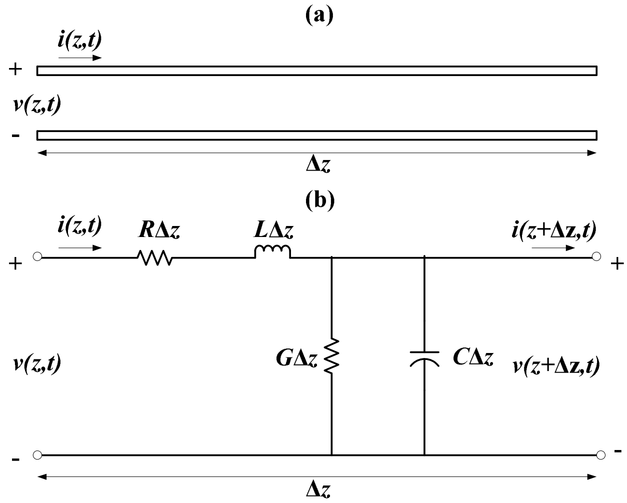

Fig. 1. (a) The voltage and current definitions of two-wire transmission line (b) The equivalent lumped-element circuit

3. Theoretical background of TDR

The most common method for evaluating a transmission line and its load has traditionally involved applying a sine wave to a system and measuring waves resulting from discontinuities on the line. From the measurements, the standing wave ratio (SWR) is calculated and used as a figure of merit for the transmission system. When the system includes several discontinuities, however, the SWR measurement fails to isolate them. In addition, when the broadband quality of a transmission system is to be determined, SWR measurements must be made at many frequencies. This method soon becomes very time consuming and tedious.

When compared to other measurement techniques, TDR provides a more intuitive and direct look at the characteristics of the device under test (DUT). Using a high speed oscilloscope and a pulse generator, a fast edge is launched into the transmission line under investigation. The incident and the reflected voltage waves are monitored by the oscilloscope at a particular point on the line. The block diagram of a time domain reflectometer is shown in Fig. 2 [7, 8].

Another aspect of TDR measurements is that it demonstrates whether losses in a transmission system are series or shunt losses. All of the information is immediately available from the oscilloscope's display. Additionally, TDR gives more meaningful information concerning the broadband response of a transmission system than any other measuring technique [7].

TDR instruments work on the same principle as radar, but instead of air, they work through wires. A pulse of energy is transmitted down a line. When the launched propagating wave reaches at the end of the line or any impedance change along the transmission line, part or all of the pulse energy is reflected back to the instrument. This reflected wave is energy that is not delivered to the load. The magnitude of the impedance change can be calculated using the reflection coefficient Γ, defined in the frequency domain as the ratio between the reflected voltage wave V_r and the incident voltage wave V_i. The distance to the impedance change can also be estimated knowing the speed of the propagated wave. Γ is related to the load impedance Z_L and the characteristic impedance of the line Z_0, by the following expression [5]:

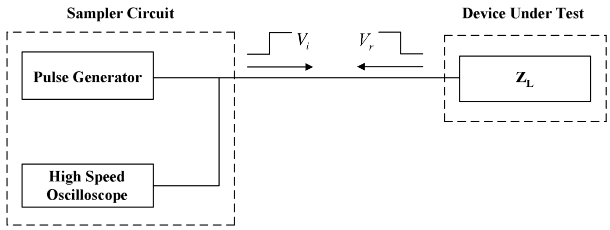

Fig. 2. Functional block diagram of a time domain reflectometer

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{10}$$

The transmission coefficient T is given as:

$$T = 1 + \Gamma = \frac{2 \cdot Z_L}{Z_L + Z_0} \tag{11}$$

4. TDR measuring set-up

TDR measurements require a special test arrangement including a high speed digitizing signal analyzer (DSA) and a fast leading-edge pulse generator e.g. producing a pulse of 5 V amplitude with 10 ns pulse-width having rise-time of 200 ps. DUT is a single-phase, 95 mm^2 aluminum conductor, 20 kV XLPE insulated power cable having 6 m length. Although not mentioned when theoretically introducing the concept of time domain reflectrometers, there are two more components in the measurement set-up, which are of extreme importance for the quality of TDR testing. These are the T-connection needed for monitoring the incident and reflected pulses by DSA, and the connection between the measuring equipment and the DUT. The TDR measuring set-up including DUT and MS is depicted in Fig. 3 [9].

In practice, a narrow electric pulse is applied to the DUT and the incident and reflected waves are measured by means of a DSA at T-connection. The measured data is transferred to the computing system (laptop) connected to the DSA through the general purpose interface bus (GPIB), where the analysis is done using MATLAB [9].

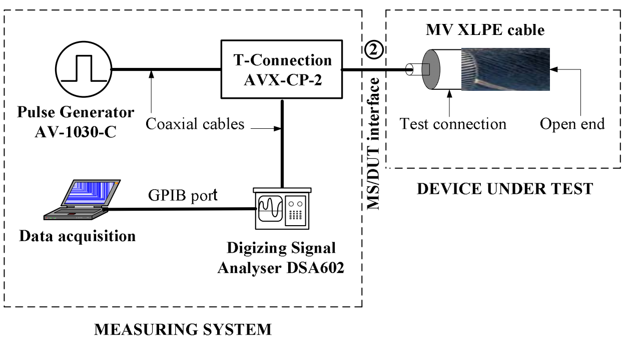

Fig. 3. Schematic drawing of the TDR measuring set-up [9]

5. TDR parameters extraction method

The propagation constant of a wave traveling along a transmission line segment of a length l is the complex voltage ratio between the output (reflected pulse V_{out}) and the input (incident pulse V_{in}) of the line segment [10].

If the cable is considered as a linear system, this ratio represents the cable transfer function $H(\omega)$ and the following relation holds:

$$H(\omega) = \frac{V_{out}}{V_{in}} = e^{-\gamma(\omega)l} \tag{12}$$

In the measuring system, the incident and the reflected pulses are measured in the time domain. For a TDR measurement, V_{out} is the signal coming back after reflection at the open end of the cable. Since the measurements are done at the input side of DUT (see Fig. 3), the total traveling distance is twice the length of the DUT, i.e. $2l$. These time domain measurements are then transformed into the frequency domain by the use of the fast Fourier transforms (FFTs) in MATLAB.

Generally, MV power cables have characteristic impedance in the range of 25 Ω. As the power cable has an impedance different from that of the MS (50 Ω), a significant reflection occurs at the MS / DUT interface (see Fig. 3). This reflection is recognized to have a major influence on the precision of the cable response measurement. A calibration procedure has already been developed for this purpose in order to identify and remove the influence of the different effects on the parameters extraction [9]. The transfer function can be modified after calibrating MS as:

$$H(\omega) = e^{-\gamma 2l} = \frac{V_{-3} V_{-3}^{short}}{\left(V_{-3}^{m}\right)^2 - \left(V_{-3}^{short}\right)^2} \tag{13}$$

where V_{-3}^{m} is mismatch reflection, V_{-3} is DUT response, and V_{-3}^{short} is the measured signal reflected at the short-circuited end of cable 2 and is referred as incident pulse. The attenuation and phase constant can be deduced from (13) as:

$$\alpha = -\frac{1}{2l} \times \ln\left|H(\omega)\right| \tag{14}$$

$$\beta = -\frac{1}{2l} \times \angle H(\omega) \tag{15}$$

The propagation velocity v (m/s) can be determined using phase constant as:

$$v = \frac{\omega}{\beta} = \frac{2\pi f}{\beta} \tag{16}$$

6. Results and discussion

The following two TDR measurements have been captured in the data acquisition system (see Fig. 3) and are processed in MATLAB for the extraction of wave propagation characteristics from the measurements.

i. *TDR-DUT response:* This measurement is captured when the DUT is open-circuited. The time domain waveform for this measurement is shown in Fig. 4.
ii. *TDR-calibration:* This measurement is captured when the coaxial cable 2 is short-circuited. The time domain waveform for this measurement is shown in Fig. 5.

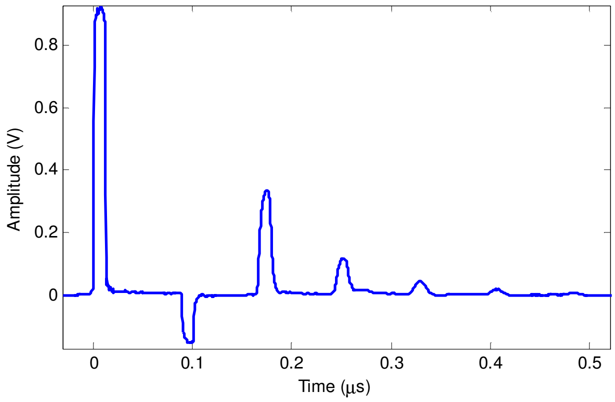

Fig. 4. TDR response when the DUT is open-circuited

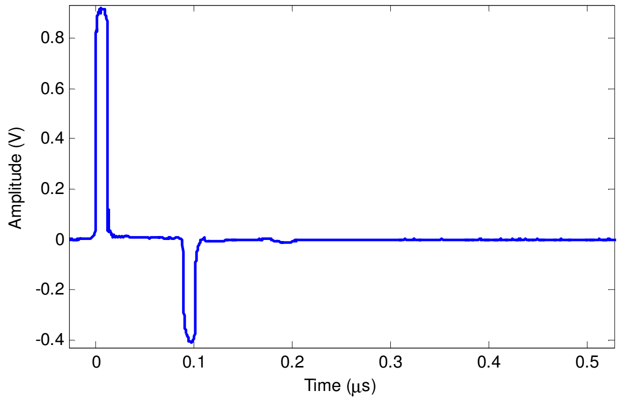

Fig. 5. TDR response when the coaxial cable 2 is short-circuited

The mismatch reflection V_{-3}^{m} and the DUT response V_{-3} are extracted from the TDR-DUT response measurement, while the incident pulse V_{-3}^{short} is extracted from the TDR-calibration measurement. These pulses are taken and padded with zeros up to the length of N = 2^n; for n = 16. The modified zero-padded waveforms are shown in Fig. 6. Using FFTs of the modified zero-padded pulses in (13-16), the measured attenuation constant and wave propagation velocity in the DUT can be determined, and the dependency of these parameters on the frequency of the propagated signals is shown in Fig. 7. A time step of 0.2 ns is used in the Fourier analysis.

It is revealed from Fig. 7 that the attenuation and propagation velocity of the signals in the cable under investigation are fairly constant at lower frequencies (0.02 dB/m and 154 m/μs). At higher frequencies (beyond 10 MHz), these parameters begin to increase with an increase in frequency of the propagated signals.

The significant signal attenuation is attributed to the highly dispersive materials of the conductor insulation/shields and concentric neutral beds. The latter is used for improved potential distribution and mechanical properties at the interface between concentric neutral and the insulation shield.

The resolution of the measured wave propagation characteristics (see Fig. 7) is good up to 81 MHz, beyond which it is lost in the certain repetitive disturbances or noise level. One possible way to explain the disturbances in the measurements is to have a look at the FFTs of the incident pulse and DUT response as shown in Fig. 8. The magnitude of these FFTs remains constant up to 10 MHz, therefore, the attenuation is also constant up to this range of frequency.

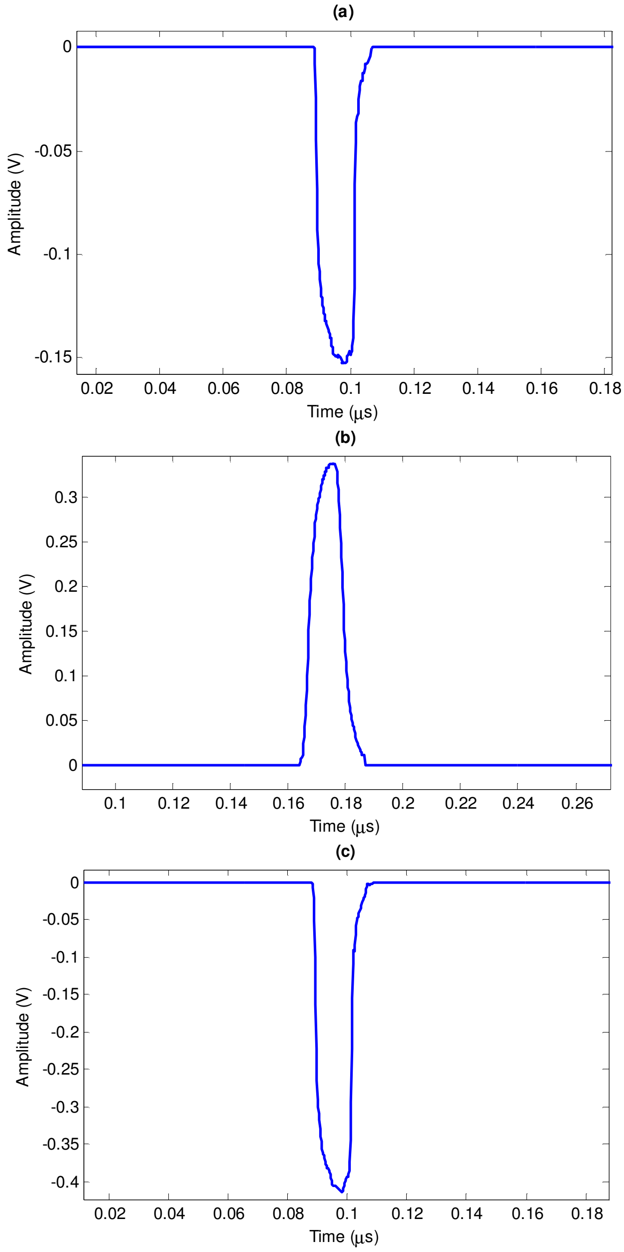

Fig. 6. Modified zero-padded waveforms; (a) mismatch reflection, (b) DUT response, and (c) incident pulse

Beyond this frequency, FFT of the DUT response starts to decrease at a higher rate, resulting in linear increase in the attenuation. Beyond 81 MHz, FFTs suffer in noise that has different values than the actual functions. The noise level has some peaks, which are taken into account instead the actual functions, resulting in the noisy peaks in the attenuation.

Another mathematical interpretation is on the basis of the Fourier transform function. For an ideal square pulse as [10]:

$$f(t) = \begin{cases} 1, |t| < a \\ 0, |t| > a \end{cases} \tag{17}$$

The analytical Fourier transform function is in the form:

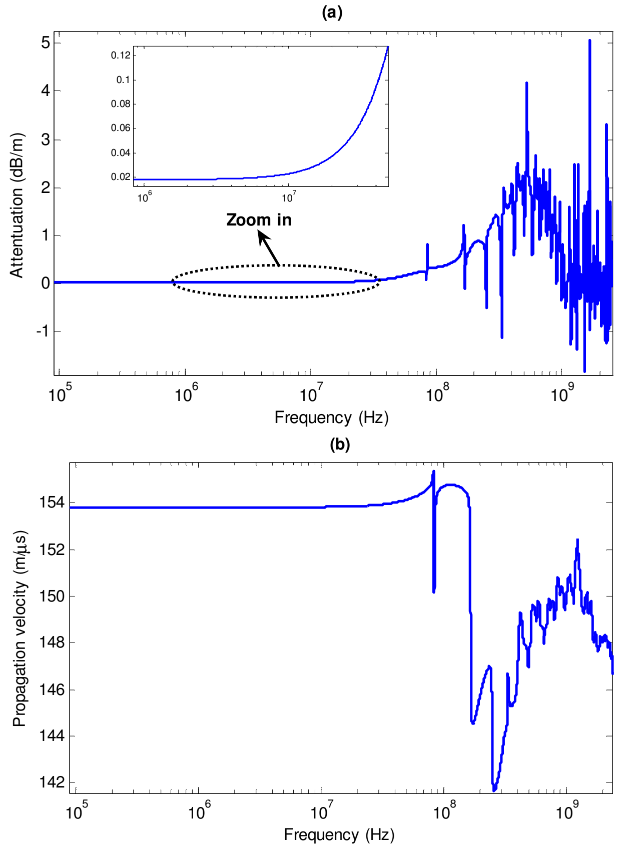

Fig. 7. Measured wave propagation characteristics of single-phase MV XLPE power cable; (a) attenuation constant, (b) and propagation velocity

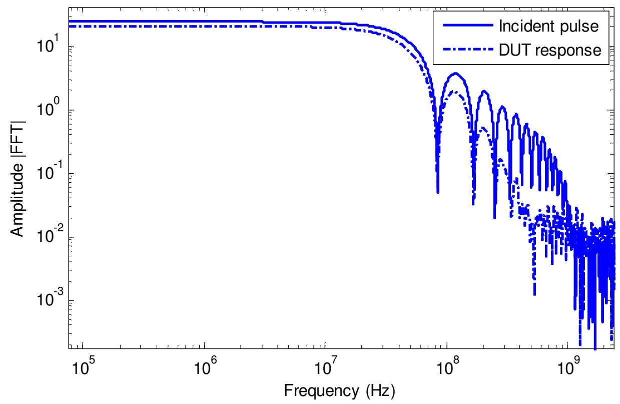

Fig. 8. FFTs of the incident pulse and the DUT response

$$F[f(t)] = \frac{2\sin a\omega}{\omega}, \omega > 0 \quad (18)$$

It can be concluded that Fourier transform function would periodically equal to zero; the zero crossings can be defined as:

$$f_0 = \frac{k}{2a} \quad (19)$$

where $k=1,2,....,N$ and f_0 is the frequency at which the Fourier function equals to zero. In the presented case the pulse width for the incident signal is $2a$=12 ns (see Fig. 4), so it could be expected that zero crossings and the respective numerical artefacts to be in the vicinity of $f_0 = 81\ k$ MHz.

7. Conclusions

The TDR measurement technique has been used to extract the frequency-dependent wave propagation characteristics of single-phase MV XLPE power cables.

It is revealed that the signal attenuation and propagation velocity in power cable are fairly constant at lower frequencies (0.02 dB/m and 154 m/µs), but these parameters are frequency-dependent at higher frequencies (beyond 10 MHz), i.e. their values increase by increasing the frequency of the propagated signals. The wave propgation characteristics of power cable are changing at different voltage levels because of the difference in cable construction based on insulation design. The TDR measurement results on XLPE power cable can be used to localize the discontinuities as well as the design of communication through distribution power cables.

8. References

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