**REDUCTION OF NON-TECHNICAL LOSSES BASED ON TIME DOMAIN REFLECTOMETER (TDR) PRINCIPLES AND FUNCTION**

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**SUMMARY**

The main idea of this paper is presentation of the useful tool for detection of electric energy stealing on main power cable. Transmission line theory and Time Domain Reflectometer (TDR) was starting point for developing described application for determining of exact length location of illegal connection. Several examples, presented here, show our experiences in method applying.

**INTRODUCTION**

Electric energy distribution process starts in the transformer substation, located on interconnection point between transmission and distribution lines, and end with energy meters at the customers. Distribution system usually consists of power lines of two or even more voltage levels where power transformers step down the voltage. Total distribution power losses are shared due to its cause: technical losses (conductors heating, transformers heating and forced cooling, transformers core magnetizing, isolation imperfections, faults) and unpaid consumption losses.

Total technical power losses in distribution system are sum of the losses of each voltage levels lines and transformers between the voltage levels. Technical losses participation depends on the system geometry, electrical parameters and line effects.

The most of the end-users and power delivering are on the low voltage; so supreme participant of unpaid consumption losses are at low voltage too. They are based on customer pay-ability (payment delays and companies bankruptcy) and stealing of electrical energy. Stealing of electrical energy is electricity serving without energy measuring at the legal meter. It is very important problem during the electric power distribution process that must be corrected. Sometimes, energy stealing in distribution network has deep consequences in power quality (voltage range) for other consumers. Also, power system economy commerce and possible profit depends on losses reduction.

Low voltage network is either overhead or underground, situated usually on public area, and in both cases it is hard to make illegal connection directly on network. Overhead line has got very good check ability so it is almost impossible to do the connection without company permission and if someone manages to do it, connection is probably well visible and endures very short time with serious problems for illegal user. Underground network is not visible at all, but complicated terrain activities have to be done around the power cable. Consequently, power stealing takes place on home connection.

It is hard to find and locate the illegally connection between the home service entrance and the metering point, because the most of illegal connections are inside walls, invisible. Certain households and firms or a part of their installed electric devices are connected on power network without metering of electric energy. Majority household connections are designed in way that metering point is inside the object, so inside parts of house connections are placed inside the walls, through the object tubes and walls that are in the customer ownership or underground in private yard, suspicion become more and more valid.

Today, proposed method for consumer’s power cable inspection and simultaneously detection of length location of eventual illegal connection is in deep use in Croatian Power Company. Understanding the transmission line theory and Time Domain Reflectometer (TDR) principles and practical use is the first step of provided method.

**TRANSMISSION LINE THEORY**

**Basic Principles**

A transmission electric line is well approximated by continuous network structure of the circuit parameters distributed throughout the line. The model circuit segment describes either balanced or unbalanced line by values of four parameters: R1 (conductor’s resistance per unit length), L1 (conductor’s inductance per unit length), G1 (conductance of the dielectric per unit length) and C1 (capacitance between the conductors per unit length). Parameters R1 and G1 are zero for lossless ideal power line.

Transmission line theory differentiates forward travelling waves and reflected waves. Several measurement methods useful for analysis of electrical parameters at discontinuities have been developed using theory, for example application of Inverse Fast Fourier Transform with parameters in the frequency domain or measurement with oscilloscope in the time domain.

**Characteristic Wave Impedance Of Power Line**

Characteristic wave impedance of power line is the ratio between the voltage and the current for an infinitely long line. It depends on lead radius, inter conductor distance and isolation type, but it is independent of line length. The characteristic impedance ($Z_0$) is derived as equation (1):

$$Z_0 = \sqrt{\frac{R_1 + j\omega L_1}{G_1 + j\omega C_1}} \ (\Omega) \ (1)$$
Propagation Constant

Transmission line theory observes the voltage as function of two independent variables: time (t) and distance (x). The voltage travelling down the cable will be attenuated comparing the voltage introduced at the generator by a factor α (nepers per unit length). Similar, the phase of the voltage will be shifted by a factor β (radians per unit length); so propagation constant γ is defined as equation (2):

$$\gamma = \alpha + j\beta = \sqrt{(R_i + j\omega L_i)(G_i + j\omega C_i)} \quad (2)$$

The Propagation Velocity Factor (PVF) is a measure of how cable construction (nowadays isolation) affects the speed of pulse travelling down the cable conductor. To improve measurement accuracy between two cable points, it is need to know exact PVF along the cable lead.

If it is about ideal cable, without resistance and conductance, PVF is calculated as:

$$PVF = \frac{1}{\sqrt{L_1 \cdot C_i}} = \frac{1}{\sqrt{\mu \cdot \epsilon}} \quad (3)$$

where L_1 and C_i are parameters per unit length of ideal cable. Cable design (isolation type and thickness, lead material and geometry), its relative dielectric and permeability are basic parameters for calculating PVF. PVF is usually defined in relative attitude against vacuum light velocity (1 or 100%). PVF in coaxial cable is 0.85, in twisted pair telephone cable is 0.65 and in power cables is 0.5. In practice, it is easy to measure PVF of the cable type as ratio of known length of cable and half of sum of transit and reflection pulse time.

Voltage Reflection Coefficient

The reflected pulse arises depending on impedance (Z) at the end cable point. Assumption made here (losses conditions) is that reflection pulse has equal amplitude at point it starts to propagate back up the line toward the source and at the device screen because of negligible choke. The quality of the power cable is well described by the voltage reflection coefficient, derived as ratio between reflected pulse amplitude and incident pulse amplitude:

$$r = \frac{U_R}{U_p} = \frac{Z - Z_0}{Z + Z_0} \cdot 100\% \quad (4)$$

where $Z = \text{impedance at cable end}$

$Z_0 = \text{characteristic cable impedance}$

If the impedance at cable end (load impedance) is equal to the characteristic cable impedance, there is no reflected pulse, respectively voltage reflection coefficient is zero.

Reflection Shapes

There are several reflected pulse shapes, differs one from another by its polarity and amplitude. The type of characteristic cable point (impedance change) can be determined by analysis of the displayed waveform. Displayed reflected waveform (polarity, amplitude and shape) makes the engineer aware of cable state or cable fault type. Basic cable states are open circuit (high impedance series faults), short circuit (low impedance shunt faults), different cable junction types (series impedance) and cable fault (partial parallel impedance) or illegal cable connection.

TIME DOMAIN REFLECTOMETER

Function Principles

The most usual approach to understanding the time domain responds of any power system is to solve Maxwell’s equations in the time domain. TDR is measurement device designed for cable testing, electrical installation fault investigation, detection of the fault location and cable length measurements. TDR is used for cables investigation in power and telecommunication systems; wherever there are no direct connections with the ground - so, other simpler methods can’t be used for the same purposes.

TDR is comprised of sinusoid signal generator and simple oscilloscope. Connection cable investigation operates in phases, depending on a number of leads in the cable. The two tested leads have to be connected at the one cable end to exact locate cable end, while TDR is connected between two leads at the other end of cable. Short duration incident pulse is launched into the cable connection under examination by wave generator. That pulse travels along the lead and split in two new pulses - transmitted and reflected, at the place of cable damage, other cable end or whatever other geometry changes along the connected leads (caused by any impedance change). The time taken by the incident pulse to travel between TDR and place with impedance change and return time of reflection pulse is a measure of the two points cable distance knowing the wave speed. The incident, transmitted and reflected pulse are monitored by the oscilloscope at a definite point on the cable. So, basic principle of TDR function is pulse reflection, similarly as for radar operation.

Characteristic point location in power cable

Distance from the one end of cable to characteristic point is determined by product of PVF and half of sum of transit time - required for the incident pulse to come to characteristic cable point, and transit time required for reflected pulse to propagate back to monitoring point.

Illegal Connection Shape of Pulse Response

Here, expression for reflection coefficient is derived from equation (4) by replacing impedance at cable end with parallel impedance of metering and connected cable. Voltage reflection coefficient shows negative polarity of reflection pulse at the “T” connection, independent on illegal cable length. In this case, voltage reflection coefficient can be written as in equation (5):
where,
\[ Z_{0p} \] - characteristic impedance of illegal cable
\[ Z_0 \] - characteristic impedance of metering cable

Following characteristic reflected pulse shapes on real cables registered by TDR are shown on Figure 1:

- A - Open circuit,
- B - Short circuit,
- C - Same type cable junction (\( Z = Z_0 \)),
- D - Different type cable junction (\( Z < Z_0 \)),
- E - Different type cable junction (\( Z > Z_0 \)),
- F - Illegal cable connection

Figure 1. Characteristic reflected pulse shapes

**METHOD OF TESTING THE MAIN POWER CABLE**

This method can be divided in two parts:
- testing the main power cable section between main fuses and electric power measurement device (cable opened on both ends),
- testing live main power cable section by the AC blocking filter between main fuses and distribution low voltage network.

**Opened Ends of the Main Power Cable**

Testing the main power cable section between main fuses and el. power measurement device is made in following steps:
- disconnect the cable in the beginning (main fuses) and in the end (el. power measurement device) so we can use “clean” cable opened on both ends,
- connect TDR between two leads at the one end of cable, set the parameters (measurement range, pulse width, gain, PVF), record the pulse transmission picture and all reflected pulses, repeat for all phase and neutral leads combinations,
- short the leads on the other end of tested cable, record the picture of transmit and all reflected pulses, define the characteristic point of the end of the cable and measure the length,
- in the case of regular tested main power cable without illegal connection it is clear to see transmit pulse and next reflected pulses: TDR’s test and cable leads junction and open or short circuit on the end of the tested cable,
- TDR can be connected to the other end of tested cable if certain suspicious parts can be seen more clearly from the other end.

If there’s illegal connection on the tested main power cable, picture of reflected pulses is changed, depended on place, length and condition of illegal connection. So we have following cases and their combinations:

1. the spot of illegal connection closer to the beginning, middle or end of main power cable,
2. shorter or longer illegal connection,
3. end of illegal connection opened respectively to connect any kind of electric device.

1. The spot of illegal connection: TDR can be connected on both ends of tested cable for better visibility of illegal connection reflected pulse shape closer to end of tested cable, because of pulse attenuation in real cable.
2. Length of illegal connection: Longer cable of illegal connection results with better visibility of illegal connection reflected pulse shape as well as reflected pulse shape extra attenuation of main power cable open end.
3. Condition of illegal connection: If customer have connected el. device of the end of illegal connection cable, reflected pulse shape of main power cable open end is almost completely smothered.

**Live Main Power Cable Testing**

This option is used in:
- partial control of main power cable from main fuses to overhead low voltage network connection through private customers building,
- control of underground main power cable from main fuses to connection with "T" joint on underground low voltage network, if cable is placed through customer private yard.

In this case, only useful method in illegal connection location is step-by-step review with proper gain and zooming each section of tested cable.

**GRAPHICAL EXAMPLES**

**Opened Ends of the Main Power Cable**

Figure 2. shows incident pulse of instrument, transmit pulse marked with left cursor and open end reflected pulse marked with right cursor on regular main power cable without illegal connection. Return loss (pulse attenuation) has to be within expected parameters.

Figure 3. shows comparison (dual mode-red and green line) and difference (black line) method in order to locate an illegal connection more easily with connecting TDR to two different pairs of leads on the same end of a cable.

Figure 4. is similar to Figure 3., where TDR is connected to the same pair of leads on both ends of a cable.

**Live Main Power Cable Testing**

Figure 5. shows comparison (dual mode) and difference method for regular pair of leads (red line), and another pair of leads with an illegal connection (green line).
Figure 2. Regular main power cable (main fuses - meter)

Figure 3. Main power cable with illegal connection (usage of dual and difference mode from the same end of cable)

Figure 4. Main power cable with illegal connection (usage of dual and difference mode from the both ends of cable)
CONCLUSION

Described method is recommended for finding out all illegal connection types, located on main home power cable. Testing measurement duration of a main home power cable is about 30 minutes. Transmit and reflected pulses of main power cables, recorded in TDR internal memory, can easily be stored on PC and used for future comparing and analyzing of same main power cables testing. This method enables almost immediate look on connection cable correctness and improve power quality and loss reducing. Best results are accomplished by combining this method with usage of Wire Tracer. With this instrument we can efficiently locate traces of main power cable and eventual illegal connection within walls, and so confirm the results of testing with TDR.

REFERENCES