Test Procedures of Electric Underground Electric Lines Using Real Time Reflectometry and Spectrum Analysis

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Abstract*—Detecting and locating faults in LEC cables is a complex activity that basically involves conducting measurements and controlling the cable or tracking the indications of the measuring and signaling equipment during the switching operations performed during the fault detection. The fault type and its location are determined by specialized equipment operating on real-time reflectometry. At one end of the electric cable line, an impulse with a fast rise slope is injected, and the reflected impulse senses the impedance changes or the impedance discontinuities, provided the incident signal is reflected back to the source. Pulses generated by the source and the reflected ones are typically displayed on the screen of the analyzer, initially set at a certain pulse propagation rate, which allows the distance between the analyzer mounting location and the defect location to be determined. This paper examines the possibilities of time domain reflectometry (TDR) to locate and identify faults along a cable, due to the degradation of the cable insulation and of inappropriate connections. The total energy losses of a power system consist of technical and commercial losses. Commercial losses are reduced by detecting new cable connections that allow unauthorized use of electricity. The analysis of cable TDR impulses is done by modeling the system as a line, which is used in the design phase, to facilitate the adjustment to the cable voltage and to the network frequency. Through TDR technique, the cable provides a response pulse, a signal that distorts the injected impulse. Distortion is caused by cable losses, which are frequency dependent. The longer the cable, the greater the distortion. Simply, the two major sources of distortion of the TDR impulse are mitigation and dispersion. The paper also includes the analysis of experimental data on low voltage cable using spectral analysis of reflected impulses.

***Keywords*-cable, fault location, fault types, spectrum analysis, time domain reflectometry.**

I. INTRODUCTION

The most common method for evaluating a transmission line and its load traditionally involves the application of a sine wave to a system and the measurement of waves resulting from line discontinuities. Compared with other measurement techniques, time-domain reflectometry provides a more intuitive and direct view of the DUT features.

Cable power lines are equipped to transport and distribute electrical power at different points in the network. They are mounted underground, in channels or in tunnels, overhead or multi-line cables. The elements of the lines include the power cables, connectors, junctions, sleeves, and internal or external terminal ends. The line of the electric line is the projection in the horizontal plane of the line, the depth of laying being chosen depending on the nature of the place where the line and the obstacles cross over. The power cable is the cable used in primary circuits. According to the construction type of the cable, Fig. 1, monopolar or multipolar cables are distinguished.

Figure 1. Different types of cables

During probation, the general behavior of the operation of the supplied voltage line is checked, namely: overburdening or partial discharge on insulators; possible imperfect contacts; the functional check of the controls, signaling and jamming, circuit breakers [1], [2] and separators; sample interaction of protection [3]; the indication of the measuring instruments; measuring of the capacitive current; the voltage at both ends, and inscribing both ends for identification and security.

The main problem of underground electrical lines is the detection of their own defects. The causes of defects in cables are numerous and of different nature: manufacturing defects; insulating structural cracks and air or gas inclusions in the cable dielectrics, etc. The most important defects are: insulation faults with or without ground contact; interruptions or serial ohmic defects; discharges or insulation breakings; coupling defects; discontinuity defects, and cable jacket faults.

Time-Domain Reflectometry (TDR) is based on a functioning principle similar to how the radar works. At one end of the electric cable line, a pulse with a fast rise speed is injected, and the impulse reflects Ur sensing the impedance changes or impedance discontinuities, provided the signal incident is reflected to the source. The reflected impulse may contain positive or negative components, which highlight the increase or decrease of the impedance, relative to the characteristic impedance of the analyzed cable. The pulses generated by the source, Fig. 2 and the reflected ones are usually graphically presented on the screen of the analyzer used, Fig. 3, which is initially set at a certain pulse propagation velocity, which represents the quantity that determines the distance between the analyzer and the place of defect.

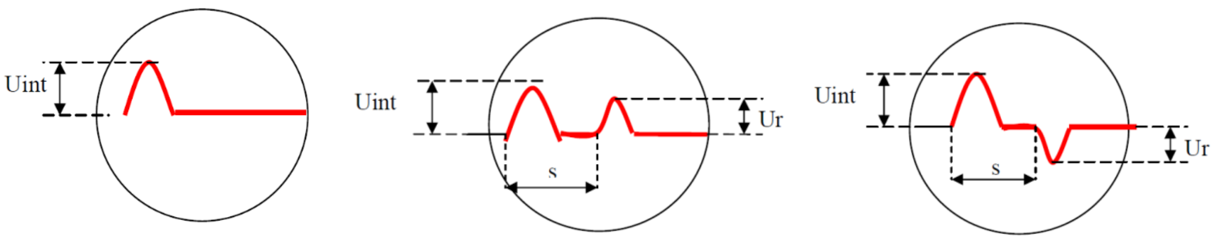

Figure 2. Injected impulse U_{int} and reflected impulse U_r.

This information can also be used to locate the discontinuities indicated in the reflected impulses. In addition, the reflected pulse shapes, displayed by the instrument indicate the nature of the discontinuity. The amplitude of the reflected impulse allows the calculation of the reflection coefficient ρ for a certain discontinuity, using the relation:

$$\rho = \frac{Z_d - Z_0}{Z_d + Z_0} \tag{1}$$

where Z_0 is the impedance of the cable, and Z_d is the impedance until the point of discontinuity. The value of the reflection coefficient ρ varies from 1 (open circuit) to -1 (short-circuit). A null reflection coefficient indicates the lack of reflection, which means that the impedance to the end of the cable is equal to the characteristic impedance of the conductor under test.

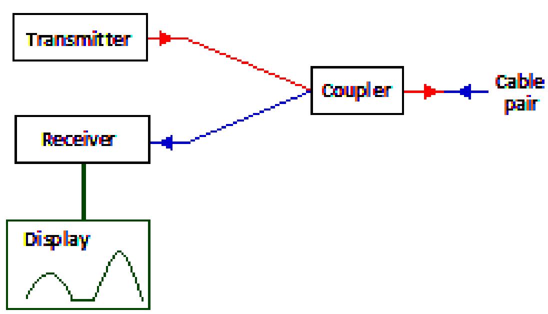

Figure 3. Transmitted impulse and received displayed impulse.

This technique is usually applied to non-live cables. The pulse with a steep slope is applied between the low-voltage conductor and the cable insulation screen, on the cable connection cells or the cable end. The impulse is transmitted through the cable, and the reflections are caused by the discontinuities and the impedance changes. Impulses generated by the impulse transmitter and those reflected at the pulse receiver are displayed in real time on the analyzer and interpreted by the testing staff. Since the pulse propagation velocity of the impulse generated by the impulse transmitter is known or at least can be estimated, the time can be converted into distance and consequently the point of defect can be located. The experience of the testing staff can appreciate the cause of discontinuity due to an impedance modification by analyzing the shape and the magnitude of the signals reflected at the impulse receiver. The duration of the test, including interpretation time, is between five and ten minutes after the TDR analyzer and test cables have been connected. However, one of the most important issues in making TDR measurements is that the length displayed on the TDR analyzer screen is the real length of the cable. One must not confuse the indication on the TDR analyzer screen with the distance at the surface between the conductor ends. This raises two issues that need to be addressed in detail: the first issue is how the cable system was arranged underground and how it affects the precise location; the second is the propagation velocity error V_p that directly affects the determination of the cable route due to the interpretation of the results. An illustration of different positions for different cable lengths is shown in Fig. 4.

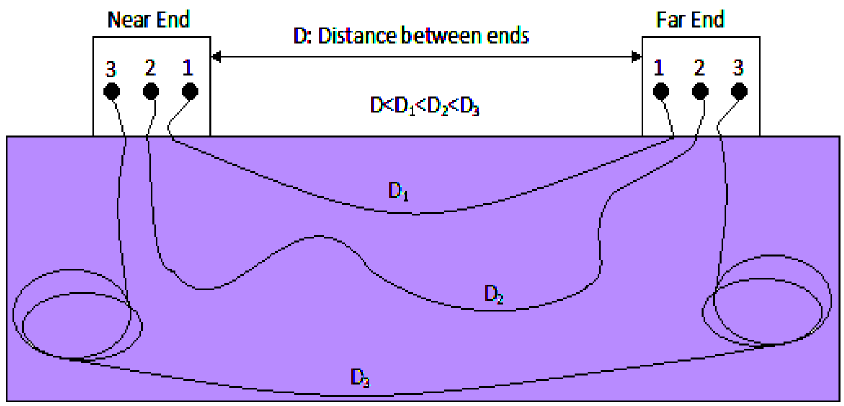

Figure 4. Distance Between Ends

II. Diagnosis through the Waveform Analysis and Length Comparison

Interpreting the signal for a correct TDR status assessment requires a certain experience. TDRs with similar status evaluations, but with changes, even if the cable is of the same type and length, can be presented. In a series of field tests, a connection failure occurs after testing a power cable in an area where the cable has suffered more defects. Upon examination, water in the connection terminal might appear. The length of the tested cable and the estimated fault location based on the TDR analyzer records are correlated with the actual cable length and the location of the fault. During another series of cable tests, a significant change in the typical impedance of cable insulation detected at a location by TDR testing may occur.

The comparison of the length is simple and particularly useful for three-phase circuits, because the phase length is almost identical. Measurements performed at both ends of the system are effective for identifying single or multiple discontinuities in the neutral conductor. For example, the method can be applied to a shielded three-phase cable.

The most important conditions for TDR analysis [5] consist in the knowledge of the characteristic impedance Z_0 and the propagation velocity V_{op}. The characteristic impedance is used for the TDR analyzer settings so that it matches with the characteristic impedance of the cable, in order to improve pulse transfer from the TDR analyzer to the test cable. The propagation velocity V_{op} is used to characterize the cable, identify connections and possible anomalies. One way to minimize the identification error is to use the correct propagation velocity V_{op} for the cable under test. The propagation velocity V_{op} is a cable specification that indicates the speed at which high-frequency signals are transmitted through the cable. To ensure accurate distance measurements, the V_{op} propagation rate of the cable must be determined. V_{op} is generally defined by reference to the speed of light in vacuum (0.3048 m/ns), and a percentage of 100%. All other pulses are transmitted through the cable at lower speeds, representing a percentage of the speed of light. Knowing the propagation velocity V_{op} of a cable is the most important factor when a TDR analyzer is used to determine the fault point. The analyzer can be calibrated to the cable by correctly inserting the propagation velocity. The propagation velocity of a cable is determined by the insulation dielectric material, the operating temperature and its life service. Normally, the propagation speed of a test cable is given in the data sheet

III. Time Domain Mode with Vector Network Analyzer

Even though the Vector Network Analyzer provides a TDR – like display, there are differences between traditional TDR and Vector Network Analyzer (VNA) time domain techniques. Traditional TDR measurements are made by launching an impulse or step into the test device and observing the response in time with a wideband receiver such as an oscilloscope. The VNA transform used resembles time domain reflectometry, however, the analyzer makes swept frequency response measurements and mathematically transforms the data into a TDR – like display. The Vector Network Analyzer measures the frequency response of the device and mathematically calculates a time domain transform of the data to convert the frequency domain information into the time domain, with time as the horizontal display axis. The Vector Network Analyzer makes this mathematical calculation using the – Z Fast Fourier Transform technique.In the reflection mode, a network analyzer measures reflection coefficient as a function of frequency. The reflection coefficient can be viewed as the transfer function relating the incident voltage and reflected voltage. An inverse transform converts the reflection coefficient to a function of time (the impulse response). Step and impulse responses can be calculated by convolving the input or pulse with this reflection coefficient impulse response. In the transmission mode, a network analyzer measures the transfer function of a two-port device as a function of frequency. An inverse transform converts the transfer function to the impulse of the two-port device. Step and impulse responses can be calculated by convolving the input step or pulse with the impulse responses. The resulting measurement is a fully – corrected time domain reflection or transmission response of the test device, displayed in near real-time. Response values (measured on the vertical axis) now appear separated in time or distance, providing valuable insight into the behavior of test device beyond simple frequency characteristics. Figs. 5a and 5b illustrate the frequency and time reflection responses of the same cable. The frequency domain reflection measurement (Fig. 5a) is the composite of all the signal reflected by the discontinuities present in the cable over the measured frequency range. It is difficult to estimate the location of those mismatches. However, the time domain measurement (Fig. 5b) shows the effect of each discontinuity as a function of time (or distance) and easily allows one to determine the location and magnitudes of the mismatches.

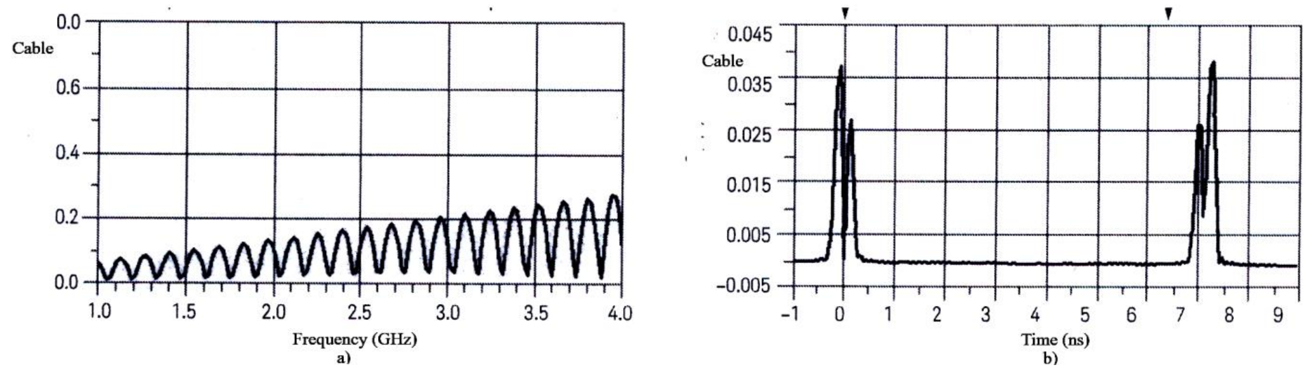

Figure 5. a) Reflection responses of a cable in frequency domain; b) Reflection responses of the same cable in time domain.

IV. CONCLUSIONS

The applications of the analyzed procedures meant to determine the defective cable location are established by comparing the advantages and disadvantages of Real-time Reflectometry and Vector Network Analysis.

Real Time Reflectometry - TDR is a measurement method which has several advantages and also drawbacks.

The main advantages are:

- TDR testing is easy to use;
- Real-time Reflectometry equipment is suitably dimensional and low in cost;
- The TDR equipment uses low voltage below the U_0 value of the nominal voltage of the cable;
- Periodic testing provides information and data that enhance the facility for future testing by studying changes and trends over time, in order to preserve accurately preserved the measured data;
- Locates cable zones with impedance problems.

The main drawbacks are:

- Requires qualified personnel for testing and analysis of measurement results;
- Changes of the injected pulse due to the noise effect may appear at the near end of the cable.
- The length of the cable inside the zone depends on the injection method and the width of the pulse;
- Electric noise may interfere with low-voltage TDR;
- Determining the correct impedance discontinuity depends on the correct impulse propagation speed and the cable route.

The transform used in the Vector Network Analyzer is similar to time domain reflectometry. The analyzer makes swept frequency response measurements while mathematically transforms data into a TDR – like display. In low – pass mode, the Vector Network Analyzer measures discrete positive frequency points, extrapolates DC, and assumes that the negative frequency response is the conjugate of the positive, i.e., that the response is Hermitian. In the bandpass mode, the Vector Network Analyzer measures discrete frequency points centered between the start and stop frequencies and will work over any frequency range. Using a narrowband receiver (an architecture with down – conversion and filtering in order to obtain an intermediate frequency, IF), the Vector Network Analyzer allows greatly reduced systems noise levels. The translation into an enhanced signal – to – noise ratio permits a superior dynamic range to a TDR. This is relevant in applications where low levels of crosstalk need to be measured in gigabit per second range and higher.

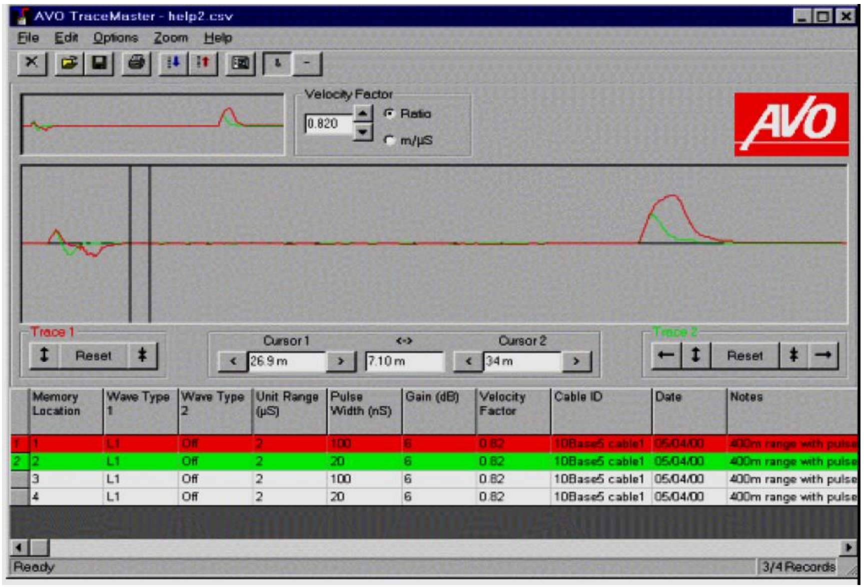

Figure 6. The software oscillogram of a measurement [6]

In any case, time domain analysis continues to be an effective tool which has a wide variety of applications, like:

- fault location;
- identification of the impedance variations in connectors;
- selectively removal of unwanted responses;
- simplified filter tuning.

The main aim of the authors' research [6] is to determine the impedance of the cable electric line in the fault point in order to determine the type of fault and its nature:

- insulation faults with or without ground contact;
- interruptions or serial defects;
- unloading or puncture defects;
- coupling defects;
- defects of discontinuity and cable jacket faults.

For the measurements the TDR 2000 reflectometer in time domain was used, produced by Magger [7], and the processing of the measurements was performed by using the AVO TraceMaster firmware, (see Fig. 6).

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